Biotechnology in Agriculture and Forestry 67

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Series Editors

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Convergence of Food Security, Energy Security and Sustainable Agriculture

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Convergence of Food Security, Energy Security and Sustainable Agriculture

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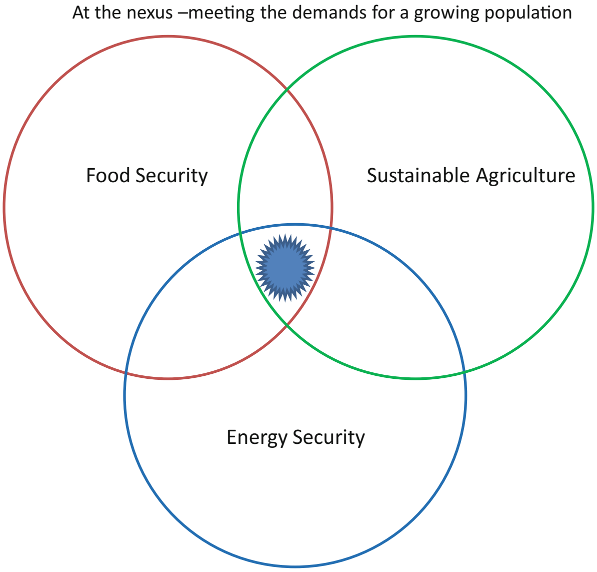
Foreword



Climate change, elevated carbon dioxide levels, exponential growth of humankind over the next half century, insufficient arable land to support the population, polluted fresh and marine waters, and decreased easily accessible and available energy sources are among the principal concerns of governments, scientists, and people across the globe as we continue into the twenty-first century. We are constantly bombarded and reminded with increasing urgency of the need to find solutions to these problems from a number of media sources, including nightly television newscasts. However, the “lay” opinions of various perceived problems often do not accurately reflect scientific knowledge and opinion. Furthermore, the popular press, as well as numerous scientific papers and reviews, have tended to key on only a few of these concerns at a time, but have failed to consider them in the context of their relatedness to each other. The diagram above is symbolic of the convergence of the ideas expressed in this book. Food/energy security and sustainable agriculture are inseparable issues in that each significantly affects the other. For example, changes in food prices are often attributed to the price of oil. A focus only on food security often results in unrealistic conclusions that are not energy secure or sustainable. In order to examine all three related issues within the context of each other, *Biotechnology in Agriculture and Forestry: Convergence of Food Security, Energy Security and Sustainable Agriculture* has integrated them into a focused discussion of sustainability and security. This book contains chapters written by renowned international authors, whose first-hand experiences have made them uniquely qualified to address and define the problems as well as to synthesize and propose potential solutions.

The book is launched by three poignant chapters concerned with sustainable food and energy policy in Part I. In these chapters, the authors remind us that among the critical needs in the near future will be food and energy security. The authors pursue sustainable solutions through innovation and research including rethinking and reconfiguring bioenergy production as well as regulatory issues.

Part II contains two chapters that are primarily devoted to sustainable land and water use. Soil conservation tactics including control of erosion, tillage, enhancement, and improvement are discussed in the context of sustainable agriculture. The second chapter also features the impact of technology and policy on land use.

Part III includes two chapters devoted to sustainable and secure food production. In this section, the first chapter explores why GMOs have received bad press from the popular media in the past and how corporations might better package their message to allay public mistrust. In the second chapter, the authors make a case for using soybeans as an excellent economical and sustainable source of omega fatty acids for human diets instead of depending on cold water fish species, which are less sustainable and perhaps even unsustainable in the future given overfishing.

Part IV has three chapters that discuss sustainable agriculture. In the first chapter, current and future "best practices" are examined in the context of sustainable agronomic systems. The authors of the second chapter in this section discuss soybean breeding throughout the twentieth century and related the gains made in yield to sustainability. The third chapter explores the tremendous impact that herbicide-tolerant crops have had on the food and fiber sources in the world as well as links the use of GMO crops and reduced tillage to soil quality improvement.

Part V looks at sustainable agricultural and food security at the international level. The first chapter in this part examines how the introduction of Bt resistant cotton varieties has significantly reduced use of herbicides, increased yield, and resulted in economic improvement in west Africa. The second chapter outlines the international educational and training programs of the Borlaug Institute. These programs have tremendous impact on sustainable agriculture in developing nations. The third chapter in this part describes a partnership between traditional breeding and biotechnology (Bt) to develop higher yielding, drought-tolerant white hybrid corn cultivars for farmers of sub-Saharan Africa.

Part VI examines the importance of agricultural chemicals and nutrient management in sustainable agricultural systems. The first chapter relates herbicide usage and weed control to soil management of erosion and water and fuel economy. The second chapter explores a program nutrient best management practices and improving nutrient use efficiency for crops.

Biotechnology in Agriculture and Forestry: Convergence of Food Security, Energy Security and Sustainable Agriculture will serve as an important source of information for regulators, scientists, and laymen alike. It will stimulate a much-needed discussion of food and energy security as they relate to sustainable agriculture and foster a rational basis for making decisions on crucial issues that affect our daily lives.

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Preface

One of the greatest concerns of the current generation is how are we going to provide food for the next generation in a manner that respects our finite natural resources. However, perhaps the critical question is how are we going to feed the next two generations especially with a global population expected to exceed nine billion people by 2050 (http://esa.un.org/UNPP and http://www.census.gov/main/www/popclock.html). With the expectation of feeding a growing population, additional pressure is placed on how we more efficiently utilize the natural resources required for food production. This includes land, water, fertilizer, and other resources and how to employ these in a sustainable manner. We are concerned about appropriate management of our agricultural resources at the beginning of the twenty-first century; therefore, it is imperative that we start to plan now for managing these resources in a sustainable way for the year 2050 and beyond.

From the time man made the transition from a nomadic to agrarian society, land has been altered for the purpose of growing cultivated crops. The earliest record of deforestation for the purpose of plant cultivation was approximately 9,000 years ago in the Ghab Valley of Northwest Syria (Yasuda et al. 2000). Since this time, man has primarily relied on incorporation of more land for agricultural production as the primary means for increasing food production at the expense of the native species that were originally present. Increased incorporation of arable land for food production continues today, particularly in developing countries. The FAO in a 2012 report by Alexandratos and Bruinsma described both increase and decrease of arable land for food production projections. More specifically, there will be a reduction in arable land in developed countries (North America and Europe primarily) and an increase in land for producing food in developing countries (primarily Asia, South America, and Africa). Within Latin America, it has been estimated that the rate of deforestation of humid tropical forests to be 5.8 ± 1.4 million hectares lost each year, with a further 2.3 ± 0.7 million hectares of forest visibly degraded (Achard et al. 2002). The net change across all world regions inclusive of developing and developed countries is for more land to be used for food production (Alexandratos and Bruinsma 2012). With land being a finite resource, continuing this pattern is not sustainable. Therefore, it is imperative that food production be increased on the land that is currently utilized for agricultural purposes.

In a recent FAO report, How to Feed the World in 2050, the three drivers affecting food security are population growth, increase in urbanization, and increase in income (FAO 2009). A good example of increased urbanization and increased income over the past decade has been in Asia, particularly China and India (Zhou et al. 2004; Bloom and Finlay 2009). It is expected that additional demand on the food system will come from those individuals living in countries with rapidly growing economies where the variety of foods consumed will likely increase (Edgerton 2009). This additional pressure on food production will increase in addition to the pressure placed by the demand due to an increase in the sheer number of people by 2050.

The World Health Organization in 1996 defined Food Security as when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life. The USDA, in a 2013 study by Coleman-Jensen et al., defined Food Security as households that have consistent, dependable access to enough food for active, healthy living. Furthermore, the authors quantified this and determined that 85.5% of U.S. households were Food Secure throughout all of 2012, indicating that 14.5% of U.S. households were Food Insecure at least some time during the year in 2012. The WHO and USDA definitions are certainly similar in scope, and there is some ambiguity in the details.

Hand-in-hand with Food Security is Energy Security. The International Energy Agency (IEA) defines Energy Security as uninterrupted availability of energy sources at an affordable price. The United States Congressional Budget Office defines Energy Security as the ability of households and businesses to accommodate disruptions of supply in energy markets. Clearly these definitions define energy security from two different perspectives and leads to ambiguity regarding the discussion involving energy security.

What is the definition of Sustainable Agriculture? Recently, in the United States, there has been considerable pressure to alter the definition of sustainable agriculture from how it is defined by the United States Department of Agriculture. It is important to have a definition that is endorsed by the Federal government as it will serve as the central element for program grants, such as the Sustainable Agriculture Research and Education (SARE) program through NIFA. The definition of sustainable agriculture utilized by SARE is as follows:

The term “sustainable agriculture” (U.S. Code Title 7, Section 3103) means an integrated system of plant and animal production practices having a site-specific application that will over the long term:

- Satisfy human food and fiber needs.
- Enhance environmental quality and the natural resource base upon which the agriculture economy depends.
- Make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls.
- Sustain the economic viability of farm operations.
- Enhance the quality of life for farmers and society as a whole.

The 1990 U.S. Farm Bill emphasizes sustainable agriculture upon three key components: environmentally friendly, economically viable, and accepted by society.

The debate over the definition of sustainable agriculture has been ongoing for several years (see Redick, Chap. 3) and extends far beyond the United States to virtually every country in the World. In the future, there will be a need for a global definition of Sustainable Agriculture that spans all the continents. Clearly a balance is necessary regarding the definition of Sustainable Agriculture and, more so, regarding the interaction of Food Security, Energy Security, and Sustainable Agriculture. This was the impetus behind the creation of this book and its title "Convergence of Food Security, Energy Security and Sustainable Agriculture." It is the convergence where we need to be as a global community to serve the caloric needs of humanity. It is the convergence where we need to be as a global community to grow the food that we need for life. It is the convergence where we need to be as a global community to insure that our children and grandchildren have food to eat in the next generation and beyond.

San Diego, CA David Songstad

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Part I

Food and Energy Security and Sustainable Agriculture Policy

Chapter 1
Creative and Innovative Research: Our Only Hope for Achieving Sustainable Food and Energy Security

Gale A. Buchanan and Raymond L. Orbach

1.1 Introduction

1.1.1 Energy Security

Few issues grabbed the attention of the American people as did $4 gasoline in the summer of 2008 (U.S. Energy Information Administration http://www.eia.gov). Since then, any decrease in the price of petroleum and petroleum-based products carries the potential for a return to the days of profligacy. Sales of fuel efficient vehicles spiked at the height of gasoline prices but slowed with softening of gasoline prices. However, there is evidence of increasing public concern with development of more hybrid and electric cars. In fact there are approximately 30 companies developing hybrid or electric vehicles at present. Success of each of these ventures remains to be seen. While there are those who are no longer concerned about the seriousness of energy challenges, it is clear that basing our country's energy future on fossil fuel alone, a finite resource, is not a viable course for the United States or any nation.

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1.1.2 Food Security

Food security is quite a different matter, but is just as serious. Today there are some one billion people who do not receive adequate caloric intake for good health (Gates Foundation, http://www.gatesfoundation.org/agriculturaldevelopment). Approximately 80 % of undernourished people live in seven countries: China, India, Bangladesh, Pakistan, Ethiopia, Indonesia and the Democratic Republic of Congo (UN-FAO 2010). Adequate nutrition is the first step toward societal advancement in education and infrastructure development in rural and urban communities (http://www.gatesfoundation.org). Associated with this are the people, perhaps as many as a billion, that do not receive adequate protein, fat, important minerals, and/or essential vitamins. For example, it is estimated that several hundred thousand individuals lose their sight or perish each year due to vitamin A deficiency (Potrykus 2010). The FAO reports that a child dies every 6 s from undernourishment (UN-FAO 2010).

Achieving sustainable food security and energy security are two of the most important challenges facing our planet. Both food and energy are critically necessary for survival of our civilization as we know it. While agriculture is only a part (most would argue a critical part) of the energy challenge, agriculture is totally responsible for the food challenge. This challenge involves not only increasing supply but also facilitating the movement of produce from farms to communities where the food is needed. In many regions of the world, linking the harvest of crops to the market is a challenge because of a variety of issues including transportation, infrastructure and lack of commodity price information in the marketplace (Gates Foundation, http://www.gatesfoundation.org/topics/Documents/agricultural-development-fact-sheet.pdf).

1.2 Challenges and Expectations

1.2.1 Energy Consumption

Global energy consumption is going to increase steadily for the next several years. The United States Energy Information Administration estimates that world marketed energy consumption will increase by 49 % from 2007 to 2035. Total energy demand in non-OECD countries will increase by 84 % compared with an increase of 14 % in OECD countries (http://www.eia.doe.gov/oiaf/ieo/highlights.html). The estimated energy consumption in 2035 will be 739 quadrillion British Thermal Units (BTU), which is double of that consumed in 1990 (http://www.eia.doe.gov/oiaf/ieo/world.html).

If we attempt to supply the total transportation fuel needs with fossil fuels, the rate of increase of greenhouse gases (GHG) emitted into the atmosphere will continue to accelerate (U.S. Energy Information Administration http://www.eia.

doe.gov/oiaf/ieo/emissions.html). We must find ways to meet the increasing demand for energy without adding irresponsibly to greenhouse gases. Wang et al. (2007) reported that GHG emissions for corn-based ethanol are reduced by as much as 52 % compared with that from gasoline. This, of course, may be reduced because of slightly less energy content of ethanol. Furthermore, considering the impact of research as a whole, Burney et al. (2010) estimated that each dollar invested in agricultural yields has resulted in 68 fewer kgC (249 kgCO_2e) emissions relative to 1961 technology ($14.74/tC or approximately $4/t$CO_2$e), avoiding 3.6 GtC (13.1 GtCO_2e) per year.

1.2.2 Future Food Production

Dr. Norman Borlaug, recipient of the 1970 Nobel Peace Prize, the U.S. Presidential Medal of Freedom, and the U.S. Congressional Gold Medal is known as the "Father of the Green Revolution" for his pioneering work developing high-yielding wheat varieties for areas with limited cultivated land and increasing population. In 2002, Dr. Borlaug gave a speech commemorating his receiving the 1970 Nobel Peace Prize where he stated, "It took some 10,000 years to expand food production to the current level of about five billion tons per year. By 2025, we will have to nearly double current production again. This cannot be done unless farmers across the world have access to current high-yielding crop-production methods as well as new biotechnological breakthroughs that can increase the yields, dependability, and nutritional quality of our basic food crops." In Dr. Borlaug's (see Borlaug et al., Chap. 12) last written words to the scientific community, in CAST Issue Paper 45 he recounts, "We made great strides in the first Green Revolution by bringing improved agricultural techniques, seeds and technology to poor underdeveloped and developing countries. But in the next 50 years we're going to have to produce more food than we have in the last 10,000 years, and that is a daunting task. I, therefore, have called for a second Green Revolution" (Council for Agricultural Science and Technology (CAST) 2010).

The demand for both food and energy will increase dramatically in the coming decades. Agricultural economists have projected the demand for agricultural production at 143 % of year 2000 output in 2025 and 179 % of 2000 output in 2050 (Tweeten and Thompson 2009). This is primarily driven by the fact that demographers predict that world populations will reach 9.2 billion by mid century (Bongaarts 2009), over a two billion increase above the approximately 7.2 billion people living on the planet in 2014 (http://www.census.gov/main/www/popclock.html). Specifically, nearly all of this future growth occurs in Africa, Asia (excluding Japan, Australia and New Zealand) and Latin America (Bongaarts 2009).

People around the world have rising expectations for enhanced quality of life that includes improved health, better nutrition, more meat and dairy products (Deaton 2008; Edgerton 2009). People also want many of the other things that make for a better life such as a comfortable home and personal transportation.

Dahl (2005) reported that in 2001 China identified auto manufacturing as one of the key "pillar" industries of the Chinese economy and announced a 5-year plan to implement a primarily domestic industry that could offer a Chinese family car at a price that would encourage widespread ownership. As a result of this, between 2000 and 2004, production of passenger cars in China jumped from 605,000 to 2.33 million. This is just one example of an emerging economy that will increase the demand for energy. As this demand for energy increases, the need for renewable fuel development will become paramount. This is especially true given total fossil fuel production will continue to grow, but only slowly for the next 15–30 years and then reach a peak plateau for another 10–15 years (Nehring 2009). Ultimately, world fossil fuel production per capita will begin an irreversible decline between 2020 and 2030 (Nehring 2009). If alternatives to fossil fuels are not identified, global energy insecurity will result during this century.

1.2.3 Food Security and Energy Security Are Inseparable

It is important for society to realize that food security and energy security are inseparable. In 2008, there was concern that corn-based ethanol and soy-based bio-diesel were the reasons for rising food prices. Since this time, several economic studies have been published that describe corn and soybean use in biofuels as one of several reasons of the rise in food prices. The other reasons include the devaluation of the US dollar, rising price of oil, increased demand for food in emerging economies (e.g., China and India) and weather conditions that affected crop production (Abbott et al. 2008; Henderson 2008; Armah et al. 2009). Ironically, food prices fell in 2009 as the price of oil also decreased; however, in 2009, there was 10.6 billion gallons of corn-based ethanol produced versus 9.0 billion gallons in 2008 (http://www.ethanolrfs.org). Domestic food security in the United States has been and is a reality today because of three main assets. These include (1) our agricultural research and education system that develops and transfers new and innovative technology and business practices, (2) management skills and abilities of farmers and ranchers and the agricultural industry to adopt new and innovative technologies and (3) the natural resource base of this country that includes productive soils, a favorable climate and nutrient and water resources. A portion of our domestic energy requirement can be as secure as food in this country because it requires similar assets.

Sugarcane is also a crop with food and fuel utilities. It is predicted that by 2020, Brazil will be planting approximately 14 million hectares of sugarcane, producing more than one billion tons of cane, 45 million tons of sugar, and 65 billion liters of ethanol (Matsuoka et al. 2009). Furthermore, and also in Brazil, the burning of bagasse (crushed cane stalks) is expected to produce enough electricity to meet or exceed that produced by hydroelectric (Jank 2008). It is interesting that combustion of bagasse for power is not a new idea; it was first described as a fuel source for power production approximately 80 years ago (Adams 1934).

Meeting the demand for food and fuel in sugarcane has been met by using improved technology. Development of new sugarcane varieties has reduced the risk of yield losses to disease, and this has contributed to the 50 % increase in average yield since 1975 leading to a dramatic increase in ethanol production from 2,500 l/ha in 1975 to about 7,000 l/ha currently (Goldemberg 2008). It is estimated that sugarcane breeding can contribute significantly to realize the predicted 9,000 l/ha alcohol production for the next decade (Matsuoka et al. 2009). Again, sugarcane as a food and fuel crop joins corn and soybeans as testimony that food security and energy security are inseparable.

1.3 Energy

1.3.1 Future Energy Needs and Greenhouse Gases

One critical question today is how the energy needs of the future world economies will be met without adding dangerously to atmospheric greenhouse gases. The energy and environmental challenge confronting us in this century is truly monumental. It is one of the most important challenges our civilization has faced.

1.3.2 Alternative Energy Sources

Achieving sustainable energy security requires both more efficient use of energy and the development of new energy sources. The fundamental truth is that fossil fuels are a finite resource that will one day become so expensive that we shall be forced to seek alternatives (Nehring 2009).

It is fortunate that we have come to this realization with time to improve efficiency and to develop alternatives. It is safe to say we are rapidly exiting the era of cheap energy and entering a stage of increased cost of petroleum based on information provided by the Energy Information Administration (Fig. 1.1). We are also entering an era where the predictability of fossil energy costs is somewhat uncertain due to increased global demand and diminished supplies as evident by the variability in price shown in Fig. 1.1.

We have several alternative energy options: wind, hydro, biomass, geothermal, nuclear, solar, ocean waves, and currents. While each of these options has unique features and attributes, they have one thing in common—the need for more research to enable them to reach their full potential to become a practical part of the energy solution (Council for Agricultural Science and Technology (CAST) 2010). These alternative energy options must ultimately be competitive with fossil fuel costs eventually without subsidies, and they must be sustainable without harm to the environment.

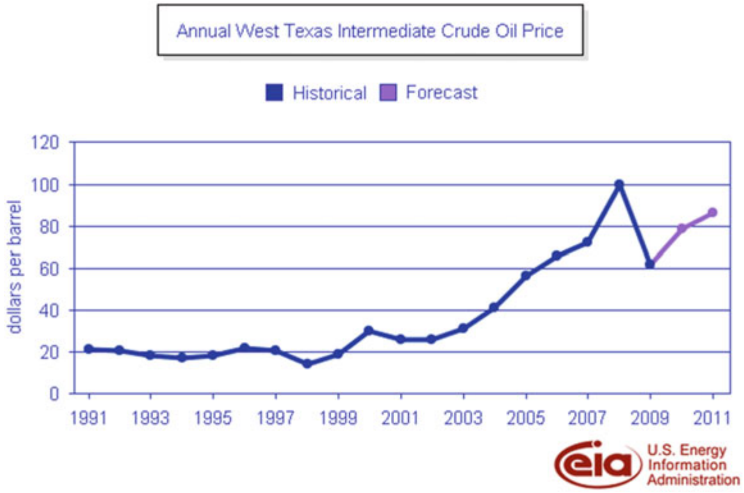

Fig. 1.1 Annual West Texas intermediate crude oil price

Each of these approaches has differing degrees of potential. Nuclear power lost luster after Three Mile Island especially the Chernobyl and Fukushima daichi disasters. The impact of the last nuclear reactor incident in Japan following the 2011 earthquake/tsunami is still being determined (Christodouleas et al. 2011). However, nuclear power's widespread use in some countries, notably France, puts this option squarely back on the table. A recent National Academy of Sciences report indicates that spent nuclear fuel can be mined for its energy through use of alternative (closed) nuclear fuel cycles that reprocess used fuel to produce new fuel. In principle, these alternative fuel cycles could extend fuel supplies and reduce the amount of long-lived nuclear waste (National Academy of Sciences 2010). Many see wind, geothermal, and hydro as great options (Lu et al. 2009), but with limited current capacity. Solar energy, utilizing photovoltaic cells and green plant photosynthesis, offers great potential (Lewis and Nocera 2006). The sun provides an inexhaustible source of energy at least for the next 3–5 billion years. Sufficient energy from the sun reaches the earth in 1 h to supply our every need for a full year (Lewis and Nocera 2006). The challenge is to capture the sun's energy in a usable form and to build systems that can supply energy on an uninterrupted basis to meet demands. Another advantage of the sun's energy is that it is available to all nations on the planet. Harnessing the sun's fusion energy process on the earth, though complex and difficult, is yet another avenue to explore. The construction of ITER is underway in France, with hopes for provision of electricity into the grid by 2050 (Harding et al., 2012).

1.4 Food

1.4.1 Development of an Agrarian Society

At one time in our civilization, food was a finite resource just as fossil energy is today. The development of agriculture not only enabled food to become a sustainable resource, the transition from a nomadic to agrarian society has resulted in a positive human experience where we now live longer and have generally happier lives (Veenhoven 2010). As this occurred, more and more people were freed to make the kind of contributions needed to build a civilization as we know today.

1.4.2 Domestication of Plant and Animals

Over the past 8,000 to 10,000 years man has become adept at agriculture (Diamond 2002). He has learned, mostly by trial and error, what species of plants and animals can be domesticated, how different geography and climates can be employed to grow such plants and animals, how to harvest the most desirable part of such plants and animals, and how to process and preserve the desirable aspects of these plants and animals. But man didn't stop there. One can speculate that for most of the first 8,000–10,000 years, his only tools were selection of the most desirable plants and animals. Perhaps the best example of early domestication of a crop is the domestication of modern maize from teosinte (Beadle 1939). However, it was the rediscovery of Mendel's publication that led to the serious effort towards incorporating research in agricultural experimentation and improvement. In this country, with the coming of the land grant universities, research was greatly strengthened, particularly in agriculture and the mechanic arts.

1.5 Energy Research

We remain convinced that achieving sustainable energy security can be accomplished through focused, dedicated, and adequately funded research and education programs. The successful pursuit of achieving a greater degree of energy security can be achieved through development of information, knowledge and technology. We must understand the long-term opportunities and risks before we deploy a proposed technology or process. Bypassing the research step will waste money and will lead to disillusionment and delay of success. There are many unknowns, and it is impossible to predict when a particular problem will be solved. However, the greater the commitment to research, the sooner there will be a solution.

1.5.1 USDA and DOE Committed to Energy Security

The Department of Energy (DOE) and the Department of Agriculture (USDA) are committed to performing the research that enables each of these agencies to reach their full promise. It is encouraging to see other Federal agencies, the Nation's universities and American industry becoming committed to these grand challenges. Nevertheless, government investment in research must be done in a stepwise manner that prevents overinvestment and promotes prudent investment in experimentation designed to promote energy security.

Achieving sustainable energy security for this country is one of the most daunting challenges we have ever faced. So far, the Nation's commitment to scientific research to deal with these challenges often ends in contentious debate rather than reaching consensus directed toward specific outcomes that can be measured and evaluated. However, there does appear to be an awakening to the need for greater investment in research. The past administration has made a sound, yet modest start. Hopefully, the current administration will pick up the challenge and keep the emphasis on strengthening research efforts.

1.5.2 Research Required to Reach Full Energy Potential

Each of the approaches to addressing the energy challenge including wind, geothermal, nuclear, solar electricity, solar biofuels, ocean and river currents, ocean waves and perhaps others require considerable research in order to achieve full potential of the approach. For example, the solar biofuels approach requires a far better understanding of sustainable production and harvesting of biomass. While we have had literally thousands of years to identify the most desirable plant species for food, there is great need to identify and settle on the most desirable species for energy. There is the long process of genetic improvement of these species for best energy production. It's a bit ironic that the most successful solar-biofuel approach to date is using centuries old plant species (sugarcane and corn) and centuries old conversion technology (yeast fermentation) to make ethanol. Other research challenges involve developing better approaches to conversion technology. This requires new and innovative technology for fuel production from cellulose, hemicellulose and lignocellulose. Arguments could be made for each of the other approaches to meeting the energy challenge. It is abundantly clear that there is significant research that must be done if we are to achieve sustainable energy security.

1.6 Food Research

1.6.1 Civil Stability Through Agriculture

Civilization as we know was made possible by agriculture. Indeed, as agriculture evolved, more of the population could pursue an education and contribute directly to the development of the activities that are now integral parts of our civilization. As the concept of research developed, the pace and advance of our civilization quickened. Associated with this development was an increase in population of the planet. This "transformation" has occurred in such a slow and deliberate fashion that most people do not realize or even appreciate how agriculture made our civilization possible. The demands and expectations facing agriculture and our current global civilization are daunting and can only be met by a constant infusion of new information, knowledge, and technology that can be gained only by research.

1.6.2 Second Green Revolution

There are several potential areas for research that could provide the new information and knowledge that could bring about a second green revolution. Briefly, this includes enhancing the quality of soils (see Hatfield, Chap. 4), enabling C_3 plants to utilize the C_4 photosynthetic pathway, nitrogen fixation in nonlegumes, incorporating the process of apomixes into crop plants, enhancing water and nutrition efficiency of crop species, improving energy efficiency of plants, improving pest resistance in plants and developing commodities with enhanced health benefits. Another important approach would be to develop new processing and conversion technology to provide for more efficient conversion of cellulose, hemicelluloses, and lignocelluloses to fuel (Council for Agricultural Science and Technology (CAST) 2010).

1.7 Ensuring Success

It is quite apparent that our planet must achieve sustainable food and energy security if our civilization is to survive and certainly to thrive. Furthermore, the need to realize that food and energy security are inseparable is key to our ability to achieve sustainability for each. Examples of this exist in corn-based ethanol (see Hughes et al., Chap. 2) where dried distillers grains (DDGS) are produced and used as animal feed where it can provide 35 % to 40 % of the nutritional value to feedlot cattle (Council for Agricultural Science and Technology (CAST) 2006). Ultimately, the inseparable nature of food and energy security goes back to the sun and the fact that it provides the energy required to produce plants for food and biofuels.

Research is a deliberate methodical process where every success answers questions but always opens vista with more questions to be addressed. This is, of course, how progress is made. There are no shortcuts to success. Most research advance comes in several incremental successes and with an occasional "breakthrough." Production of ethanol from cellulosic materials is receiving much research focus and funding, especially through the Department of Energy (Miller and Keller 2009). The path forward has been described in a review paper by Ragauskas et al. (2006) as one with options that must keep the carbon balance in perspective as well as recycling carbon waste from the refining process. In addition to fermentation as a means of producing biofuels, themochemical conversion of cellulosic biomass to biofuels is also an option (Phillips et al. 2007; Tao and Aden 2009). While cellulosic ethanol is being developed, Carlson et al. (2010) has proposed harvesting ethanol from corn-based ethanol and then combining the DDG by-product with biomass residue (corn stover, grass hay, wheat straw, etc.) to provide a cattle feed of elevated nutritional value.

Our survival requires that we have sustainable food and energy. This requires that we first conduct the research necessary to provide information, knowledge, and technology to address the challenge necessary for an adequate supply of both food and energy. It is foolish to try and implement a technology before fully understanding the research and its applications. Assuring success requires understanding the strengths and weaknesses of any new technology, which is the "development" portion of R & D.

We urge the U.S. Administration and all levels of Government and private industry to build on earlier efforts and commit resources to ensure a robust effort led by the Federal government and joined by the Nation's universities, nongovernmental organizations, and industry to perform the research that will enable this nation to achieve sustainable energy and food security.

We have no alternative.

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Chapter 2
Moving Toward Energy Security and Sustainability in 2050 by Reconfiguring Biofuel Production

Stephen R. Hughes, Bryan R. Moser, and William R. Gibbons

2.1 Introduction

For secure and sustainable bioenergy and biofuel production to become a reality by the middle of the twenty-first century, building on the current infrastructure and existing technology is essential. However, at the same time, we must make substantial improvements and/or changes in the feedstocks used, the process technologies applied, and the fuels produced, to achieve true sustainability (see Buchanan and Orbach, Chap. 1). A critical question is: What role will advanced biofuels play in the energy portfolio of the world 20–50 years from now? There is increasing evidence that commercial biofuel production can be reconciled with feeding humanity and preserving the environment, provided that we invest the time and effort needed to make the improvements necessary to achieve this goal (Lynd and de Brito Cruz 2010).

The biofuel production concept described in this chapter has the potential to meet the challenges of sustainability, sufficient supplies, and economic feasibility by combining proven technologies with promising innovations that are currently under development. We envision a decentralized, community-based system with integrated crossover bioprocessing units to convert biomass into third generation drop-in biofuels (long-chain alkenes, alkanes, and alcohols) and bio-derived chemicals. These systems could be developed on green-field sites or built onto first or second generation biofuel (biodiesel, ethanol) facilities.

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Such systems will require advancements in feedstocks used to produce biofuels and chemicals (Perlack and Stokes 2011). Plants (trees, row crops, grasses) bred for rapid growth, high yield, and desirable composition will be needed to support multiuse production of food, feed, fuels, and chemicals. Perennial plants able to grow with minimal inputs (fertilizer, pesticides, irrigation water) on lower quality (fallow) land would be most desirable in terms of sustainability. However crop residues or cover crops could provide dual use of land, as well as increased sustainability (Perlack and Stokes 2011; see Sripada et al., Chap. 8). Single-celled phototrophs (e.g., algae or cyanobacteria) that can fix CO_2 into oil are also emerging as potential feedstocks. Compared to the current biofuel production system, cyanobacteria, as autotrophic prokaryotes, do not require arable land and can grow to high densities by efficiently using solar energy, CO(2), water, and inorganic nutrients. Moreover, genetic techniques for cyanobacteria have been developed, and recently several chemicals including ethanol, isobutanol, and isoprene have been produced directly by engineered cyanobacteria (Zhou and Li 2010).

Advanced conversion systems are also needed to transform biomass feedstocks into biofuels and chemicals. Efforts to improve the biochemical platform are focused on pretreatment strategies and engineering microbes and their enzymes to deconstruct carbohydrate polymers and produce long-chain hydrocarbons or alcohols. Thermochemical efforts are being directed toward integrated thermocatalytic processes that can readily switch among a multitude of feedstocks. Conversion systems of the future must optimize the value of products produced, minimize energy and water use, be scalable to distributed processing networks (to minimize feedstock logistics challenges), and produce minimal waste products.

While the United States has produced corn-based fuel ethanol for over 30 years, a comprehensive energy security plan was lacking prior to the Energy Policy Act (EPAct) of 2005. To meet the requirements of the EPAct, EPA adopted a limited program that applied to the year 2006. This was followed by a more comprehensive program in May 2007 referred to as the Renewable Fuels Standard 1 (RFS1). Under RFS1, the required renewable fuel mandate for 2006 was set at 4.0 billion gallons, and this was to ramp up to 7.5 billion gallons by 2012. The Energy Independence and Security Act of 2007 (EISA) made significant changes in the structure and magnitude of the renewable fuel program. The revised statutory requirements of EISA specify the volumes of cellulosic biofuel, biomass-based diesel, advanced biofuels, and total renewable fuel that must be used in transportation fuel yearly from 2010 to 2022. The EISA fuel program, designated RFS2, mandates the use of 15.2 billion gallons/year of renewable fuel by 2012 and 36 billion gallons/year by 2022 (Federal Register 2010).

In 2010, US corn ethanol plants produced over 12 billion gallons of ethanol from 4.568 billion bushels of corn (Wilson 2011). The majority of the increased biofuel production called for in RFS2 is mandated to come from cellulosic feedstocks and is targeted at 16 billion gallons by 2022. Second generation biofuels include cellulosic ethanol and cellulosic diesel. Along with a projected 15 billion gallons/year of corn ethanol and 5 billion gallons/year of other renewable biofuels, such as biomass-based diesel, renewable hydrocarbons, and higher alcohols, the goal is to replace 20 % of current crude oil use in the United States by 2022 (Regalbuto 2009).

Replacing traditional gasoline, diesel, and jet fuels with renewable fuels will have a wide range of environmental, societal, and economic impacts. The significance and timing of these impacts will be affected by how rapidly biofuels replace petroleum-derived fuels, which in turn is affected by market forces (crude oil price and availability, feedstock prices), technology development, political conditions, and regulatory factors. The impacts of biofuel production on environmental, societal, and economic factors will be affected by the: (1) type of fuel produced and its use, (2) types and locations of the feedstocks, (3) locations, methods, and scale of conversion systems, (4) yields of products and coproducts from a given feedstock, and (5) challenges associated with use of these feedstocks (Federal Register 2010).

2.2 Present-Day Biofuel Production

2.2.1 Ethanol

The United States is currently the largest ethanol producer in the world (Renewable Fuels Association 2014c). The US ethanol industry expanded rapidly from the late 1990s to the present (Table 2.1), spurred by the phaseout of the gasoline additive methyl tertiary butyl ether (MTBE) and by state and federal mandates and tax incentives. The majority of present-day domestic ethanol biofuel production comes from approximately 190 operating facilities, processing mostly corn and similar grains, such as milo and barley. Most of these facilities are located in the Midwest near the site of feedstock production (Fig. 2.1); however, some are colocated with dairies or beef cattle feeding operations outside the Corn Belt. Seven small facilities convert simple sugars from food or beverage waste into ethanol, and in 2010, 3 million gallons were produced from two facilities using woody biomass as the feedstock (Renewable Fuels Association 2014a).

Over 90 % of corn ethanol plants use dry-grind technology, while the remaining facilities use wet-milling processes. Dry-grind facilities grind the entire corn kernel and generally produce one primary coproduct, dried distillers' grains with solubles (DDGS), which is a valuable livestock feed. Some distillers' grains are sold in a wet or modified wet condition for local use; however, storage and transportation are limiting factors. Two companies operate dry-mill ethanol plants that fractionate the corn upstream of ethanol production. They produce additional coproducts such as food- or fuel-grade corn oil and corn bran. Wet mill facilities separate the corn kernel into its components, germ, fiber, protein, and starch, prior to processing, and from these produce other coproducts, including gluten feed, gluten meal, and food-grade corn oil, in addition to DDGS (Federal Register 2010).

Ethanol production requires the use of water, electricity, and steam; the steam needed to heat the production process is usually generated on-site by burning natural gas. At least 27 plants use combined heat and power technology, producing their own electricity and using waste heat from power production for the process

Table 2.1 United States ethanol production capacity

Year	Total ethanol plants	Ethanol production capacity (BGY)	Plants under construction or expanding	Capacity under construction or expanding (MGY)	States with ethanol plants
1999	50	1.70	5	77	17
2000	54	1.75	6	92	17
2001	56	1.92	5	84	18
2002	61	2.35	13	391	19
2003	68	2.71	11	483	20
2004	72	3.10	15	598	19
2005	81	3.64	16	754	18
2006	95	4.34	31	1,981	20
2007	110	5.49	76	6,130	21
2008	139	7.89	61	5,536	21
2009	170	12.48	24	2,066	26
2010	187	13.03	15	1,432	26
2011	204	14.07	10	560	29
2012	209	14.91	2	140	29
2013	211	14.84	2	50	28

BGY Billion gallons per year; *MGY* Million gallons per year
Source: Renewable Fuels (2014b)

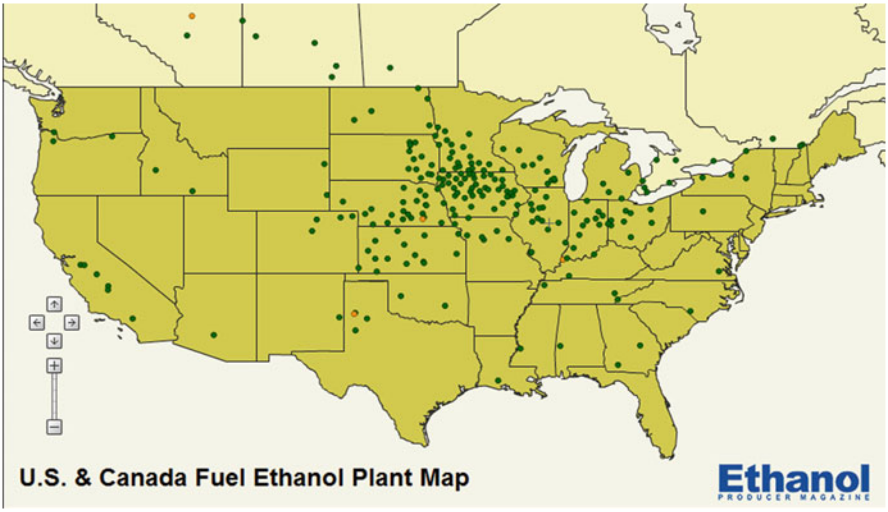

Fig. 2.1 United States and Canada fuel ethanol plant map (Source: Ethanol Producer Magazine)

steam. The large amounts of carbon dioxide gas produced during fermentation are vented in most plants. However, at sites where local markets exist, carbon dioxide gas is captured, purified, and sold to the food processing industry for use in carbonated beverages and flash-freezing applications (Federal Register 2010).

Because of poor ethanol margins in 2008 and 2009, a number of ethanol producers idled production, halted construction projects, sold off plants (frequently to oil refining companies), or filed for bankruptcy. However, as market conditions improved in 2010, many of these idled facilities came back on line. Although RFS2 does not have a specified volume requirement for corn ethanol, EISA allows up to 15 billion gallons of the 36 billion gallon requirement for total renewable fuel in 2022 to be met by conventional biofuels, such as corn ethanol. Future growth in the corn ethanol industry will depend upon the relationship between crude oil and corn prices. Crude oil prices fluctuate in response to political turmoil (primarily in the Middle East), new supplies (e.g., Canadian tar sands, US fracking), and the world economic activity. Corn prices depend on worldwide food and feed demands, yields as affected by weather conditions, development of improved hybrids, and competing uses (Federal Register 2010).

2.2.2 *Biodiesel*

The United States was the world's largest producer of biodiesel (long-chain fatty acid monoalkyl esters prepared from lipid-bearing feedstocks) in 2008, with Germany, France, Brazil, and Argentina rounding out the top five. However in 2010, as US production remained at nearly the same level, Brazil became the largest producer and the United States moved to fifth in the top group (US Energy Information Administration). Domestic production of biodiesel is considerably lower than for ethanol. Biodiesel production in the United States was just under 1.1 billion gallons in 2012 (National Biodiesel Board). First generation commodity vegetable oils such as soybean (see Redick, Chap. 3 and Stojsin et al., Chap. 9), along with waste lipids such as animal fats, are currently the most commonly used feedstocks for biodiesel production in the United States. However, the limited supply of these lipids is insufficient to displace a significant percentage of middle distillate fuel (diesel) consumption in the United States. For example, it has been estimated that if all US soybean production were dedicated to biodiesel, only 6 % of diesel demand would be satisfied (Hill et al. 2006). Therefore, exploration of high lipid-yielding alternatives suitable for fallow lands that require minimal agricultural inputs and do not compete with the food chain has emerged as a priority (Tilman et al. 2009). Crops such as camilina and carinata are leading options for use in rotation with wheat in arid regions.

Lipids can also serve as feedstocks for the production of renewable hydrocarbons via traditional catalytic hydrotreatment. The chemical composition and fuel properties of renewable diesel derived from lipids are different from biodiesel and in many cases more approximate than that of petrodiesel. While the renewability aspect of renewable diesel is retained versus biodiesel, advantages of biodiesel such as biodegradability, positive energy balance, excellent lubricity, and high flash point are sacrificed. However, disadvantages such as poor oxidative stability, cold flow properties, and energy density as well as elevated NO_x exhaust emissions versus petrodiesel are eliminated if renewable diesel is prepared instead of biodiesel

(Knothe 2010). The process for producing renewable jet fuels from lipids is similar to that for renewable diesel. To date, commercial production of renewable diesel and jet fuels from lipids is essentially limited to pilot scale for demonstration purposes.

2.3 Achieving the Biofuel Production Mandate of 2022

2.3.1 RFS2

As a result of the statutory requirements of RFS2, the most important step for the next decade in the biofuels industry will be commercial production of ethanol from cellulosic feedstocks. Biomass is the most promising sustainable source of liquid fuels, and the DOE has estimated that 1.3 billion tons of un- or underutilized biomass is available annually (Perlack et al. 2005; Perlack and Stokes 2011). Cellulosic ethanol would contribute significantly to the larger goals of creating a sustainable energy supply, reducing greenhouse gas emissions, assuring energy security, and promoting rural economic development. Ethanol will very likely be the world's first cellulosic biofuel because several large-scale demonstration and commercial-scale production facilities will begin operation in 2014. Moreover, the infrastructure for distributing and using ethanol is already available. Future research will develop technologies to convert lignocellulosic sugars into drop-in biofuels (long-chain hydrocarbons and alcohols). However, it is likely that these processes will follow commercialization of lignocellulosic ethanol, where issues such as feedstock supply and logistics will be resolved (Lynd and de Brito Cruz 2010).

Electric and hydrogen powered vehicles are also being developed as alternatives to petroleum-driven spark-(gasoline) and compression-(diesel) ignition engines. While biomass could also be used to generate either electricity or hydrogen, storage of these energy sources is problematic. Batteries are impractical for aviation and on-highway heavy-duty long-haul trucks. Due to the significant weight of the battery pack, electric drivetrains are less likely to be used for long-haul applications, unless applied in combination with on-the-road charging technologies such as inductive charging or overhead catenary wires (den Boer et al. 2013). In the most aggressive scenarios for electrification of light-duty vehicles, liquid fuels still provide more than 50 % of US transportation energy. Hydrogen-based fuels may be a possibility for fleet vehicles, but wider use would be limited by the lack of a hydrogen distribution infrastructure. Therefore achieving a sustainable transportation sector is more likely with liquid biofuels than without them (Regalbuto 2009).

Ethanol has been used in automotive fuels in the United States since the late 1970s. As a high-octane oxygenated additive, ethanol improves combustion, which allows clean air standards to be met. The drawbacks to using ethanol as a complete replacement for gasoline are its hygroscopicity and lower energy density. Ethanol has only two-thirds the energy density of gasoline, and cars running on E85 (85 % ethanol and 15 % gasoline) get about 30 % lower gas mileage (Regalbuto 2009).

Un- or underutilized cellulosic feedstocks have the potential to greatly expand biofuel production, both volumetrically and geographically (Federal Register 2010). Efforts to scale-up and deploy cellulosic biofuel technologies have increased dramatically in the United States in the last few years as a result of the $1.01/gallon tax credit for cellulosic biofuel introduced in the 2008 U.S. Farm Bill and the aggressive targets for cellulosic biofuel volume mandated by the RFS2 program. A wide range of feedstocks, conversion technologies, and fuels are under investigation for biofuel production. Cellulosic ethanol and other alcohols are considered promising for long-term use in gasoline blending. There is also growing interest in synthetic hydrocarbons from cellulosic feedstocks (Federal Register 2010).

Feedstocks from a wide variety of sources are being investigated for cellulosic biofuel production. Urban waste is cheap, abundant, and available where the fuel would be used. Agricultural residues, such as corn stover and cereal straws, are being evaluated widely in the Midwest for potential coprocessing at corn ethanol plants. Woody biomass, including forest thinnings, pulp and paper mill waste, and yard waste are significant resources in the eastern and southern parts of the United States. Dedicated energy crops such as switchgrass, cane, sorghum, poplar, and miscanthus are also being considered for cellulosic biofuel production. These crops have the potential for high yields and sustainable growth. While urban waste, agricultural residues and forest residues will likely be the first feedstocks used in the production of cellulosic biofuel, land availability and sustainable removal rates may be limitations. The US billion-ton update (Perlack and Stokes 2011) modeled energy crop potential using an agricultural policy simulation model taking into account additional energy crop sustainability requirements. As a result of the spatially explicit land-use change modeling that was used, energy crop potential was estimated to be much greater than in the 2005 US billion-ton study (Perlack and Stokes 2011 Table ES.1). In the Final Rule for RFS2, the EPA estimated that a majority of the feedstocks for the production of the 16 million gallons of cellulosic biofuel mandated by RFS2 for 2022 are expected to come from dedicated energy crops (Federal Register 2010, p. 14754). Viable harvesting, transportation, and storage solutions still need to be developed for these feedstocks.

2.3.2 Cellulosic Ethanol

Two general approaches are being developed to convert cellulosic biomass into ethanol: the biochemical platform and the thermochemical platform. The biochemical platform uses various pretreatment strategies to open the structure of biomass, followed by use of acids or microbial enzymes to deconstruct cellulose and hemicellulose into monomers. Yeast are then used to ferment the sugars to ethanol. The non-fermentable solids, including lignin, are typically used to generate heat and electricity to power the biomass-to-ethanol conversion process. Lignin can constitute up to 40 % of the stored energy in biomass. Despite recent developments, such as more efficient enzymes, breeding more readily deconstructed plants, and consolidation of processing steps, production costs remain higher than that of fermenting corn starch (Federal Register 2010). The thermochemical platform for ethanol production from cellulosic substrates uses gasification to convert biomass into syngas, which is then converted into ethanol by metal or microbial catalysts. The main limitations of this approach are metal catalyst poisoning by impurities in the syngas or low ethanol tolerance of microbes that convert syngas into ethanol.

Lignocellulose, as well as plant lipids, can also be converted to hydrocarbon biofuels like gasoline, diesel, and jet fuel as “drop-in” petroleum replacements. Conversion routes may combine a variety of biochemical, thermal, and catalytic processes. For example, sugars produced through the biochemical process can be fermented into hydrocarbons instead of alcohols by genetically altered microorganisms (Lee et al. 2008). Genes have been isolated that, when expressed in *Escherichia coli*, produce alkanes, the primary hydrocarbon components of gasoline, diesel, and jet fuel. If commercialized, this single step conversion of sugar to fuel-grade alkanes by a recombinant microorganism would lower the cost of producing “drop-in” hydrocarbon fuels that are low-carbon, sustainable, and compatible with the existing fuel distribution infrastructure. The process does not require elevated temperatures, high pressure, toxic catalysts, or complex operations. The recombinant *E. coli* secretes the hydrocarbons from the cell, so it is not necessary to rupture the cell. In addition, because the hydrocarbons are insoluble in water, they will form a separate organic phase that can be recovered without distillation. Moreover, this phase separation will minimize inhibition of the microbes by the accumulating fermentation product as that occurs with alcohol (Schirmer et al. 2010).

Dissolved sugars can also be converted into hydrocarbons through routes that resemble petroleum processing more than fermentation. Dumesic and coworkers have developed several routes in which dissolved sugars react in the presence of solid-phase catalysts under carefully controlled conditions that avoid unwanted by-products. They can convert carbohydrates into targeted ranges of hydrocarbons for use as fuels or chemical feedstocks (Kunkes et al. 2008; Chheda et al. 2007).

Themochemical conversion processes that transform biomass into synthesis gas or pyrolysis oil can also be adapted to produce third generation biofuels. An updated pyrolysis approach developed by Huber and coworkers uses catalysts to convert biomass into high-octane gasoline-range aromatics in a single, simple, inexpensive step (Carlson et al. 2008; Huber and Dale 2009). These chemical methods produce heat and water, which preserves resources and helps lower cost. Like pyrolysis, gasification also uses whole biomass but converts it spontaneously at very high temperatures into a mixture of carbon monoxide and hydrogen, or syngas, so named because it is a starting material for processes such as Fischer-Tropsch synthesis (FTS). Schmidt and coworkers (Dauenhauer et al. 2007) have combined the three reactions of older thermal gasification processes into a single, small reactor in which gasification takes place over a catalyst to directly produce third generation biofuels.

2.3.3 Algae, Photosynthetic Bacteria, and Cellulosic Ethanol

The need to develop other biomass feedstocks has helped to reinvigorate interest in algae as one of the most promising feedstocks for biofuels. The productivity of algae and photosynthetic bacteria is roughly 100 times than that of agricultural crops, without competing for arable land (Schirmer et al. 2010). Algae store chemical energy in the form of biological oils, such as neutral lipids or triglycerides, when subjected to stresses such as nutrient deprivation (Wijffels and Barbosa 2010). The oil can be extracted from the organisms and converted into biodiesel by transesterification with short-chain alcohols such as methanol or ethanol (Chisti 2007). Research and demonstration programs are being conducted worldwide to develop the technology needed to commercialize algal lipid production. For example, Arizona State University has an ongoing project working to generate biodiesel from lipids produced by a photosynthetic cyanobacterium (Arizona State University 2014). Algal oil can also be converted into linear hydrocarbons by catalytic deoxygenation/hydrogenation (Lestari et al. 2009). Algae also synthesize other fuel products such as hydrogen, ethanol, and long-chain hydrocarbons that resemble crude oil, or the algal biomass can be converted to biogas through anaerobic fermentation (Wijffels and Barbosa 2010).

In a similar fashion, photosynthetic cyanobacteria are also being targeted for their potential to produce biofuels directly from CO_2 and sunlight. Because they are more amenable to metabolic engineering compared to eukaryotic algae, cyanobacteria are being engineered to optimize yields of lipids containing C16 and C18 fatty acids for biodiesel production. Furthermore, companies such as Joule Biotechnologies and several universities are engineering cyanobacteria to directly produce hydrocarbon fuels (Halfmann et al. 2014). Cyanobacteria can be cultivated over a wide range of salt and fixed-nitrogen concentrations and at CO_2 levels up to 5 %. Some cyanobacteria are able to fix atmospheric nitrogen. These traits make the microorganism well suited for growth using flue gas effluent from power plants or CO_2 from ethanol plants as a carbon source before release into the atmosphere. Cyanobacteria and algae can also use agricultural runoff water contaminated with fertilizers as a fixed-nitrogen source when it is available. This renewable solar energy-to-biofuels approach is well suited to arid regions with high levels of sunlight. Biofuel production from cyanobacterial photobioreactors should be scalable to a point where it represents a major source of carbon-neutral fuel within the next 10–15 years (Arizona State University 2014).

Most cellulosic ethanol companies are in various stages of proving their technologies. Many have fallen behind in their commercialization schedules, primarily due to lack of funding. Obtaining capital is challenging given the state of the economy. At the present rate of development, maximum cellulosic ethanol capacity is estimated to be 337 million gallons in 2013, which is less than currently mandated by RFS2 (Federal Register 2010). Renewable hydrocarbons derived from biomass may win out over cellulosic ethanol because of their high energy density and compatibility with existing energy infrastructure. If recent technological innovations result in competitive production costs, hydrocarbons rather than ethanol may be the dominant biofuel.

2.4 Prospects for Biofuel Production by 2050

Based on current energy policy in the United States, it would appear that ethanol, derived from corn and lignocellulose, will be the main liquid transportation biofuel through 2020. EISA allows 15 billion gallons of the 36 billion gallons of renewable fuel mandated for 2022 to be met by conventional biofuels. It is expected this will be filled by corn ethanol (Federal Register 2010). EISA increased the cellulosic biofuel mandate to 16 billion gallons by 2022, representing the bulk of the renewable fuels mandate. To become cost competitive with corn ethanol, lignocellulosic ethanol will require further improvement in pretreatments, enzymatic conversion to simple sugars, and mixed sugar fermenting microbes (Hughes et al. 2008, 2011; Kumar and Murthy 2011; Laluce et al. 2012). Current investments in demonstration and small commercial-sized lignocellulosic ethanol facilities should speed up technology improvement. If total ethanol production (15 billion gallons from corn and 16 billion gallons from cellulosic feedstocks) reaches 31 billion gallons by 2022, that would meet approximately 20 % of the US liquid fuel transportation needs and would come close to achieving the EISA goal of 36 billion tons of biofuels. This degree of market penetration by ethanol will require a further increase in the allowable level of ethanol blended into gasoline (United States Environmental Protection Agency) and/or substantially more flex-fuel vehicles in the US transportation fleet.

Expansion of the biofuel market share above 20 % will likely involve production of third generation, drop-in biofuels (i.e., liquid hydrocarbons) in order to overcome infrastructure limitations of ethanol (United States Department of Energy 2012). Hydrocarbons can be made from lignocellulosic sugars through microbial fermentation or liquid-phase catalysis or directly from biomass via catalytic pyrolysis or gasification and Fisher Tropsch reactions. Lipids from nonfood crops, as well as algae, can also be converted to renewable hydrocarbon fuels (National Science Foundation 2008). The direct conversion of CO_2 with solar energy to biofuel by photosynthetic microorganisms such as microalgae and cyanobacteria has several advantages compared to traditional biofuel production from plant biomass, such as (1) oxygenic photosynthesis, (2) high per-acre productivity, (3) nonfood-based feedstock, (4) growth on nonproductive and nonarable land, (5) utilization of a wide variety of water sources (fresh, brackish, seawater, and wastewater), and (6) production of valuable coproducts along with biofuels (Radakovits et al. 2010; Parmara et al. 2011; Machado and Atsumi 2012).

Logistical challenges of transporting, storing, and maintaining acceptable quality biomass will restrict the size of future biorefineries. As pretreatment, conversion, and separation technologies continue to improve, it is likely that these platforms will be scalable to the community level, which will enhance

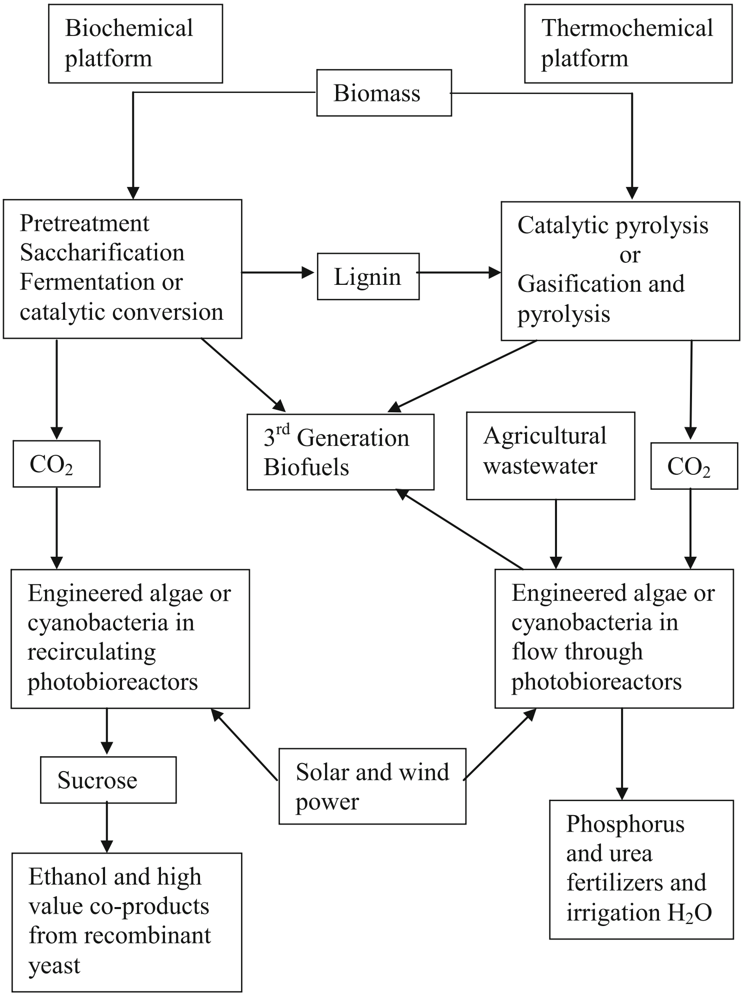

Fig. 2.2 Integrated, community-scale biorefinery

environmental, economic, and social sustainability. These biorefineries are also likely to be most economical and energy efficient if they are able to transform coproducts of one process into higher-value products through an integrated design. Both biochemical and thermochemical processes will be needed to convert biomass into third generation biofuels and bioproducts. Underutilized resources of these processes will be CO_2 and heat which can be used to culture engineered algae or cyanobacteria in photobioreactors to produce a range of products via photosynthesis.

A proposed integrated biorefinery concept outlining the biochemical and thermochemical platforms is shown in Fig. 2.2.

This multiproduct, community-based system will produce third generation biofuels, valuable coproducts, and fertilizer. The system can be used in any location due to its self-contained and autonomous design. The primary inputs are biomass, CO_2, and sunlight for photosynthesis, as well as solar or wind power to provide electricity (see Buchanan and Orbach, Chap. 1).

Algae and cyanobacteria possess the characteristics to produce third generation, energy-dense biofuels compatible within this proposed community scale system. They can grow in fresh or salt water, using sunlight to drive CO_2 photosynthesis and fix N_2, and have a photosynthetic efficiency fivefold greater than terrestrial plants. Another option in this community-based system would be to culture the algae/cyanobacteria on domestic or animal wastewater effluent, taking advantage of mixotrophic metabolism to use both CO_2 and dissolved nutrients. Cyanobacteria are particularly attractive, as they grow even more rapidly than algae and are easier to genetically engineer. Some strains are already grown at industrial scale for production of food and nutritional supplements. Because these organisms are generally regarded as safe (GRAS), coproducts from cyanobacterial biofuel production should be acceptable for feed and food applications.

Research is currently underway to engineer cyanobacteria to produce and excrete specific energy-dense liquid fuels (Halfmann et al. 2014). This would allow cells to remain circulating within the photobioreactor, while the product could be recovered via gas stripping or phase separation. Solar or wind power could generate electricity for pumps and control systems. CO_2 for photosynthesis would come from the biomass conversion units or could also be obtained from the air via enrichment membranes. The cellular biomass byproduct can be used for animal feed. Additional coproducts are urea and phosphorus fertilizers. Urea could reduce the use of anhydrous ammonia. Also, there will be a need for urea for the new tier 4 truck diesel emissions standards that must be met worldwide.

In addition, the cyanobacteria could be engineered to produce sucrose, which could feed a recombinant yeast that produce a high value protein-based coproduct. This algal or cyanobacterial photobioreactor system can be assembled from UV resistant polymers, with fluid circulation powered by solar- or wind-generated electricity. Pumps powered by solar/wind energy are already being used for remote water pumping applications at the USDA-ARS Conservation and Production Research Laboratory (CPRL) near Bushland, TX. The wind turbine will generate 3-phase variable voltage, variable frequency AC electricity.

In the near- to mid-term future, revenue streams aside from fuels will be needed to render production of biofuels from algae profitable. Other factors improving the economics of biofuel production from algae include high petroleum oil prices, high yield of lipids from algae, and continued biofuels subsidies and/or tax credits (Gallagher 2011). Technical hurdles to be solved include: (1) the ability to cultivate stable algal cultures under industrial conditions while achieving both high productivities and lipid content, (2) the capacity to increase the volume of algal oil produced per unit of surface area per year, (3) the development of low-cost harvesting and oil extraction methods, and (4) strategies to utilize the biomass remaining after oil extraction.

2.5 Conclusion

A secure and sustainable system for bioenergy and biofuel production must build on the current infrastructure and existing technology, but must also develop and implement new technologies and innovative concepts. This chapter described a biofuel production system that could combine existing and future technologies and has the potential to provide energy security by 2050. This system could not only produce third generation, drop-in biofuels from both biomass and CO_2, but could also produce a high-value coproducts, urea and agricultural fertilizers, and transform wastewater effluent into acceptable irrigation water. The integrated, community-based design could economically produce energy in an environmentally and socially sustainable manner. This system could also foster cap and trade reduction in carbon dioxide because cyanobacteria will fix carbon dioxide into fuels, foods, and fertilizer. It is clear that no single energy source can sustainably meet all future energy needs; however, biofuels provide an option that can address the energy demands of the transportation sector. It is expected that advanced biofuels and bioproducts will be obtained from lignocellulosic and algal biomass. The biofuels industry must continue to develop technologies for converting biomass to biofuels that are economically and environmentally sustainable on a large scale.

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Chapter 3
Sustainability Standards

Thomas P. Redick

This chapter provides a review of sustainability initiatives and standard-setting initiatives with a brief overview of legal barriers to such standards. These barriers including green marketing liability for companies marketing food with sustainability-related claims and grower concerns over legal ramifications of measuring impacts that may someday be subject to regulation. By anticipating the demand of regulators or customers, producers and suppliers of food, feed, biofuel, and fiber can avoid customer's refusals to accept delivery or and penalties for failure to comply with regulations.

3.1 Defining Sustainable Agriculture: Governmental Approaches

Governments are one source of guidance on sustainability in agriculture. Governments tend to a baseline of environmental and social regulations, but also provide funding and general guidance for production practices that go beyond regulation in search of more sustainable production practices. This chapter compares the United States (USA) and European Union ("EU") approaches to sustainability standards (which can be adopted or discouraged depending on conformance to state policy), and the trade implications that can arise when one nation's definition of sustainability (e.g., the EU's Renewable Energy Directive) lacks the scientifically grounded basis that international trade law may require.

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3.1.1 USDA and "Sustainable" Agriculture

The 1985 Food Security Act began support for more "sustainable" agriculture, followed by the US Department of Agriculture ("USDA") and its Low-Input Sustainable Agriculture Program ("LISA") program in 1988. LISA funded interdisciplinary teams that developed farming methods that sought to be economically profitable, environmentally sound, and socially acceptable. LISA funded specific "component" research (i.e., evaluating specific technologies) with industry support, as well as the "whole farm/integrated systems research" sought by the "sustainable" farmers and NGO members (Constance 2010).

LISA became USDA's Sustainable Agriculture Research & Education ("SARE") Program with the 1990 Farm Bill (Food, Agriculture, Conservation, and Trade Act of 1990) (Constance 2010). SARE activities are discussed below under the National Institute of Food and Agriculture (NIFA) at Sect. 3.1.1.3.

Sustainability initiatives in agriculture, like the ones discussed in more detail below, can anticipate regulatory demands. To the extent that "safe harbors" (i.e., being exempt from further regulation) can be granted by regulators for voluntary efforts to control environmental impacts of agriculture, those options are explored below.

3.1.1.1 Farm Bill Definition

The concept of "sustainable agriculture" defies definition, but for some "sustainable agriculture" may be defined by practices that [are continually evolving to] leave the soil (see Hatfield, Chap. 4) and surrounding environment in as good—if not better—condition after harvest. This movement toward sustainability in agriculture can be encouraged through governmental influences (e.g., appropriate zoning, USDA or EPA grants). In addition, government regulation can encourage performance-based standards to meet anticipated future regulatory objectives (Clay 2004). While agreement on a uniform definition may never be reached (reflecting the need for continual improvement and adjusting to changing circumstances), the U.S. Congress addressed the term "sustainable agriculture" in the 1990 Farm Bill (Food, Agriculture, Conservation, and Trade Act of 1990).

Under this law, "sustainable agriculture" was given the following big tent to occupy, as an "an integrated system of plant and animal production practices having site-specific application that will, over the long term:

- Satisfy human food and fiber needs.
  - Enhance environmental quality and the natural resource base upon which the agricultural economy depends.
  - Make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls.

- Sustain the economic viability of farm operations.
- Enhance the quality of life for farmers and society as a whole."

Dr. Roger Beachy, as Director of the NIFA and Chief Scientist at USDA, invoked this reference in February 2010 as one way to engage in discussions and practices leading to a more "sustainable" form of agriculture in the USA. For Dr. Beachy, "sustainable agriculture" is a goal, not any given set of practices now in use; indeed, multiple approaches to "sustainable agriculture" will likely arise, given the diversity of agriculture and varying objectives.

Today, USDA has a team of experts called the Sustainable Development Council which monitors sustainability standards and may take a leadership role in domestic and international efforts to define sustainability. USDA participates in an Interagency Committee on Standards Policy (ICSP) and Ms. Erin Morris of the Agricultural Marketing Service (AMS) is its "Standards Executive." USDA also has a Global Food Security Council that works with International Food Aid and Development Conference (IFADC) on global food security. The IFADC annually hosts USDA and the U.S. Agency for International Development (USAID), along with private sector companies and voluntary organizations to coordinate delivery of America's food aid and assistance to the world's neediest people. As evidence of potential food shortages mounts around the world, consumer opinion may support higher levels of "industrial" food production and mainstream commodity production.

3.1.1.2 NRCS and Environmental Sustainability

The Natural Resources Conservation Service (NRCS) handles environmental issues for the United States Department of Agriculture (USDA). Major programs with potential roles in improving the sustainability of US agriculture include the Grassland Reserve Program (GRP) Wetlands Reserve Program (WRP), Conservation Stewardship Program (CSP), Wildlife Habitat Incentives Program (WHIP), Farm and Ranch Lands Protection Program (FRLPP), and Environmental Quality Incentives Programs (EQIP) (USDA NRCS 2011).

All of these programs contribute toward increasing the sustainability of agriculture. For example, the voluntary Conservation Stewardship Program (CSP) encourages agricultural and forestry producers to address environmental issues. Participating growers report to USDA annually on conservation activities toward improving and maintaining existing conservation systems. The CSP provides financial and technical assistance to help land stewards conserve and enhance soil, water, air, and related natural resources on their land.

Similarly, NRCS promotes energy auditing of farms through its "Rural Energy for America Program" ("REAP") under Section 9007 of the 2008 Farm Bill. REAP grants fund energy projects in all 50 states, with grants varying from cellulosic ethanol research to management methods for pests, diseases, and other agricultural problems. Under the 2009 REAP program, USDA funded 75 % of the energy efficiency auditing cost for farmers and rural small businesses. In addition, USDA requires energy audits in any REAP-funded energy efficiency project exceeding $50,000. USDA has funded rural electric cooperatives and public power entities to conduct these energy audits.

As of 2010, energy auditing availability spurred by USDA funding is driving an increase in demand for agronomic energy consulting. Both the level of interest and the availability of consulting make auditing somewhat limited in rural areas. While the initial impetus for an energy audit may be to qualify for USDA funding (e.g., under REAP), the demand for farm energy audits will probably continue to rise as energy prices increase and farmers recognize the benefits.

For example, REAP-funded energy audit findings can help farmers find ways to make their farm buildings more energy efficient through insulation and better sealing of the enclosures. Machinery energy audits and carbon footprint calculators help to assess the greenhouse gas (GHG) contributions of equipment and agronomic practices and provide additional data to reduce on-farm energy consumption and GHG emissions. In sum, the USDA grant program should be able to demonstrate significant returns on investment as the low-hanging fruit of energy efficiency is identified, and farmers reap the benefits of energy conservation.

NRCS can also provide US growers with support to become more sustainable via: (1) Conservation Innovation Grants (“CIG”), (2) regulatory enforcement “Safe Harbors” for growers who participate in management of nutrients—e.g., when the TMDL enforcement via “best management practices” or other regulatory enforcement comes around (perhaps including citizens suits by Sierra Club and the like), (3) reduced premiums for crop insurance if growers operating sustainably could make a case for reducing risk, (4) lower interest rates on federal loans, and (5) allow preferred access to the Conservation Stewardship Program (“CSP”). In time, green payments for “ecosystem services” might be something USDA’s new office of Ecosystem Services might facilitate (NRCS 2011).

Voluntary sustainability standards can often anticipate regulatory moves to regulate impacts, providing the regulated community with an opportunity to determine the optimum methods for control of the impact. For example, a grower involved in a sustainability initiative may be taking steps to control runoff of nitrogen and phosphorous to nearby waters. In time, this effort may lead to more favorable treatment from a regulatory agency imposing a mandate for “best management practices” (BMPs) following a “Total Maximum Daily Load” (“TMDL”) hearing under the Clean Water Act. To the extent that regulators understand and acknowledge the existence of such voluntary initiatives, there is an opportunity for the creation of “safe harbors” from regulatory enforcement.

3.1.1.3 NIFA and Sustainable Agriculture

Sustainable agriculture is also enabled by USDA’s Sustainable Agriculture Research and Education (“SARE”) initiative—which publishes success stories each year, including organic growers and conventional producers. For example, the 2009–2010 profiles included organic producers as well as Dan Forgey, a grower of biotech corn in South Dakota (USDA SARE 2011).

Since 1988, USDA SARE has funded nearly 5,000 projects that fulfill its mission to promote innovation that improves the "profitability, stewardship, and quality of life by investing in groundbreaking research and education" (USDA SARE 2006). Under the 2008 farm bill, the National Institute of Food and Agriculture (NIFA) replaced the Cooperative State Research, Education, and Extension Service (CSREES), assuming oversight of the SARE program. NIFA's mandate is to promote science-based agriculture via research and education to address some of the world's toughest problems through agriculture: global food security and hunger; climate change; sustainable energy; childhood obesity; food safety; and similar challenges (USDA NIFA 2009).

The USDA has a "Feed the Future" (FtF) action plan that allow it to partner with other US government agencies, civil society, industry, foundations, and agricultural ministries overseas. USDA hopes to integrate science-based approaches to managing nutrition, health, trade, conservation of natural resources, ethical agribusiness, adapting to climate change, and management of new technologies. A number of initiatives will be rolled out in coming years and trigger further development in the next Farm Bill.

The USDA's Specialty Crop Research initiative was also created by the 2008 Farm Bill to solve critical industry issues through research and extension activities. Projects must address one of five focus areas for specialty crops: (1) plant breeding, genetics, and genomics to improve crop characteristics; (2) threats from pests and diseases, including pollinators; (3) production efficiency, productivity, and profitability; (4) new technology, including improved mechanization and delayed-ripening technologies; and (5) methods to prevent, detect, monitor, control, and respond to potential food safety hazards.

USDA's National Organic Program (NOP) is a voluntary program for producers of agricultural products who wish to use the term "organic" or similar on the label of their products and agree to use a specified set of procedures (e.g., no pesticides, no preservatives, free range, etc.) that minimize use of off-farm inputs in production. USDA accredits certifying organizations who audit farms and certify that farm products have been produced in accordance with the organic standards. Organic producers often seek to claim leadership in sustainable agriculture (LaSalle et al. 2008; Constance 2010). The 2008 Farm Bill provided an increase in mandatory funding under the Organic Agriculture Research and Extension Initiative (to $50 million from $15 million).

Under USDA's National Organic Program (NOP), certified organic farming requires:

- "Use of cover crops, green manures, animal manures, and crop rotations to fertilize the soil, maximize biological activity, and maintain long-term soil health.
- Use of biological control, crop rotations, and other techniques to manage weeds, insects, and diseases.

- An emphasis on biodiversity of the agricultural system and the surrounding environment.
- Use of rotational grazing, alternative health care (e.g., no antibiotics), and mixed forage pastures for livestock operations.
- Reduction of external and off-farm inputs and elimination of synthetic pesticides and fertilizers and other materials, such as hormones and antibiotics.
- A focus on renewable resources, soil and water conservation, and management practices that restore, maintain, and enhance ecological balance" (USDA SARE 2006).

In the USA, however, such certified organic production only accounted for 0.57 % of the agricultural acreage in 2008. In major commodity crops, the percentage is even lower; for example, USDA reported that less than 0.2 % of the total acres of soybeans were certified organic in 2005, and more recent reports show a continuing decline in organic soybean acreage. In contrast, organic fruits and vegetables that are seeing steady increases are 37 % of total US organic sales, with most of the products having premiums that are less than 30 % more than conventional alternatives. Organic milk is often quite costly (e.g., 60–100 % premiums over conventional) (USDA ERS 2008).

The World Wildlife Fund [an environmental nongovernmental organization (ENGO) that has set many sustainability standards for various crops] has made it clear that "sustainable agriculture" is not defined as "certified organic" agriculture. The organic production sector needs to seek greater sustainability (Clay 2004).

Lacking no-till methods or other means to avoid runoff, organic growers may use cover crops, rollers, and other tools to suppress weeds. If they plow to control weeds, and also apply manure that runs off to nearby watercourses, this can lead to harmful nutrient runoff (even careful containment can be breached in flooding events). Such runoff could contribute significant nutrient pollution to the surface waters of the USA, particularly in areas where organic producers congregate. The US EPA is increasingly finding ways to regulate such agricultural runoff to nearby waters.

In contrast, herbicide use paired with herbicide-resistance biotech crops are rapidly becoming an axiom of US conventional soybean production as well as other crops that are using herbicide-resistant to enable no-till production (Nill 2006). The move to no-till in most corn and soybean production systems has led researchers to explore the comparative environmental impacts of these no-till systems using herbicides versus certified organic practices. Depending upon the scope of the life cycle analysis, and whether bushels per acre (yield) is considered, organic operations may be competitive with no-till systems for carbon foot print and sustainability measures of soil health such as soil organic matter. A careful scientific approach to the life cycle analysis will be required to ensure that the representations made by particular growers are correct (see Gianessi and Williams, Chap. 14).

According to the Rodale Institute, farmers that "make the switch" to an organic-plus form of farming and use cover crops complex crop rotations, less fertilizer, herbicides, and pesticides will eventually improve on soil health and biodiversity criteria. Organic growers who work at improving their performance in areas outside organic criteria (e.g., fair labor, climate change, energy efficiency, no-till) could build a marketing niche for such extra “embedded values” in products.

While the Rodale Institute calls upon conventional agriculture to make an “across-the-board shift in conventional agriculture” away from “volume production” toward a model with “toxic reduction, sequestering soil carbon or ecological services” in the vast majority of US agriculture, this approach might reduce yields, increase runoff to watersheds, increase labor costs, and unduly raises prices of food across the board (Bowman 2009). The inability to use commercial fertilizers also presents a limiting factor in broad adoption of organic practices that would replace highly productive conventional/biotech production processes using such fertilizers. Another limiting factor in broadening the organic production system is the high labor costs associated with managing pests, weeds, and other requirements relating to organic production.

Given the lack of adequate fertilizer sources and other challenges, organic agriculture globally will remain a niche practice for years to come. For the next 100 years or so, there will be many mouths to feed and certified organic food will not meet their needs during that time frame. A recent report on “energy smart food” from the Food and Agriculture Organization of the United Nations (FAO) states: “Inorganic fertilizer use has contributed significantly to increasing crop yield in recent decades (see Reetz, Chap. 15). This demand for inorganic fertilizers will probably continue to expand, mainly in low-GDP countries” (Sims 2011). The FAO report furthers suggests that organic agriculture’s potential energy savings (from not using inorganic fertilizer) may not work for all growers, since “yield reduction will tend to increase the energy intensity.”

Moreover, the same report states that “some analyses of organic farms have shown lower energy demands, but this may be partly offset by increased human labour inputs” (Ziesemer 2007; Sims 2011). While consideration of the entire production life cycle could consider human labor and its impact, there are social advocates who would find this employment in menial tasks a positive social benefit (Rifkin 2005).

While necessary to feeding the world, the loss of fertilizer inputs to the air and water is a challenge that must be managed better to improve the sustainability of production (Tilman et al. 2011). It can be presumed that no grower wants to waste nitrogen and cause pollution if it is feasible to avoid this. Fortunately, agricultural research and education has provided producers with tools to control these impacts. For example, producers are warned that ammonia fertilizer applied when soil temperature is over 50° Fahrenheit leads to nitrogen loss. Such losses reduce crop development and also leach into adjacent groundwater (Nitrogen and Phosphorus Knowledge 2011).

3.1.2 Technology Transfer to Developing Nations

In a recent article entitled “Freeze the Footprint of Food,” Jason Clay of WWF-US stated that “100 million hectares” of degraded agricultural lands need to be “rehabilitated by 2030 and 250 million by 2050.” Citing the examples of Ethiopia and South Africa, he suggest that soil rehabilitation works where governments support control of soil erosion and use a combination of trees, grasses, and crops to build up soil organic matter.

Another article expands on this concept, suggesting that high-yielding agricultural methods found in the USA and elsewhere could be adapted to degraded areas of Africa, Asia, and other corners of the world that missed out on access to the best agricultural technology. If the world hopes to meet the demand for agricultural products in 2050, these nations who lag behind in productivity must show “moderate intensification focused on existing croplands” via “adaptation and transfer of high-yielding technologies” and “global technological improvements” (Tilman et al. 2011).

The United Nations, however, seems to consider organic agriculture to be the answer. In March 2011, the United Nations Human Rights Council released the Right to Food Report, finding “agroecological” systems the best route to achieving food security for many vulnerable groups (UN 2010). This is consistent with an earlier 2007 report by a UN senior officer who found that modern, innovative organic agriculture would feed the world sustainably in 2050 (El-Haage Scialabba 2007). Furthermore, a 2008 report from an intergovernmental process with over 400 experts and cosponsors including the FAO, the World Bank, United Nations, and WHO (the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) panel), suggested, over the opposition of mainstream agricultural representatives, that food producers should use “natural processes” like crop rotation and organic fertilizers rather than industrial fertilizer and chemicals.

While more attention should be paid to improving the productivity of smallholder agricultural practices, organic farming will always be a niche practice, due to the limited availability of nutrients meeting its requirement for strictly natural sources. Given the dependence upon animal manure and cover crops to generate organic matter, organic production cannot build degraded soils as rapidly as the world will require (Tilman et al. 2011; Kirchmann and Bergman 2009).

For example, the leading soil scientist for Gates Foundation projects, Pedro Sanchez, has opted to use industrial fertilizer and hybrid corn and improved water management in Millennium Villages, which is not the organic production model suggested in the UN report (Sanchez et al. 2009). Corn (maize) yields increased from 1.7 to 4.1 tons per hectare, enabling Malawi to transform from a recipient of food aid into a food exporter, including food aid to neighbors that failed to produce enough food. Malawi also subsidized seed and fertilizer. As of November 2011, university researchers reported plans to plant biotech cotton starting immediately (in December) because biotech cotton would increase average yields from 800 kg per hectare to around 2,400 per hectare and is “well known for reduced chemical use, clean environment, higher yield and better quality of cotton, and reduced use of chemical weeding” (Kashoti 2011).

This move toward biotech crops is opposed by former UN leader Kofi Annan, who chairs an NGO called the “Alliance for a Green Revolution in Africa” (AGRA), and recently confirmed that the group “does not fund the development of GM crops.” This comes as no surprise when their “Partnerships” page lists “Association of European Parliamentarians for Africa (AWEPA)” who will “support African parliamentarians as they promote policies to help smallholder farmers’ transition from subsistence to market-oriented agriculture” (AGRA 2011). The European Parliament has consistently voted against planting of biotech crops, recently enabling member states to ban them completely (Parliament 2011). Research comparing the relative yields in nations using biotech crops versus those, like Romania, that were forced to abandon them are startling. European row crop yields are lagging behind other developed countries—indicating that the opposition to newer technologies has undesirable long-term consequences (Edgerton 2009).

As land is restored using the best technology (including “GMOs”), it could be adapted to organic models that coexist with conventional, including biotech, forms of production, to the extent that yields are maintained in an economically sustainable manner. Chinese producers have proved that developing nations with lower labor and land costs can compete well against producers in more developed nations (Roseboro 2007).

The blind opposition to use of biotech crops may forever doom Africa to less productive agriculture as Europeans expand their expansion of organic experiment to African nations that are dependent on European export markets and aid.

In time, however, some African nations may lead the way to higher productivity and follow the US model, which would support both approaches (e.g., certified organic and conventional/biotech.) while encouraging innovative approaches to maintaining high yield agriculture. This may include use of chemicals, advanced fertilizers, genetic engineering (see Borlaug et al., Chap. 12 and Oikeh et al., Chap. 13), and perhaps nanotechnology as products like nano-pesticides enter the marketplace. In contrast, the EU will follow a more precautionary course, with limited adoption of new technology and devotion to supporting the organic models—with high premiums paid by those who can afford those niche products.

3.1.3 Green Marketing Regulation

For companies marketing products as “sustainable” in the USA or EU, there are laws governing “green marketing” that can limit what a food company can say about its products. While agricultural products may increasingly adopt voluntary product labeling for sustainability, they risk running afoul of “green marketing” regulation.

A November, 2007 report from the consulting firm "Terra Choice" reviewed 1,018 consumer products making 1,753 "green" claims and found only one that completely avoided some level of false or misleading information (Terra Choice 2007).

Since1992, the Federal Trade Commission (FTC) has "Guides for the Use of Environmental Marketing Claims" 16 CFR Part 260 ("Green Guides"), providing guidance on legally valid environmental claims in labeling, advertising, promotional materials, and other marketing (FTC 2010). The FTC can penalize greenwashing if a false statement is an "unfair or deceptive acts or practices in or affecting commerce" and is likely to mislead a reasonable consumer.

In addition to this federal oversight, the consumer fraud laws of 50 states can be used to penalize "green marketing," and state attorneys general have been enforcing such laws against "greenwashing" since the early 1990s (NAAG 1999).

3.1.4 EU Laws and Standards

The European Union ("EU") has a mix of governmental and voluntary standards that promote sustainability in agriculture. In general, however, EU laws and standards tend to favor organic production and discriminate against the use of biotech crops and agricultural chemicals.

3.1.4.1 Organic Endorsed as Sustainable

In European nations that have fully embraced the certified organic production system as the most sustainable, ambitious targets have not been met. Sweden, for example, set an objective in 2006—25 % of its agricultural acres would be certified organic by 2010. With under 10 % organic acreage (around 12.5 % if acres under conversion to organic are included), Sweden fell short of its 2010 goal. Moreover, Swedish growers may find it difficult to maintain the same level of productivity on organic acres that their government is encouraging.

For "organic" nutrients, growers are often dependent on other agricultural operations (including animal feed operations) and not industrially produced fertilizer (Kirchmann et al. 2009). If organic agriculture also has "consistently lower yields than conventional production (up to 50 % less) and is thereby a less efficient method of land use" (Kirchmann et al. 2009) while certain environmental impacts (e.g., nutrients leaching into nearby watercourses) are equal or greater, encouraging organic production on greatly increased acreage worldwide could be counterproductive in an era of increasing food scarcity and price spikes.

Industrial fertilizer, created from abundant atmospheric nitrogen, can help create plant matter (an estimated "five to tenfold energy return in the form of biomass") and build degraded soil. Where "green manure" cover crops are used, an organic production process may use land for cover crops that could have produced a crop.

Over time, the conventional producer might produce more food using much less land to produce the same amount of food.

Similarly, industry estimates indicate that twice as much land would be required to grow all US rice if no pesticides were used (see Gianessi and Williams, Chap. 14; Croplife America 2011). Organic producers also shun biotech crops based on theoretical negative environmental and social impacts (Snell et al. 2011)—which limits the potential to increase yields. As such, unless the organic production system overcomes the limits on available organic nutrient inputs (and containing their negative impacts), organic production appears destined to always occupy a minority position in the process of sustainable food production.

3.1.4.2 Global GAP

Global GAP is a nongovernmental organization that sets voluntary standards for the certification of agricultural products around the globe. Formerly known as EUREPGAP (for European "Good Agricultural Practice" (G.A.P.), this standard seeks worldwide harmonization of sustainability standards.

This standard reflects the European bias against biotech crops, stating a "Major Must" (CB. 2.5.4): "Is there a plan for handling GM material (crops and trials) setting out strategies to minimize contamination risks, such as accidental mixing of adjacent non-GM crops and maintaining product integrity? There must be a written plan that explains how GM material (crops and trials) is handled and stored to minimize risk of contamination with conventional material" (Global GAP 2009).

Like other sustainability standards that seek to have the biotech crop producer "prevent migration" to other producers, this standard fails to recognize the realities of agricultural production down on the farm. A producer of biotech crops will not have reliable sources of knowledge about what his neighbors may choose to grow—this can change during planting season depending on prices, adverse weather that requires replanting of seed, and simple refusal of a neighbor to share competitive intelligence.

In contrast, a "non-GMO" or certified organic producer who has promised to deliver—at a premium price—a specialized non-commodity product in an identity-preserved production system is better positioned to ensure that he has set up buffers and testing to ensure that any stray pollen does not prevent him from collecting the premium on his crop.

This obvious assumption of business risk by one producer should not be shifted to an uninformed neighbor who is being paid nothing for his role in preserving his neighbor's premium. Even assuming that the biotech producer, to gain certification as "Global GAP," is willing to establish his buffer, and he has been given knowledge of that, if the biotech crop producer has nothing as profitable to produce in the proposed buffer zone, he is incurring a loss of profit for no purpose beyond protecting his neighbor's organic or non-GMO premium. It is difficult to see what is "sustainable" about this unfair shifting of business-related risk to the producer of a biotech crop. Without any adequate rational for this measure, such anti-biotech risk-shifting can be presumed to be the result of a standard-setting organization's bias against biotech crops, inexplicable but for the European origin of the standard.

Even in Europe, however, where laws require GM crops to maintain buffers, there appears, after years of use, to be no sound scientific basis for fears relating to the food safety of biotech crops. A recent study by European scientists look at a wide range of scientific studies looking for adverse health impacts, including for long-term animal feeding, and concluded "there is no scientific space left for fear about a food safety risk inherently linked to the 'GM' nature of varieties marketed after the currently performed risk assessment." This research looked at 12 studies each covering crops ranging from maize (corn), potato, soybean, rice to triticale. This included long-term toxicological studies, where feeding time exceeded 2 years (a 90-day study is typically used in toxicological studies) and studies extending over several generations of test animals (Snell et al. 2011).

Under the most extreme application of the "precautionary principle" as it is applied by some opponents of biotechnology, however, such studies are either disregarded as biased or considered insufficient to rebut the hypothesis of long-term adverse health effects. As a result, the EU bias represents an economic policy that protect the interests of EU consumers who are wary despite the rising evidence. Other nations are reporting significant economic benefits (e.g., Argentine study recently reported economic benefits of biotech crops, attributing $72.6 billion in benefits over 15 years of planting biotech crops—over 70 % accruing to growers.)

3.1.4.3 Renewable Energy Directive

The EU's 2009 Renewable Energy Directive is part of the EU's commitment to reduce greenhouse gas emissions and has endorsed a mandatory target of a 20 % share of energy from renewable sources in overall energy consumption by 2020 (Directive 2009/28/EC). The EU also has a mandatory 10 % minimum target to be achieved by all Member States for the share of biofuels in transport petrol and diesel consumption by 2020, to be introduced in a cost-effective way. The EU hopes to control European energy consumption and use more renewable energy to reduce greenhouse gas emissions via its new "Renewable Energy Directive" to implement obligations under the Kyoto Protocol to the United Nations Framework Convention on Climate Change.

The United States Trade representative has scrutinized the EU's RED and found its calculations lacking the scientific basis that trade law requires. The RED used only Brazilian production to calculate impacts of soybean production to determine all of the world's soy-based biodiesel's greenhouse gas (GHG) emissions' reduction compared to petroleum diesel. Given troubles with destruction of habitat and long transport by trucks, the EU measured most Brazilian biodiesel at a mere 31 %, just short of the 35 % reduction compared to petroleum GHGs that is required to be eligible for EU tax credits and usage mandates (the percentage will steadily increase in years to come, e.g., to 50 % in 2017 and 60 % in 2018). Accurate US data set the GHG emissions reduction value for soy biodiesel as high as 52 %.

While US soybean producers have made major steps toward more sustainable production in the past decade, the EU use of erroneous data probably violates international trade law.

After Germany implemented the RED on January 1, 2011, US soybean exports were projected to decline and perhaps lead to US-origin soybean oil being shipped out of Germany for failure to provide data in compliance with the RED. US exports of whole soybeans are crushed in the EU and divided into meal and oil; the US could lose one billion dollars annually in trade if importers refuse to accept delivery of US-origin soybeans lacking certification to one of the RED's standard (over 20 referenced standards are cited as compliant).

EU-approved sustainability standards may discriminate against US soybeans (see Stojsin et al., Chap. 9) or use of biotech inputs, and the USA would have little or no soybeans meeting the demand of EU buyers. Indeed, history shows that EU "GM" food labeling drove "Non-GMO" standards for food products, leading EU food manufacturers to use canola oil sourced from non-American sources (leaving both North and South America with reduced EU markets) (Bernauer 2003).

The EU can point to voluntary efforts to certify Brazilian soy at a higher percentage than the 31 % baseline set for Brazil. The "Traceability and Market Claim working Group" of the Roundtable on Responsible Soy ("RTRS") discussed below admits that "Segregated trade and transport of certified soy is expensive" but claims to have "solved that problem by combining existing traceability systems in a pragmatic stepwise approach that will stimulate production of responsible soy *and* will keep the price of responsible soy reasonable." While most farms are not adopting RTRS, and no segregated delivery system exists to the EU, there is a combined percentage under the RED that can raise the 31 % calculation just enough to maintain the flow of exports and make "EU RED compliant (the EU directive which is compulsory for mainstream biofuels in Europe)." (RTRS 2011).

US soybean complex stakeholders, including the American Soybean Association, National Oilseed Processors Association, and National Biodiesel Board, want US officials to challenge the RED's requirement that biofuels sold in the EU must receive a "proof of sustainability" certificate going back to the farm level, with sustainable land use criteria. It is not feasible, economically, to accurately document each farm's sustainable land use practices. The USA is entitled to a determination independent of Brazilian practices an aggregate approach that meets EU criteria will need to be presented to ensure that crop-based biofuel feedstocks produced in the USA qualifies for certificates based on compliance with US renewable biomass requirements under the Renewable Fuel Standard. (Wellman & Callanan 2011).

3.1.4.4 UK-ASA Denies Use of "Sustainable" Labels

The World Wildlife Fund ("WWF") set a standard on sustainability for palm oil Roundtable on Sustainable Palm Oil (RSPO). After it was marketed in the United

Kingdom (UK), the UK's Advertising Standards Authority (UK-ASA) ruled that the palm oil company "sustainability" certification by the third-party Roundtable on Sustainable Palm Oil (RSPO), and the certification of biofuels in general, was "still the subject of debate." This ruling was in favor of the Environmental group Friends of the Earth, which challenged claims calling palm oil product the "green answer" as the "only product able to sustainably and efficiently meet a larger portion of the world's increasing demand for oil crop-based consumer goods, foodstuffs, and biofuels." The Malaysian Palm Oil Council (MPOC) and WWF defended the RSPO to no avail, pointing to measurable environmental and social progress (UK-ASA 2009).

In March 2008, UK-ASA also ruled that the claim that cotton was "sustainable" in the US Cotton Council advertising had "misleadingly implied the sustainability of CCI's cotton" upon which ASA found untrue and not a matter of "universal" agreement. Under the UK's "Green Claims Code" which sets the legal boundary for green marketing in the UK, green claims should not be vague or ambiguous, for instance by simply trying to give a good impression about general concern for the environment. Claims should always avoid the vague use of terms such as "sustainable," "green," "non-polluting," and so on...". The UK-ASA concluded that there was no universally agreed upon definition of the term "sustainable" citing a "significant division of informed opinion as to whether cotton production in the USA could be described as sustainable or not under the various available definitions." The ads were barred from appearing in the UK (UK ASA 2008).

In its defense, Cotton Council International (CCI) argued that US cotton production, both conventional (over 99 % of US production) and organic (less than 1 %), met or exceeded "generally accepted" definitions of "sustainability." CCI quoted definitions from the United Nations Brundtland Commission, the US Environmental Protection Agency, and the 1990 US Farm Bill [Food, Agriculture, Conservation and Trade Act of 1990, P.L. 101-624 (1990)] noting the basic "three pillars" principles remained constant: (1) Economic viability, (2) Environmental protection, and (3) Social responsibility. CCI suggested that conservation tillage was difficult if not impossible to use in organic cotton production, while conventional US cotton production—using biotech seed—had used no-till to good effect. Increased planting of biotech cotton in the USA led to less pesticide usage, with increases in beneficial insects. Cotton growers saved about 500 million metric tonnes of soil per year and significant fuel savings, reducing greenhouse gas (GHG) emissions (UK-ASA 2008). Moreover, with higher yields, UC conventional cotton required less land, water, and labor to be produced than organic cotton; since 1930, land devoted to cotton farming in the USA dropped by 30 million acres as it was set aside for conservation, while cotton yields rose significantly.

CCI denied the allegation that cotton was an "insecticide intensive" or "water intensive" crop and suggested that "organic" cotton could not claim sole title to being "sustainable" despite the benefits attributable to its use of less pesticides and inorganic fertilizers. At a very low acreage, organic cotton alone could not sustain and supply the global demand for cotton, and it was too land and labor intensive.

UK-ASA refused to allow US cotton to call itself "sustainable," citing "reputable scientific opinion that was concerned about the longer term impact of GM crops on the environment and the need for more than 10 years to assess the long-term impact of such crops." UK-ASA refused to equate the undisputed environmental benefits of biotech cotton production in the USA with the *undefined* term "sustainable." Citing the Ogallala aquifer (aka High Plains aquifer) and a US Geological Survey report from 2000, UK-ASA questioned US cotton's water consumption sustainability figures, given a 6 % decrease in the volume of stored Oglalla water in the past 50 years, with Texas and Kansas reporting steep declines (27 % and 16 %, respectively). UK-ASA concluded that for water conservation, CCI did not establish that US cotton production on the High Plains region of the US was "sustainable." (Cotton Incorporated 2011).

UK-ASA also found US cotton subsidies competed unfairly with cotton farmers in the developing world and a World Trade Organization (WTO) ruling against US cotton subsidies in rejecting CCI's view that the US cotton industry had no negative impact on local economies elsewhere therefore did not command universal acceptance.

In light of this decision, the ability of any claim of "sustainable" food may not pass muster, given the lack of an accepted definition. This places proposals to put "sustainable" on food labels in doubt, at least in the UK.

3.1.5 Greening of Food Companies and Retailers

The world's largest food and beverage corporations are increasingly filing "sustainability reports" (driven in large part by investors and retailers, not necessarily food consumers) with continuous improvement goals that eventually require the measurement of indirect "embedded" environmental impacts such as carbon emission, water use, and the like. Competition for stock price, goodwill, and brand identity has led major global food companies to launch sustainability initiatives. For example, the EU-based global food and consumer products manufacturer, Unilever, has launched a "sustainable living plan" that will reduce its footprint considerably over the next decade (Neff 2011).

Food companies may encounter opposition to such moves within the supply chain, since the process of managing and reducing environmental impacts entails significant costs for producers of agricultural products. The food companies, however, will buy both commodity grains and "specialty" crops that are traceable to their source. The food companies often have production contracts with specialty crop producers—as opposed to commodity production—called "vertical integration" (corporate-owned or leased land, corporate-owned harvest, etc.). This contractual relationship allows the food company to manage growing practices.

For example, Miller-Coors enlisted its best barley producers in particular barley producing regions to study their water footprints, generating a GIS-based mapping system with dialogue boxes detailing information for each grower, describing their water supply-related risks (SABMiller plc 2011).

For some fruit producers, a sustainability certification opens doors to key markets in the USA (NY Fruit 2009). This drive for sustainability also raises a risk of being accused of greenwashing (Vijayaraghavan 2011). To avoid this, food companies will adopt plans to continuously improve their own footprint as well as their suppliers, including the producers of agricultural products.

3.1.6 Support or Rejection of Voluntary Standards

This section compares various standard-setting processes and initiatives in the USA, including one controversial national standard under the American National Standards Institute ("ANSI").

3.1.6.1 Field to Market (Keystone) Commodity Initiative

In September 2006, a facilitator called the Keystone Center convened representatives from grower associations, environmental groups, commodity associations, and major agribusiness companies to develop a more sustainable approach to commodity production—the "Field to Market" Initiative (FtM). This agricultural commodity roundtable developed an online calculator to measure key impacts—Version 2.0 of the Fieldprint Calculator. This tool will help farmers track impacts to meet sustainability outcomes (Keystone 2011). By improving the sustainability of these crops, this process seeks to "become the predominant metrics" used in the USA (Keystone 2011).

Keystone's vision for measuring sustainability performance draws from input provided by soybean, corn, wheat, and cotton farmers as well as a wide range of stakeholders in the chain of commodity commerce (including WWF, Kelloggs, General Mills, etc.).

The Keystone Center released its sustainability metrics to other organizations (e.g., Bunge North America, Syngenta, etc.) who conducted pilot studies with growers in early 2011 using the FtM tool, which uses algorithms to provide feedback to a software developer. Over time, information management tools will increasingly track and report progress in managing environmental impacts of agriculture.

3.1.6.2 NRDC's Stewardship Index for Specialty Crops

The Stewardship Index for Specialty Crops is a multi-stakeholder initiative to develop a system for measuring sustainable performance in specialty crops, offering outcomes-based metrics to enable operators at any point along the supply chain to benchmark, compare, and communicate their own performance. The Stewardship Index for Specialty Crops quantitative sustainability metrics addresses 14 impact categories (Stewardship Index 2010). This project defines "specialty crops" as including fruits, vegetables, nuts, and horticulture. Its proponents hope participants will "reduce the likelihood of future industry regulation by solving problems and demonstrating improved performance to regulators." USDA funded pilots of these metrics in 2010 and funded another round of testing in 2012.

3.1.6.3 Council on Sustainable Biomass

The Council on Sustainable Biomass Production (CSBP) is another multi-stakeholder group, which has been working since 2007 to develop comprehensive voluntary sustainability standards for the production of biomass to use in energy production. Using CSBP standards for bioenergy GHG emissions, producers of biomass and bioenergy can "maintain and enhance social, economic, and environmental well-being" using a "rigorous threshold for the sustainable production of biomass," which would include energy conservation metrics.

The CSBP Standard applies to biomass produced from nonfood sources, including fuel crops, crop residues, and native vegetation. Like most standards, it begins with a management planning requirement to enable continuous improvement. It addresses soil, biological diversity, protection and enhancement of surface and ground water quality, and greenhouse gas emissions using widely accepted environmental lifecycle analysis. The CSBP Standard also addresses social sustainability issues as well as strict compliance with all human rights and labor protections laws (CSBP 2009).

3.1.6.4 ANSI Leo 4000 Standard on Sustainable Agriculture

In April, 2012, the Leonardo Academy's LEO 4000 standards committee finalized the text of a proposed national standard on sustainable agriculture under the American National Standards Institute and took public comment in early 2014. This standard would award "points" for particular agricultural practices, allowing growers to be certified, like a LEED building, at levels (e.g., basic, silver, gold, platinum). For the current text and status of the standard, which ran to 125 pages as of April, 2014, readers can check online at the Leonardo Academy website (Leonardo 2012). It appears to be headed toward setting a standard that will elevate some forms of certified organic agriculture over other more productive forms of agriculture, which use agricultural chemicals and do not place diversity in crops above productivity for the sake of diversity.

The background of this standard is helpful to understand this detour from mainstream agriculture's and USDA's understanding of sustainability (as stated in the Farm bill and as applied through various farm programs). In 2007, Scientific Certification Systems Inc. (SCS) published a Draft Standard for Sustainable

Agriculture (SCS-001, now called Leo 4000) with the American National Standards Institute (ANSI). The Leonardo Academy in Madison, WI (Leonardo), an ANSI-accredited standards development organization (SDO) specializing in sustainability, is secretariat for the standard, facilitating dialogue on the future of sustainable agriculture in the USA. Toward that end, Leonardo chose 58 voting members of the Standards Committee, ostensibly representing nearly every major material interest in US agriculture. Industry saw the selection process as lacking adequate notice to mainstream agricultural interests, and challenged the Leonardo choices of committee members, finding it tilted toward organic and floral interests (Bligh and Redick 2008).

The lack of balance (e.g., turning down the Fertilizer Institute) led to legal challenges and a caution from the ANSI Executive Standards Board. Most notably, USDA filed an appeal challenging Leonardo's accreditation as an ANSI SDO, based on Leonardo's refusal to allow USDA observers, its apparent endorsement of the "precautionary principle" in excluding "GMOs," and its lack of notice to mainstream agricultural interests.

After hearing over USDA's appeal challenging Leonardo's accreditation under ANSI, the ANSI Executive Standards Board issued a warning to the Leonardo Academy to seek greater neutrality. While denying USDA's appeal challenging the accreditation of Leonardo Academy, this ruling also warned Leonardo not to let the certifier funding the process, Scientific Certification Systems (SCS), dominate its decision making (Constance 2010).

For two years (2008–2010), the Standards Committee worked to set a science-based foundation for this standard with a representative minority of mainstream agriculture seeking consensus with organic advocates and environmental organizations. After reaching out to other standards processes, like the Keystone Field-to-Market Initiative, the Standards Committee voted in May 2009 to focus on crop production, leaving livestock operations for later. By agreeing to the use of "any technology" that serves sustainability in agriculture, they neutralized the strong objections lodged by USDA in its appeal for Leonardo's accreditation (Bligh and Redick 2008).

This allowance of "any technology" was an important precedent in standard setting for sustainable agriculture—any standard should be neutral toward the use of genetically engineered crops. The agricultural technology must be allowed to prove their worth using metrics that measure performance. Consumers who object to "GE" content are free to shop at stores selling non-biotech content, like Whole Foods Markets and others listed in activists' online references to "non-GM" retailers (Institute for Responsible Technology 2010).

As of September, 2009, the Standards Committee had formed six subcommittees to engage in the process of drafting a standard worthy of becoming the national standard for sustainability in US agriculture. Organic participants found common ground with mainstream agriculture committee members at first, recognizing that organic agriculture needed to improve its environmental footprint along with mainstream agriculture.

The standards committee agreed to proceed on a "science-based" basis with a common set of metrics to measure progress toward outcomes—a benchmark to gauge private sustainability efforts, whether certified or voluntary measures used to improve an ecological and social footprint. With the addition of two new members in October 2011, the Standards Committee had 60 members (Leonardo 2012) but relatively light participation on the subcommittees drafting the standard's text.

The first sign of a breakdown in the committee came in mid-2010 with the departure of two leading environmental organizations (who complained of the cumbersome and contentious process). Over time, with some departures of committee members being replaced with mostly organic stakeholders, the Leonardo Academy had increased the organic slant in membership to give it an apparent voting majority at the Third Meeting of the Standards Committee in 2010. In late 2010, moreover, these environmental groups were joined by at least 12 members representing mainstream agriculture who resigned *en masse* from the Standards Committee citing the organic bias in the standards committee. Later in 2010, key floral industry representatives also left the Standards Committee, leaving it even more imbalanced toward organic stakeholders.

After the mass departure of key mainstream trade groups, however, the 58-member Standards Committee did not dissolve, but Leonardo worked through 2011 to fill open seats or go forward with a Standards Committee that is not balanced as to all material interests in agriculture.

In 2014, Leonardo published the standard for public comment. Promoters of the standards hope, through ANSI's consensus-building process, to deliver practical tools that US producers can use to follow the three pillars of sustainability—environmental protection, social justice, and economic viability. As currently framed, however, the organically stacked Standards Committee may set "tiers" (like a LEED building—platinum, gold, silver, and entry level), to provide more "points" for practices that are used in organic production, making the national standard for sustainable agriculture serviceable only in niche markets—an "organic-plus" standard that might cut into existing certified organic market shares, or provide an edge over imported organic agricultural products, but do little to attract the interest of mainstream agriculture.

Lacking participation from sufficient voices in mainstream agriculture, however, such a niche standard may be fated to be marketable to a small percentage, yet to be defined, of the small percentage of crop growers that already use organic practices.

3.2 International Voluntary Standard Setting in Sustainable Agriculture

Within a market economy, *voluntary* standards are generally more efficient and flexible than regulations, optimizing practices for particular outcomes and crops. These standards may also be viewed as less discriminatory than state-imposed taxes and quotas in international trade law. By integrating politically sensitive social and environmental concerns, voluntary standards and associated codes and certification schemes represent a kinder, gentler version of globalization (Vorley et al. 2007).

3.2.1 WWF Sustainability Standards in Agriculture

The World Wildlife Fund for Nature (US), led by Dr. Jason Clay, Senior Vice President Market Transformation, has set global standards for producing and using various agricultural raw materials, particularly in terms of carbon and water. WWF has held a number of “industry roundtables” bringing together retailers, buyers, growers, and environmentalists to discuss how best to work together to reduce the key impacts of producing soybeans, cotton, sugarcane, salmon, shrimp, mollusks, catfish, and tilapia without undue impact on the yields needed to maintain the world’s food production at reasonable prices. WWF claims to have “10–25 % of global production and buyers sitting at the table” for each of the listed commodities.

3.2.1.1 Sustainable Palm Oil

The WWF-led Roundtable on Sustainable Palm Oil (RSPO) may be the most advanced in terms of global adoption. The RSPO standards were agreed to in 2007 and as of 2011 has certified over 5 million tons of palm oil out of world production of approximately 45 million tons. The RSPO has measured environmental and social progress including zero discharge for some palm operations and Regional-scale HCVF (high conservation value forest) surveys. With 75 % of new plantings on land already cleared of forest, the ecological “footprint” of palm oil is improving, reducing environmental degradation (Fitzherbert 2008).

3.2.1.2 Livestock Sustainability

Sustainable livestock has a similar tug of war between advocates of free range organic livestock production methods and the more contained “concentrated animal feeding operation” (“CAFO”) which is pejoratively called a “factory farm” by certain environmental activists. According to a report from the US National Academy of Sciences, atmospheric ammonia and nitric oxide—both produced on farms—contribute to what is known as the “nitrogen cascade,” in which each ammonia molecule “can, in sequence, impact atmospheric visibility, soil acidity, forest productivity, terrestrial ecosystem biodiversity, stream acidity, and coastal productivity” (Sustainable Table 2009).

To address these impacts, the WWF convened a roundtable addressing the sustainability of the beef system through multi-stakeholder engagement. Invited stakeholders gathered in Denver in November 2010 for a 3-day Global Conference on Sustainable Beef to plot a path toward increasing the sustainability of the beef production system as to the environment, economy, and society. Corporate sponsors included Cargill, Intervet/Schering-Plough Animal Health, JBS, McDonald's, and Wal-Mart. This meeting included key players in the global beef supply chain and a diverse stakeholders from academia and NGOs. The discussion included eight key issues—food and nutrition, community, water, labor and business, land management, energy, biodiversity, and greenhouse gas emissions. Wal-Mart's representative stated that it would make "sustainability practices of producers and suppliers a factor in deciding which beef we buy for our 8,500 global locations" (Global Roundtable 2014).

This initiative is timely, since the livestock industry will increasingly come under the reporting requirements for carbon-equivalent emissions (whether EPA or through states like WA, CA, etc.). The sustainability of beef production has been the subject of scientific debate, after the United Nations issued an analysis of the life cycle of beef production (Steinfeld et al. 2006) that was erroneous and misleading (Pitesky et al. 2009).

CH_4 emissions from the use of liquid manure waste systems may produce more methane than dry (dairy and pig operations) (FAO 2006). Controlling the emissions from such contained liquid systems is also more feasible in a contained setting. Some major emitters are using CH_4 digesters to capture CH_4 emissions from liquid manure and generate electricity, gas, and biofuel. This approach could reduce net GHG emissions from liquid manure by 50–75 %. In the USA, CH_4 emissions from manure management increased by 65.3 % between 1990 and 2011 during an increase in use of liquid manure systems (EPA 2013). Those CH_4 emissions are an energy source that is lost, if not controlled.

The digester-driven approach would address the concerns of environmental activists, who claim that the most efficient way to reduce air pollution from farms is to reduce the size and increase the number of farms. Sustainable livestock farms that are pasture-based systems and rely on the animals to harvest feed and spread manure may actually cause greater emission to water (from uncontrolled deposit or runoff to streams) than a dairy using a digester to control CH_4 emissions and convert them to energy (Pitesky et al. 2009). In time, consumers may realize that the land required for pasture-based grazing has its own impact (livestock related land-use change produces 2,400 Tg CO_2-eq yr_1 or 35 % of the total GHGs attributed to livestock) and opt to purchase carbon-neutral milk from an "industrial" operation. The measurement of relative environmental impact throughout the livestock lifecycle may become highly debatable once digesters are entered into the equation.

3.2.1.3 RTRS

The WWF convened a broad group of stakeholders in South America to create the Roundtable on Responsible Soy (RTRS), seeking to improve on the environmental footprint of South American soy production. In June, 2010, the RTRS issued its final version of global voluntary standards for environmentally and socially responsible soy production (RTRS 2010). The RTRS is technology neutral and will certify "GM" soy, to the dismay of some anti-biotech activists.

The RTRS process should be commended, however, for taking input from producers of biotech crops. The following provisions on "GMO" production (Paragraph 5.10) ensure that most biotech crop producers would not have to create a buffer zone to protect a non-GMO neighbor's premium, as the following excerpt illustrates.

> When a change in soybean production practices is introduced which could impact on neighboring production systems, it is the responsibility of the producer making the change to implement a buffer strip of 30 m. (e.g., in areas where production is generally GM, it is the responsibility of an organic or non-GM farmer to maintain the buffer around his own production. In areas where production is mainly non-GM or organic, a farmer planting GM or using chemicals should maintain a buffer) (RTRS 2010).

This language addressed biotech crop producers' objections to language that would have required a biotech producer who has been planting biotech corn for over 10 years in the same location might find his planting area severely limited to create a buffer against cross-pollination to his new neighbor, who just decided to plant Non-GMO corn to reap a premium in the marketplace. As will be discussed below, the same input was provided to the Roundtable on Sustainable Biofuels, but similar language failed to be adopted.

3.2.2 Roundtable on Sustainable Biofuels

The Roundtable on Sustainable Biofuels (RSB) is a multi-stakeholder initiative initiated by EPFL in Geneva, Switzerland. This standard seeks to develop a system for measuring sustainable performance throughout the chain of biofuel production (see Hughes et al., Chap 2).

In 2009, the RSB published Version 1.0, which contained language requiring biotech crop producers to "prevent migration" to other crops. This would have imposed a duty on a biotech grower to avoid "contaminating" his neighbor with biotech crops—even where a non-GMO neighbor suddenly appears in the midst of a county that is planted almost entirely in biotech crops. Grower groups from the US objected strongly to this imposition of a duty that would be impossible to fulfill, if the non-GMO neighbor failed to communicate his growing plans—and unfair to impose, if the non-GMO grower was collecting a premium and also expecting his neighbor, without pay, to refrain from productive use of strip of land (RSB 2011).

The RSB executive director recognized the need for legal input on this coexistence issue, drafting "Terms of Reference" in late 2010 in order to form an expert committee on coexistence and liability issues. While Version 1.1 had improved, the RSB steering committee did not adopt the input from a group of liability experts.

The difference in language is subtle enough to merit a comparison below. While the RSB would have a biotech producer "take measures to prevent migration" under

RSB version 2.0, the proposal from the liability expert group (of which this author was a member) would move "cooperate" to be the active verb, eliminating the positive duty to "take measures" to prevent migration. Unless this change is made, the text of the RSB will remain as anti-GMO as some of the laws in the EU imposing such a duty to avoid migration (Parliament 2011).

Current RSB Principle 11.b. reads as follows:

> Participating Operators using GMOs shall take measures to prevent migration of genetically modified material and shall cooperate with neighbours, regulatory and conservation authorities, and local stakeholders to implement monitoring and preventative measures. Crop-specific and technology-specific mitigation strategies shall be utilized.

Editorial Suggestion of Expert Group (May 2011) Criterion 11.b, Third Bullet

> Participating Operators using GMOs shall cooperate with neighbours, regulatory and conservation authorities, and local stakeholders to implement monitoring and preventative measures to prevent migration of genetically modified material. Crop-specific and technology-specific mitigation strategies shall be utilized.

In contrast to the RTRS above, which clearly requires a non-GMO producer to maintain his own buffer (unless he is in a non-GMO zone), the current RSB language would always impose this obligation on the biotech producer. This is similar to the EU's Global GAP standard discussed above in Sect. 3.1.4.2.

Standards are entitled to "go beyond regulation" to address adverse impacts to the environment and people. It is more troubling, perhaps, to venture into managing relative economic interests between growers of biotech or non-GMO crops. Indeed, no particular economic interest is more worthy of protection unless it links to some public benefit (e.g., standards dictating size, quality criteria for crops are common in the industry). RSB version 2.0's provisions on coexistence of biotech and organic/non-GMO crops would require a biotech producer who has grown biotech corn for 15 years, selling a commodity crop with no premium paid, to incur costs of his own to protect a neighbor next door who just decided to produce non-GM corn in the hope of getting a premium of up to 100 %.

The RSB Steering Committee is considering the input of its panel of liability experts. Unless changed, the RSB standard will have a non-GMO bias. While this might fit neatly with EU policy, it will only serve to create non-GMO production pathways in key crop-producing nations in North and South America. While the RSB professes that it "will continue to be open and flexible to integrating new information and technology developments into the Standard to stay relevant into the next decade and beyond," it has some work to do before it will be accepted outside the EU.

3.2.3 Global Bioenergy Partnership

The Global Bioenergy Partnership (GBEP), a government-level organization of 23 nations, including most of Europe, Asia, North and South America, and parts of

Africa, released 24 sustainability guidelines for bioenergy in May 2011. GBEP has an "Inventory of Current Initiatives on Sustainable Bioenergy Development" and GHG Methodologies finalized "GBEP Common Methodological Framework for GHG Lifecycle Analysis of Bioenergy—Version 1."

The link to Web site for these GBEP inventory and methodologies documents is at http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/1008_GBEP_SUST_INITIATIVES_INVENTORY.pdf.

There was a round table with the private sector at the 2010 World Biofuels market Congress. Such "Side Meetings" held in conjunction with other meetings of the GBEP partners are a common occurrence. Given the linkage to governments, this is a bioenergy initiative worth watching.

3.3 Conclusion

While there will always be debates over what is "sustainable," there are clearly benefits to be reaped from better management of environmental and social impacts of agriculture. A balanced approach would simply recognize the resource limits on expanding organic production and also encourage continuous improvement in managing the environmental-social impacts of mainstream agriculture. This process appears to be well underway in various sectors of the agricultural economy, with sustainability standards providing a vehicle, if they are drafted with sufficient input from relevant sectors—particularly the producers who would be asked to change particular practices.

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Part II
Soil and Water

Chapter 4
Soil Degradation, Land Use, and Sustainability

Jerry L. Hatfield

4.1 Introduction

Soil resource is a critical part of all agricultural production systems, and maintenance of a high quality soil capable of supplying water, nutrients, and gases is necessary to sustain the production needed to meet the demands of an ever increasing world population on the same or smaller land mass. Lal (2009) described ten tenets for sustainable soil management that included:

- Causes of soil degradation and human suffering.
- Soil stewardship.
- Nutrient, carbon, and water balance.
- Marginality principle.
- Organic versus inorganic source of nutrients.
- Soil carbon and greenhouse effect.
- Soil as a sink for atmospheric CO_2.
- Productive soil combined with productive germplasm.
- Soil–plant interface—the engine of economic development.
- Traditional knowledge and modern innovations.

These factors provide a foundation for the assessment of the impact of soil degradation on our future ability to produce food, feed, fiber, and fuel from varied land resources. Both world population growth and the higher living standards expected by all peoples will drive the demand for food and require that we consider the present state of our soil resource and the role it plays in efficient agricultural production. We have lost sight of the fragile nature of the soil resource and how quickly it can become degraded and the effort it will take to restore our soils to their productivity capacity. Soils are the foundation of sustainable agriculture and in

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order to develop systems capable of meeting the world food needs and protecting environmental quality, there needs to be a renewed emphasis on enhancing the soil resource. These are challenges we need to address and develop strategies to implement solutions across a wide range of soils, climates, and cropping systems. Throughout this chapter, these concepts will be developed to help spur discussion and action on the need to understand soil degradation and how we can begin to increase our understanding of how to enhance our soil resource.

4.2 Soil Degradation

4.2.1 Processes

Degradation of the soil is a complex process and involves changes in the physical, chemical, and biological processes with the soil. If we look at degradation from landscape and soil profile perspectives, then degradation will have both depth and horizontal components. Changes in the soil will occur at the surface more than with depth because the forces causing degradation will manifest themselves at this part of the soil profile more than with depth. These changes will not be uniform across a landscape because different soils will respond differently to the forces causing degradation.

Physical degradation is linked with changes in the water and air exchanges in the soil. Primarily, this can be considered as a degradation of the soil structure that no longer allows the soil particles to maintain their ability to withstand either mechanical or hydrological forces. Thus, a breakdown in soil structure through reduction in aggregate strength or stability leads to increased slaking, crusting, and bulk density (compaction). This change in soil structure reduces soil porosity and diminishes gas exchange leading to less oxygen available in the soil profile. Erosive processes are increased when there is a diminished soil structure at the surface because under rainfall events, the stability of the soil surface decreases and as the water infiltration rate is no longer maintained then the soil will begin to move and if rainfall events continue long enough there will be erosion. Hamza and Anderson (2005) stated that potential methods for the alleviation of compaction involve increasing the organic matter content of the soil and incorporation of crops into the rotation which add a deep rooted crop to restore structure to the lower soil profile.

Chemical degradation incorporates changes in the chemical processes within the soil which will in turn affect plant growth. Soil acidification from a reduction in pH can be caused by leaching of bases through the soil profile or the continual addition of acid-producing fertilizers. Depletion of nutrients by removing plants or leaching without resupplying these nutrients is another form of chemical degradation. Conversely, soils can become toxic through the buildup of elements like Al, Fe, and Mn to levels where they become toxic to plants. Continual increases in soluble salts in the root zone to increase the electrical conductivity above 4 ds m^{-1} creates salinization of the soil while additions of Na ions through sodic salts can lead to alkalinization of the soil. Vanderpol and Traore (1993) found nutrient depletion in the soils of Mali to be substantial due to erosion and denitrification of N. The magnitude of the nutrient losses were equivalent to 40 % of the annual income from the farms in Mali.

Biological degradation is associated with the dynamics of the microbial systems within the soil profile. Microbial activity and soil biodiversity are linked with the soil organic carbon (SOC) pools in the soil and ultimately are associated with the depletion of SOC and the turnover rates of the SOC pool. Bastida et al. (2008) proposed the use of a biological index for soil quality, and when they compared different methods found metabolic quotient (ratio of respiration to microbial biomass) as an index to evaluate ecosystem disturbance or its maturity. They proposed that any method which incorporated some aspect of soil biological status or function would be a valuable indicator of soil quality or soil degradation. Soil biological systems are a critical component of soil function and implementation of indices which can quantify the changes in soil biology in response to soil changes.

There are a number of soil management practices that create conditions in which there is potential for increased soil degradation. One of the most critical decisions is the maintenance of crop residues on the soil surface and the effect on surface sealing and crusting because the direct impact of raindrops on the soil is to consolidate the surface layers leading to the formation of crusts. Surface soil properties are sensitive to the maintenance of stable soil aggregates which are created through the continual addition of organic material. For example, Ruan et al. (2001) found that it was necessary to maintain surface residue cover in order to prevent surface sealing. Tillage practices, e.g., no-till, which maintain crop residue on the surface and application of compost and manure as sources of organic materials reduce surface sealing and crusting (Cassel et al. 1995; Pagliai et al. 2004). Blanco-Canqui et al. (2006a) found that soils without residue cover developed crusts with a thickness of 3 cm and cracks with widths of 0.6 cm during periods in which there was no rainfall. Removal of crop residue affects the stability of aggregates, arrangement of soil particles glued together by organic materials, and depends upon the soil organic matter (SOM) concentration in the surface soils (Blanco-Canqui et al. 2006b; Rhoton et al. 2002). These changes in the soil structural stability are rapid and often degradation of the surface soils can occur within the first year when the soil has the residue removed (Blanco-Canqui and Lal 2009). Blanco-Canqui et al. (2009) conducted a regional scale study on various tillage systems across the US Great Plains and found aggregates under no-till systems were more stable under rain but didn’t show any effect on dry aggregate stability (see Chaps. 5 and 10). Stable aggregates under rainfall event will lead to increased resistance to the soil erosion. Since erosion is one of the major causes of soil degradation, any change in a soil property increases the risk to intense rainfall events.

Implementation of any tillage practice compared to a virgin soil or sod may lead to a decrease in the physical quality attributes of the soil (Reynolds et al. 2007). They observed that converting bluegrass (*Panicum dichotomiflorum* Michx.) sod to a corn (*Zea mays* L.)-soybean (*Glycine max* (L.) Merr.) rotation with moldboard plow caused the surface soil physical characteristics, e.g., bulk density, macroporosity, air capacity, plant available water capacity, and saturated hydraulic conductivity, to decline within 3–4 years to levels similar to long-term corn-soybean with moldboard plow systems. Compared to virgin soil and sod systems, even the no-till system with the corn-soybean rotation showed declines in soil physical quality.

Tillage not only decreases the SOM content in the surface soil and causes a corresponding decrease in soil biological activity (Mahboubi and Lal 1998). Mahboubi and Lal (1998) found there was a seasonal response to tillage effects on aggregation and soil structure, which needs to be accounted for any assessment of the impacts on tillage on soil properties. Salinas-Garcia et al. (2001) observed that removal of crop residue from the soil surface decreased the soil microbial biomass C and N concentrations. After comparing three tillage systems in Nebraska, Doran et al. (1998) found a loss of soil carbon (C) from all three systems; however, the loss from no-till was less than conventional tillage. There was an increase in soil microbial activity near the soil surface in the no-till system. Similar observations were found by Karlen et al. (1994) in which removal of crop residue caused the soil aggregates to be less stable and decreased soil biological activity. The advantage of the no-till system was the maintenance of the protective soil cover and partially decomposed organic material near the soil surface that reduced the rate of soil degradation. Reeves (1997) stated that maintenance of SOM is critical for soil quality. Soil organic matter in the soil is a critical component in the soil. Loveland and Webb (2003) reviewed the literature from around the world and concluded that when organic C declines below 2 % there will be a decline in soil quality.

4.2.2 Extent

Soil degradation is extensive throughout the world. Lal (1993) stated that soil degradation is a major threat to agricultural sustainability and environmental quality and is particularly serious in the tropics and subtropics. For example, Nyssen et al. (2009) reported that nearly all of the tropical highlands (areas above 1,000 m asl covering 4.5 million km^2) are degraded due to medium to severe water erosion. Zhao et al. (2007) evaluated the change in the Horquin sands because of the conversion of farmland from the original pasture and found significant decreases in crop yield and poorer soil properties after conversion to cropland. Kidron et al. (2010) suggested that the increasing pressure for food alleviating the traditional practice of 10–15 years of cultivation followed by 10–15 years of fallow with a continuous cropping practice has increased the rate of soil degradation. They found that SOM content showed the strongest relationship to soil degradation and practices which accelerated the removal of SOM increased the rate of degradation.

In the subhumid and semiarid Argentinean Pampas, Buschiazzo et al. (1998) observed that intensive cultivation for over 50 years had resulted in soil degradation leading to moderate to severe erosion across the region. A similar conclusion was developed by dos Santos et al. (1993) for southern Brazil in which they attributed the severe soil degradation to the widespread use of wheat (*Triticum aestivum* L.)-soybean or barley (*Hordeum vulgare* L.)-soybean double cropping systems coupled with intensive tillage. Krzic et al. (2000) observed that in the maritime climate of the Fraser Valley in British Columbia with over 1,200 mm of annual rainfall that conventional tillage over a number of years has contributed to poor infiltration, low organic matter content, and poor soil structure.

In southern Brazil and eastern Paraguay, Riezebos and Loerts (1998) observed that mechanical tillage resulted in a loss of SOM leading to soil degradation across this region. The conversion of semi-deciduous forests to cultivated lands has the potential for soil degradation, and proper management will be required to avoid degradation. Degradation of the soil resource occurs in many different forms and in Nepal, Thapu and Paudel (2002) observed watersheds are severely degraded from erosion. They found erosion has impacted nearly half of the land area in the upland crop terraces. This degradation was coupled with depletion of soil nutrients which in turn is continuing to affect productivity in this area. This is similar to the observation in Ethiopia by Taddese (2001) where severe land degradation caused by the rapid population increase, severe soil erosion, low amounts of vegetative cover, deforestation, and a lack of balance between crop and livestock production will continue to threaten the ability to produce an adequate food supply for the population.

Wang et al. (1985) observed that differences in soil structure and saturated hydraulic conductivity were related to cropping systems and degradation of soil structure in the profile led to corn yield reductions as large as 50 %. This decrease in yields could be related to the shallow root growth and limitations in water availability to the growing plant. Impacts of poor soil structure on plant growth and yield can be quite large, and continued degradation of the soil resource will have a major impact on the ability of the plant to produce grain, fiber, or forage.

Eickhout et al. (2006) stated that over the next 20 years, in order to meet food demand, there may have to be an additional clearing of forest land for production to offset the declining soil quality in the current land resource base. They advocated that we need to consider nitrogen (N) dynamics in current and future food production systems and increase our emphasis on N use efficiency and focus on improvements in agronomic management to offset the impacts of soil degradation (see Sripada et al., Chap. 8, Reetz, Chap. 15).

4.2.3 Impacts

The impacts of soil degradation on food security are profound and examples from developing countries (see Chaps. 11, 12 and 13), e.g., Hadgu et al. (2009) are available. In their study from Ethiopia, spatial variation in agro-biodiversity and soil degradation assessed in 2000 and 2005 at 151 farms in relation to farming operation, productivity, wealth, social, developmental, and topographic characteristics revealed a significant decrease in agro-biodiversity between 2000 and 2005, associated with inorganic fertilizer use (see Reetz, Chap. 15), number of credit sources, and proximity to towns and major roads. Higher ratings of agro-biodiversity were observed at farms with higher soil fertility (available P and total N) and higher productivity (crop yield). Soil erosion was related to lower crop diversity and steeper slopes. The more intense the cultivation practices the lower the ratings on agro-biodiversity and conversely the less intense cultivation was linked with greater agro-biodiversity. Another study in Vietnam has found that as much as half of the total land area is already degraded by soil erosion and nutrient depletion (Clemens et al. 2010). Degradation is related to deforestation and is affecting producers in the mountainous areas in northwestern Vietnam. The main physical processes were erosion and sedimentation on lower parts of the landscape. Farmers have underestimated the impact of soil degradation productivity but were aware of the impacts of soil quality on production (Clemens et al. 2010). High fertility soils were located on less eroded upper parts of hills and where there was recent conversion to agricultural production. In their observations, they found that soils, once degraded by cultivation practices, did not recover even after more than 50 years of fallow. Unsustainable land use leads to soils on middle and lower slopes being affected by severe soil erosion, whereas foot slope soils suffer from accumulation of eroded infertile subsoil material. A unique feature of this study was the evaluation across the landscape and the connectivity among slope positions because use of unsustainable land use practices at upslope landscape positions had a severe impact on downslope areas. Soil management practices which reduce erosion will have a positive impact on soil quality and production at all slope positions.

Ahaneku (2010) observed the linkage among poverty, intensification, and extensification of marginal lands as major threats to the sustainability of soil and water resources in Nigeria (see Oikeh et al., Chap. 13). This study recommended "home grown: soil and water conservation practices and water quality management techniques are vital to ameliorate the problems of soil degradation, erosion, and water quality." Ahaneku (2010) suggested that education and training producers about soil management practices to enhance the soil resource provided the most viable option to avert food crisis in Nigeria.

Ostergard et al (2009) suggested that food security will require a radical shift in crop production practices to address the problems of soil degradation, loss of biodiversity, polluted and restricted water supplies, future fossil fuel limitations, and increasingly variable climatic conditions. They identified practices such as "(i) building soil fertility by recycling of nutrients and sustainable use of other natural and physical resources, (ii) enhancing biological diversity by breeding of crops resilient to climate change, and (iii) reconnecting all stakeholders in crop production" as necessary practices to achieve food security.

Degradation of soil structure leads to an increased risk of run-off and soil erosion and to avoid reductions in food production caused by the degraded soil resource, it will be necessary to use more sustainable management practices (Blair et al. 2006). Small-grain rotations with legumes were evaluated for their effects on total C, labile C, non-labile C, total N, aggregation (mean weight diameter (MWD)), and infiltration on a Black Earth (Pellic Vertisol) and a Red Clay (Chromic Vertisol) soil near Tamworth, in New South Wales, Australia compared with an adjacent uncropped pasture for each soil type. Cropping reduced all C fractions, total N, aggregation, and infiltration on both soils. Interestingly degradation increased when a long fallow was part of the rotation. Use of the long fallow decreased labile C by 70 % in the Red Clay soil and by 78 % in the Black Earth compared with the adjacent pasture while aggregation decreased by 61 % in the Red Clay and 91 % in the Black Earth. Adding legumes to the cereal rotation caused smaller decreases in C fractions, total N, aggregation, and infiltration compared to pasture. Adding alfalfa (*Medicago sativa* L.) to the rotation caused labile C to be 41 % higher, aggregation to increase by 45 %, and infiltration to increase by 87 % compared to the long fallow on the Red Clay soil and increase by 65, 126, and 43 % on the Black Earth soil, respectively (Blair et al. 2006). Soil sustainability may be increased by introduction of forage legumes into the rotations by altering the rate of C decrease fractions, total N, aggregation, and infiltration (Blair et al. 2006). Martinez-Mena et al. (2008) evaluated the impact of water erosion and cultivation in the semiarid region of south-eastern Spain and found the conversion of forest land to cultivated land increased erosion risk and reduced the C stock on the upper 5 cm by 50 %. An interesting observation from this study was the loss of the labile C fraction was due to mostly cultivation rather than erosion. This would suggest that cultivation of soil should be minimized to avoid degradation of the soil resource.

Changes in biological activity in soils are rapid when there is a change in the tillage practice or crop rotation. Aslam et al. (1999) observed rapid changes in soil microbial systems when permanent pasture was converted to crop rotation using corn and winter oat (*Avena sativa* L.) under both plow tillage and no-till systems. Within 2 years under the plow tillage system, there was a 45 % decline in soil microbial biomass C, a 53 % decline in microbial biomass N, and a 51 % decline in microbial biomass phosphorus (P) in the upper 5 cm of the soil profile. The changes in microbial dynamics with no-till compared to permanent pasture were insignificant suggesting that adoption of no-till can reduce the biological degradation when soils are placed under cropping systems (Aslam et al. 1999). These results are similar to those observed in West Africa by Babalola and Opara-Nadi (1993) from their study showing that mechanical tillage of the structurally unstable Alfisols and Utisols caused more adverse than beneficial effects. Increased tillage caused both a decrease in SOM and increased the release of nutrients, and they found that use of no-till with crop residue mulch maintained soil properties with favorable characteristics to resist soil degradation. In Iran, Barzegar et al. (2003) found for chickpea (*Cicer arientinum* L.) grown under three different tillage systems on a silty clay loam soil (Typic Xerorthens) after 20 years of continuous wheat, crop yields, and soil physical properties were most improved under the single point chisel plow system. This tillage system also exhibited the greatest soil water storage, which produced the highest total biomass and grain yield. In an evaluation of the changes in soil properties affected by tillage systems in the Argentinean Pampas, Buschiazzo et al. (1998) observed that reductions in tillage intensity increased SOM content of the soil more in subhumid than in semiarid regions. These differences in SOM content and aggregate stability were limited to the upper 5 cm of the soil profile. A study of tillage practices by Lal (1997) in Nigeria on corn showed that yield was related to SOC, exchangeable Ca^{2+}, and cation exchange capacity (CEC). Continuous cropping degraded soil chemical quality, and the rate of decline was faster with intensive tillage than with no-tillage practices. Any practice that can increase productivity and protect the soil surface from erosion will have a positive benefit on soil properties. Melero et al. (2009) compared conservation tillage and conventional tillage in Spain under rainfed crop rotations and found conservation tillage increased both soil microbial biomass C and enzymatic activity (dehydrogenase (DHA), o-diphenol oxidase (DphOx), and β-glucosidase (β-glu)). These enzymes are associated with microbial activity in the soil and indicative of the size of the microbial population. They suggested that active C was the most sensitive indicator to detect differences in soil management impacts. Tejada et al. (2009) added different rates of composted plant residues as a method of restoring soil and found that all composted material had a positive effect on soil physical properties. In addition, there was a positive impact on the soil chemical and biological properties in the soil, and they attributed this effect due to the more favorable C:N ratio in composted material compared to fresh plant material. Zhang et al. (2010) compared nine soil hydrolases which are related to nutrient availability including (β-galactosidase, α-galactosidase, β-glucosidase, α-glucosidase, urease, protease, phosphomonoesterase, phosphodiesterase, arylsulphatase) and five different enzyme kinetics after 10 years of different cropping systems. In their study they compared different cropping systems to the traditional wheat production system and included wheat–cabbage (*Brassica oleracea* var. capitata L.) sequential cropping, wheat–corn intercrop, wheat–sunflower (*Helianthus annuus* L.) rotation, and wheat–soybean rotation. There were differences among the cropping systems on the enzyme activities with the wheat–corn intercropping system showing the highest activities.

Changes in the soil properties can be detected quickly. Munoz et al. (2007) observed improvements in the physical, chemical, and biological parameters in direct seeding and direct seeding with cover crops after 2 years in a corn production system compared to conventional tillage systems. They observed that soil water content (see Alam et al., Chap. 5) increased by over 30 %; organic C, organic N, and aggregate stability increased after the second year of these conservation systems, and microorganism populations were twice as large in the direct seeding with a cover crop compared to conventional tillage. These improvements in soil properties translated to an improvement in corn production. In Mexico, Roldan et al. (2003) found the intensive cultivation associated with corn production had led to degradation in the soil throughout the Patzcuaro watershed and established an experiment in 1995 with legumes added as cover crops in 1998. By 2000, the effect of no-tillage and the increased crop residue cover and legumes had increased soil enzymes, SOC, biodegradable C fractions, water soluble carbohydrates, microbial biomass C, and wet aggregate stability. They found the rates of change in these parameters were directly related to the mass of residue inputs to the soil. This is different than the rate of change So et al. (2009) observed for a loam soil in New South Wales, Australia, in which they did not see any affect of tillage in the first few years, but after 14 years the no-till treatments had increased soil porosity and structural stability. In this study, the no-till system on soybean had higher infiltration, increased plant available water, water use efficiency, crop yields, and improved SOC content in the no-till of 3.37 % compared to 1.67 % in the conventional tillage (So et al. 2009).

The effects of improved soil physical properties are not isolated to grain crops; Carter and Sanderson (2001) evaluated the effect of tillage systems as part of a rotation experiment with potato (*Solanum tuberosum* L.) in rotation with barley in a 2-year cycle or barley-red clover (*Trifolium pretense* L.)-potato system. They found neither the conventional or conservation tillage systems were sustainable with a 2-year rotation; however, under the 3-year rotation, the conservation tillage system showed a significant improvement in organic C and soil structural stability but no increase in plant productivity. Carter and Sanderson (2001) concluded conservation tillage in a 3-year rotation was able to maintain crop productivity, protect the soil from erosion, and improve soil quality. Components of cropping systems coupled with conservation tillage that would have a positive impact on the soil are the inclusion of deep-rooted legumes, e.g., red clover into the rotation. In another rotation experiment in Uruguay, Ernst and Siri-Prieto (2009) observed that soil degradation induced by intensive tillage was severe and evaluated potential systems to reverse this degradation by implementing rotation systems which included pastures mixed with crops and subjected to either conventional tillage or no-tillage practices. They evaluated the changes in a number of soil properties over the course of a 12-year experiment in pasture systems composed of birdsfoot trefoil (*Lotus corniculatus* L.), white clover (*Trifolium repens* L.), and tall fescue (*Festuca arundinacea* L.) in combination with a number of different crops grown in rotations of winter and summer crops. In their experiment winter crops were wheat, barley, and oat (*Avena sativa* L.), and summer crops of corn, sunflower (*Helianthus annus* L.), sorghum (*Sorghum bicolor* L. Moench.), and soybean, all grown under conventional tillage or no-tillage systems. After 12 years, no-till (NT) had 7 % higher SOC compared to conventional tillage (CT) and 8 % higher total SOC in the 0–18 cm depth. There was no significant difference between the tillage systems for the dry matter input; therefore, the accretion of the SOC has to be related to a reduced loss rate under the no-till systems (Ernst and Siri-Prieto 2009). There was a decline in the total soil N in all of the treatments; however, introduction of rotations reduced the deletion rate. Water stable aggregates increased under the no-tillage systems, and there was less water runoff for these systems. For degraded soils, introduction of long-term rotations with pastures may be a viable method of restoring degraded soils (Ernst and Siri-Prieto 2009). Gomez et al. (2001) found there was less soil degradation using no-till on a corn–wheat–soybean rotation in Argentina on a Chernozemic clay loam soil (Vertic Argiudoll) and if continuous cropping systems were to be used, then crops with high C inputs would be necessary to avoid soil degradation in terms of soil structure. The effects of converting alfalfa to row crops doesn't always show a negative impact on soil properties and Karunatilake and van Es (2002) found there was minimal impact on soil structural properties; however, this soil was a well-structured soil at the onset of the conversion.

A study of different systems in almond (*Prunus dulcis* (Mill.)) orchards in southeastern Spain compared management systems in which intensive tillage of the soil below the trees was replaced by grass cover crops, native vegetation, cover crops, and reduced tillage (Ramos et al. 2011). All of the treatments had a positive impact on aggregate stability, SOC, total N, enzyme activity, available potassium, and phosphatase activity compared to the intensive tillage systems. In these orchard systems, the introduction of grass cover systems produced improvements in the physical, chemical, and biological properties of the soil (Ramos et al. 2011).

Water use efficiency by crops is dependent upon the available water resource in the soil under rainfed conditions and is one of the metrics often used as a measure of productivity and soil degradation (Bai et al. 2008; Wessels et al. 2007). Wessels et al. (2007) found that degraded soils have reduced precipitation use efficiency for rangeland soils. De Vita et al. (2007) compared conventional vs. no-tillage systems in durum wheat (*Triticum durum* Desf.) grown in southern Italy. No-till systems had the advantage over conventional tillage (see Chap. 5) on wheat yields because of the reduction in soil water evaporation coupled with the enhanced soil water availability induced by better water holding capacity (Hulugalle and Entwistle 1997). This degree of response is not surprising because there is a linear relationship between SOM content and water holding capacity as described by Hudson (1994). Unger et al. (1991) stated that conservation practices which maintain crop residue on the soil surface have a positive impact on water conservation, and in semiarid regions this would translate into greater water availability for the crop.

Crop production responses to changes in management vary with the climate and soil. Arshad and Gill (1997) evaluated a canola (*Brassica campestris* L.)-wheat–barley rotation with a green manure crop (field pea, *Pisum sativum* L.) under tillage systems and found that as rainfall increased there was a corresponding increase in grain yield and total dry matter. Reductions in tillage reduced the soil disturbance, increased residue cover, retained soil water, and decreased erosion from these clay soils (Mollic Solonetz). Yield increases with improved residue, or reduced tillage intensity does not always translate to enhanced crop yields even though there is substantial improvement in the soil structure and organic matter content.

4.3 Sustainability of Crop Production

Sustainable practices for the future must consider the impact of soil degradation and the potential cost of restoring soil productivity. Currently agricultural production varies because of the variation in rainfall supply to the crop and the ability of the soil to supply adequate water at critical periods of plant development. Sustainable crop production is dependent upon water storage and availability which are coincidentally the factors most affected by soil degradation. There is ample evidence from field observations that yield variation in fields is affected by water availability more than any other factor (Hatfield and Prueger 2001). Improving water availability in soils throughout the world would provide a strong foundation for enhancing the sustainability of crop production.

The attributes associated with soil degradation whether physical, chemical, or biological can have a positive or negative impact on plant growth. Positive impact allows the full expression of the genetic potential of the crop and the associated environmental conditions while practices that foster soil degradation will be the limiting factor on plant growth and yield. Our inability to overcome the limitations imposed by the soil places a barrier on our ability to adequately supply food, feed, and fiber for future generations. Our challenge is to develop effective strategies to improve the soil and link this information into crop production systems that support sustainable food production.

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Chapter 5
Impact of Technology and Policy on Sustainable Agricultural Water Use and Food Security

Mahbub Alam, Greg Kruger, Sharon B. Megdal, and David Songstad

> *When food is abundant there are many problems. When food is scarce there is only one problem* – Chinese saying

5.1 Irrigation and Water Sustainability

5.1.1 Learning from the Past

History tells us that civilization grew and prospered by irrigation. The past also tells us that these civilizations failed with time due to mismanagement and loss of land to salinity, water logging, and foreign invasion attracted by the prosperity of an irrigated society. The "lesson from history is that most irrigation-based civilizations fail" according to World Watch author Sandra Postel (1999). Naturally the question arises if it will be any different in this millennium. In contrast to present day technology, the earlier civilizations faced many engineering problems, including water storage, flood control, and drainage and system maintenance. The expenses for maintenance and removal of silt and sediment deposits became high as the systems increased in scale. Soil salinity was a problem and the scientific knowledge for tackling salinity was lacking. Tensions, such as those between upstream and downstream water users and large farmer versus small farmer, worked against the sustainability of past irrigation systems. Despite the advances in scientific

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knowledge and improvements in water management practices, many challenges remain, resulting in questions regarding the sustainability of agricultural irrigation over the long term.

Future food production is impacted by the loss of land from agriculture occurring every minute around the world. In the USA, an area of 90 hectares (220 acres) of farmland is taken out of production every hour by urban sprawl (Muir 2011). This does not include the loss of rangelands. Since 1967, the US has lost over 25 million acres of farmland, which is larger than the combined area of New Hampshire, Vermont, Massachusetts, and Connecticut (Muir 2011). Similarly, China has been losing one million acres of arable lands per year for the last three decades to industry, housing, and roads (Muir 2011). With the expansion of cities, water is diverted from agriculture to urban and industrial purposes. As an advanced society we must learn from the past and take steps to overcome future environmental and societal challenges to accomplish the goal of feeding the increasing population.

5.1.2 Global Irrigation Trends and Food Production

Sustainable irrigation from an agricultural producer perspective would be to maintain a profitable farming operation by irrigation, while ensuring water for future use with care not to degrade water and soil quality. This is a significant challenge because water has to be diverted from rivers, which will cause reduction in downstream flow, or when pumped from aquifers, the quantity may exceed the safe yield of withdrawal. There also exists the opportunity to overuse water, thereby causing salinity or water logging. Furthermore, irrigated production agriculture may involve use of fertilizer and chemicals on a soil system that could cause degradation of water quality. A present day farmer is expected to be conscientious and well educated about the best management practices to avoid these adverse impacts.

There is a consistent trend towards increased reliance upon irrigation in agriculture over the past 50 years. Figure 5.1 illustrates a tripling in the worldwide water used for irrigation. More specifically, the irrigated acreages by continent are given in Fig. 5.2. Out of 194 million hectares of irrigated land in Asia, the bulk of the area is in India (57 million hectares), China (55 million hectares), and Pakistan (18 million hectares). The USA has about 22.5 million hectares of irrigated farmland consisting of 9.3 million hectares in gravity, 11 million hectares in sprinklers, and 1.2 million hectares in micro-irrigation systems. The irrigated acreages of Australia, New Zealand, and islands of Oceania amount to 2.8 million hectares (not shown in Fig. 5.2).

In 2005, 20 % of the agricultural land equipped with irrigation produced 40 % of the global food supply (FAOSTAT 2005). In 2011, however, 60 % of global food came from approximately 25 % of the agricultural land that is irrigated. The value of irrigated crops is best reflected in the USA, where the value of agricultural

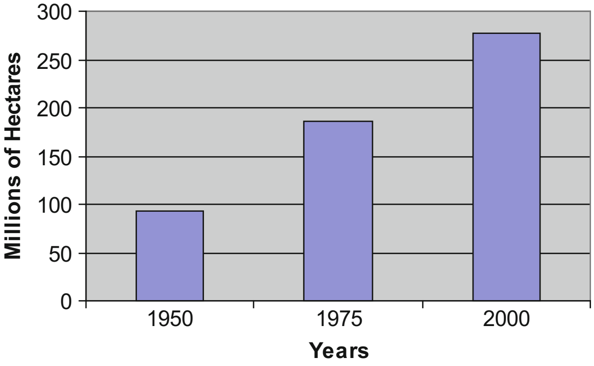


Fig. 5.1 Trend of world irrigation over the past 50 years [adapted from FAOSTAT (2005)]

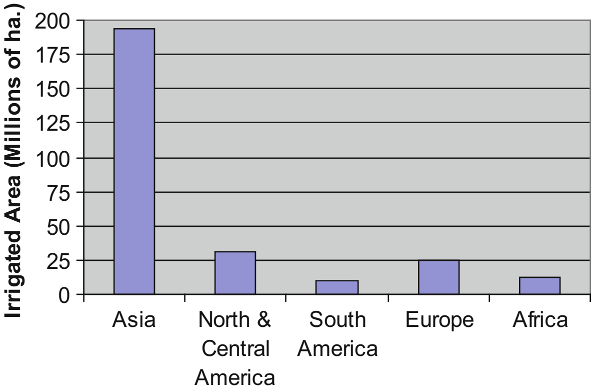


Fig. 5.2 Irrigated agriculture by continent [adapted from FAOSTAT (2005)]

production from irrigated farms accounted for $118.5 billion (USDA 2007; Schaible and Aillery 2012). This is roughly 40 % of the market value of all US crops from 18 % of all harvested croplands. Furthermore, sales from irrigated land harvest average more than three times the sales from nonirrigated land (Schaible and Aillery 2012), and irrigated and properly drained farm lands are four times more productive as an average compared to areas without water management systems. The world population has already reached seven billion (October, 2011) and is projected to reach nine billion or more by the year 2050 and ten billion by 2100 (United Nations 2011). It is quite apparent that both large scale and small scale producers (farmers) will have to provide additional food to meet the needs of this growing population, and irrigated farming will be a crucial part of the global solution.

5.1.3 Societal Interest in Water Sustainability

Production agriculture is an intensive water use enterprise; presently about 70 % of global fresh water diversion is used in irrigation (Aquastat, http://www.fao.org). Irrigation in 2000 amounted to 65 % of total fresh water withdrawals for all categories excluding thermoelectric power in US (USGS 2004). This has gradually changed the societal goals for water resources allocation. This high proportion of river flow diversion or groundwater abstraction by the agricultural sector is being questioned as other demands for water are growing and the water needs of riparian and river systems are receiving greater attention. Diminished river flow and water table declines have a direct impact on wildlife habitat. The expanding needs of the energy and industrial sectors, water oriented recreational facilities, and the increased municipal demand from the growing urban population are often in direct competition with the water demands of the agricultural sector. The diminished rate of replenishment of fresh water and increased rate of demand, which will limit the withdrawal and use of fresh water in the future, are captured by Gleick and Palaniappan (2010), where they put forward the concept of "peak water" similar to the concept of "peak oil" put forward for a nonrenewable resource like petroleum by energy experts (Hubbert 1956). Water resources fall in both renewable and nonrenewable categories. Renewable condition exists, where water quantity is recharged from rapid flows originating from precipitation or snowmelt, yet dependent on rate of recharge. Nonrenewable or somewhat nonrenewable situation exists where the aquifer is confined or restricted to recharge such as the Ogallala Aquifer. Policy makers are going to be more frequently facing decisions related to how to reconcile competing demands for water. The combination of diminishing water reserves or recharge and societal pressure to redirect water use could have a profound effect on global food production.

The advent of the twenty-first century witnessed adequate food production around the world, except for some hot spots in Sub-Saharan and North Africa region and South Asia (FAO Water 2013). How can we meet the food demands of the world's growing population in the face of competing demands for the world's limited freshwater supplies? The widespread application or diminution of irrigation as a farming practice has broad societal implications. Thus, it is necessary to understand the implications for food production of changing irrigation practices. Achieving this understanding will require interdisciplinary analyses, including economic impact studies focusing the effect of modifying irrigation practices and land uses on the price of various foods and the involvement of all facets of society.

5.1.4 Irrigation and Soil and Water Quality

Human civilization and habitation grew and prospered from the use of water for cultivation. However, past civilizations have dwindled from lack of proper operation and maintenance of irrigation and drainage systems and lack of scientific knowledge on soil care and cropping systems. Irrigation water carries dissolved salts (sodium, calcium, magnesium and potassium along with sulfates, chlorides, and carbonates) which are left behind in the soils when water evaporates or is transpired by plants. Dissolved salts present in water are measured by testing the water for electrical conductivity (EC), which increases with the increase of total dissolved solids (TDS). The electrical conductivity value is used as an indicator of salinity hazard for crop production. Electrical conductivity of less than 0.75 deciSiemens/meter (dS m^{-1}) is considered to have no limitations for irrigation use. The range of 0.76 dS m^{-1} to 1.5 dS m^{-1} has some limitations, 1.51–3.0 dS m^{-1} has moderate limitations, and above 3.0 dS m^{-1} has severe limitations (Bauder et al. 2011; Misstear et al. 2006). Classification of water quality adapted from Irrigation Water Quality Standards by Guy Fipps (Fipps 2003) is presented in Table 5.1. According to US Secondary Water Quality Standard for drinking water, the upper limit for total dissolved solids is set at 500 ppm (US-Secodary Water Quality Standards).

Ideally irrigation water seeps into the soil where it is either used by the crop plant or contributes to water table rise (see Hatfield, Chap. 4). If this does not occur, water logging may result. If not properly drained, salts will rise to the root zone impacting crop production adversely. Mesopotamian civilization in Iraq and Harappan civilization in Pakistan dwindled due to salt accumulation in soil. The global estimate that stands at 76–100 million hectares of irrigated land around the world suffer from salinity of which 20 % is severely affected (Kijne 2005; Ghassemi et al. 1995; Suarez 2010). Salinization in the US affects 23 % of irrigated land, and key western irrigated regions are most affected (Postel 1999).

The need for improved agricultural productivity is bringing increased attention to the implications of agricultural water use, including water quality issues associated with inefficient methods used to apply fertilizer and chemicals and drying of river beds resulting from diversion of water. Solutions are being identified for some of these concerns. For example, Sharmasarker (2001) reported that use of drip

Table 5.1 Classification of irrigation water

Classes of water and quality		Electrical conductivity (EC—dS/m)	Total dissolved solids (TDS—ppm)
Class 1	Excellent	0.25	175
Class 2	Good	0.25–0.75	175–525
Class 3	Permissible[a]	0.75–2.00	525–1,400
Class 4	Doubtful[b]	2.00–3.00	1,400–2,100
Class 5	Unsuitable[b]	>3.00	>2,100

1 dS/m = 1 mmhos/cm, or 1,000 μmhos/cm; TDS (mg/L or ppm) ≈ EC (dS/m) × 640 for EC <5 dS/m

[a] Leaching needed

[b] Good drainage needed

irrigation combined with fertilizer and chemicals application resulted in significantly reduced nitrate-water contamination issues.

5.1.5 Irrigation Best Management Practices: Adoption of Water Saving Systems for Improved Water Distribution and Efficient Crop Water Use

5.1.5.1 Irrigation Methods

Irrigation by flooding has been used thousands of years ago as a means to provide water for agricultural purposes, particularly along the Nile River (Bell 1970). This is where the "Nilometer" was developed as a measurement of flooding approximately 5,000 years ago. Flood irrigation has become more efficient over time due to changes in the amount of water required, uniformity of application, and means of reducing water loss by runoff and evaporation. Despite these improvements, in many parts of the world flood irrigation is being replaced by more efficient methods, such as sprinklers, drip, or micro-irrigation. The type of irrigation systems used in a particular location will depend on many factors, including the type of water available (groundwater, surface water, and/or recycled water), the cost of water to the farmer (including energy costs), and the availability of funding for installing new irrigation technologies and maintenance of existing systems.

Irrigation systems are evaluated for irrigation efficiency. Israelsen (1950) set forth the basic concept of irrigation efficiency, I_e, now considered to be one of classic approach. In this approach, I_e was set as the ratio of irrigation water consumed or evaporated by crops (CropET, or evapotranspiration) minus P_e (effective precipitation) to the irrigation water delivered from surface water source or groundwater measured at head gates, V_D.

$$I_\mathrm{e} = \frac{(\mathrm{CropET} - P_\mathrm{e})}{V_\mathrm{D}}.$$

Later, this was expanded to take care of leaching requirement of crops. Irrigation water may contain dissolved salts, which will be left in the soil as the water evaporates from surface and transpired from the root zone. An additional amount of water, V_LR, is needed for irrigation to move the salts below the root zone. Efficiency of irrigation, E_i, may now be calculated using the equation

$$E_\mathrm{i} = \frac{(\mathrm{CropET} - P_\mathrm{e}) + V_\mathrm{LR}}{V_\mathrm{D}}.$$

Keller and Keller (1995) used the E_i approach to determine the irrigation efficiency of a gravity irrigation system, known as Grand Valley Irrigation System in Colorado, USA. The efficiency of the open ditch system was found to be 26 %, which was improved to about 30.4 % by putting in interventions such as concrete lining of the ditches and using gated pipes. Gravity irrigation system in a river basin will have a return flow from upper riparian irrigation systems, where water is used multiple times. The term multiple use cycle system may be applied to systems, where seepage from excess percolation and operational spillage constituting a return flow can be economically reused (Keller et al. 1990). The actual water use for a system or region is the difference between inflow to the system or region and the reusable outflow from the system or region. The inflow volume, V_i, may be adjusted to obtain effective inflow by multiplying with the leaching fraction ($1-\mathrm{LR}_i$ for inflow) according to Keller and Keller (1995). Similarly, the effective outflow may be determined by multiplying the outflow, V_o, with the leaching fraction ($1-\mathrm{LR}_o$ for outflow).

The concept of effective efficiency, E_e, put forward by Keller and Keller (1995), is described by crop water use minus effective rainfall divided by the amount of water used (the amount of effective inflow minus effective outflow).

$$E_\mathrm{e} = \frac{\mathrm{CropET} - P_\mathrm{e}}{(1 - \mathrm{LR_i})V_\mathrm{i} - (1 - \mathrm{LR_o})V_\mathrm{o}}.$$

The effective efficiency will provide an overall higher efficiency for a river basin of multiple use irrigation systems, provided the salinity of the return flow is minimized by adopting best management practices. Thus the calculated effective efficiency was 36.8 % for Grand Valley Irrigation System prior to interventions. The effective efficiency value rose to 61.7 % after intervention because of reduction of salinity in the return flow due to system improvement.

Irrigation efficiency improved with the adoption of pressurized system where irrigation water is applied by using pipes and sprinklers. Battikhi and Abu-Hammad (1994) found that the overall project efficiency for open surface canal with surface irrigation for citrus crop in the Jordan Valley Project was 53 %. The project irrigation efficiency for a pressurized pipe system was 68 % for sprinklers and 70 % for surface drip system. The technological advancement in the science and arts of irrigation has given us the sprinkler irrigation system, which was further advanced by Frank Zybach with the discovery of a self-propelled sprinkling irrigation system (Zybach 1952, US Patent 2,604,359). This system has been further improved resulting in the current central pivot method. This greatly expanded the irrigated acreage because many tracts of land that could not be leveled for flood or furrow irrigation can receive irrigation through the central pivot approach. This agricultural engineering advancement has contributed to increasing food and feed production. The use of gated pipes and surge controllers further improved the application efficiency of a furrow flood system to a respectable 60 %. The center pivot sprinkler system boosted it to 85 % (Rogers et al. 1997). Presently, sprinkler irrigation is replacing many of the flood irrigated areas in U.S. An example of the shift in irrigation system in the state of Kansas in USA is shown in Fig. 5.3, where

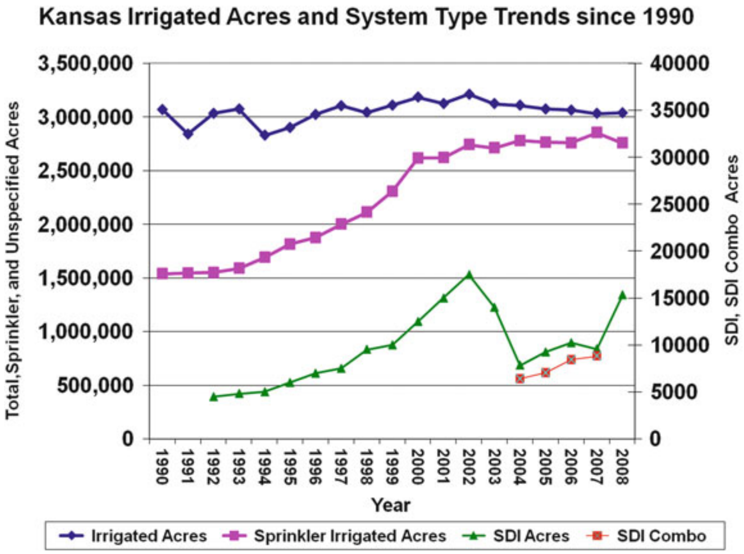


Fig. 5.3 Irrigated acres by system in Kansas by year

an increase in use of sprinkler and Subsurface Drip Irrigation (SDI) is shown (Rogers et al. 2008; Rogers 2011).

Let us consider the state of Kansas as one example. Water use by irrigation and agricultural production systems makes up 85 % of the consumptive use of water in Kansas (KDA-DWR 2008). Consumptive use refers to the use of water where all or most of the water diverted is evaporated, transpired, ingested, or otherwise removed from the local source of supply. The municipal use is at 9 %, the industrial use stands at 3 %, and the remainder is for other uses including recreation. Irrigation of three million agricultural acres in Kansas has been relatively constant since 1990 (Rogers 2011). Flood irrigation in Kansas at this time is mainly confined to an area that was historically developed under ditch irrigation from Arkansas River surface water source. The irrigation delivery from wells gradually changed to sprinkler system, and the area increased from 1.5 million acres under sprinkler in 1990 to 2.8 million by 2008 (Fig. 5.3). Adoption of sprinklers and nozzle system improvements has contributed to reduction of water pumped (Rogers et al. 2008) as illustrated in Fig. 5.4. Factors including irrigation scheduling, improved management, and monitoring system capacity also have contributed to this reduction in water used for irrigation. The volume pumped is related to price of produce rather than cost of pumping at the present price of fuel. Although pumping cost has gone up the commodity price has kept the pumped volume at the same level.

Introduction of plastic tubing around 1940 brought about the practical use of trickle irrigation. The term drip irrigation came to the use as a synonym for trickle irrigation as the water drips out from the emitter. ASAE standards for soil and water terminology define both drip and trickle irrigation to mean the same thing, but

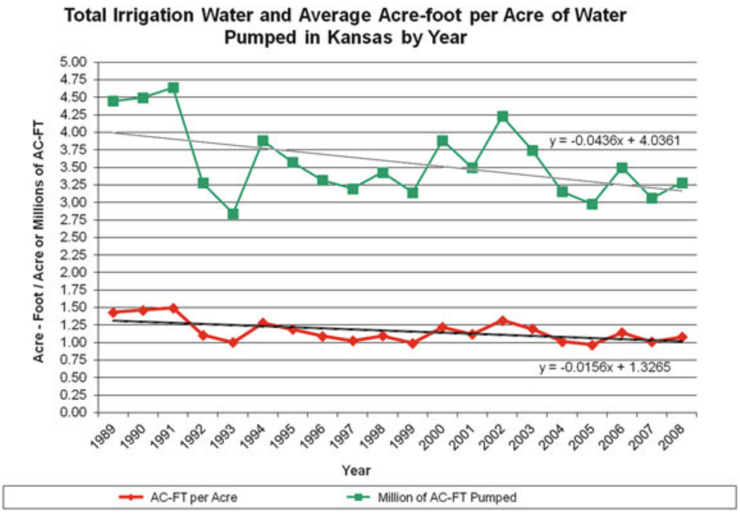


Fig. 5.4 Irrigation water use by year in Kansas

preference is given to the term drip irrigation (ASAE S 526.1, Camp 1998). The emitter is a housing of a labyrinth pathway through which water travels and the water pressure or energy is dissipated. Water comes out at the terminal opening of the emitter as a drip at an atmospheric pressure. The emitters are embedded on the polythene tubing or lateral at a uniform spacing. The development of labyrinth pathway emitters and introduction of polyethylene tubing resulted in significant changes to modern irrigation practices.

Surface drip applies water directly to the plant root avoiding wetting of the entire field surface and thereby reducing evaporation from soil surface. Precise application amount also helps to cut down the deep percolation loss. However, due to the high installation cost, the method was restricted to high value cash crops, such as fruits and vegetables. Surface drip was not suitable for annual field crops like corn in the Great Plains area. The introduction of subsurface drip irrigation (SDI) for application of water below the soil surface has also been implemented. This has helped cut down the surface evaporation and the ability to apply precisely the required amount of water avoiding deep percolation (Lamm et al. 1995). Research shows that about 25 % of water saving is possible from SDI as compared to sprinklers with similar or improved crop yield for corn (Lamm and Trooien 2003; Lamm 2005). About 3.8 million acres of orchards, vegetables, greenhouses, and field crops are presently irrigated by surface drip, trickle, subsurface drip, and low-flow micro-sprinklers in the USA (USDA 2007) at a minimal water loss. According to Sandra Postel’s posting in the National Geographic Water Currents on June 25, 2012, the global area under drip and micro-irrigation (which is drip irrigation with smaller sprinklers or misters) has risen at least to 10.3 million hectares (more than 25 million acres).

5.1.5.2 Environment and Evapotranspiration

Water stored in the root zone from precipitation or irrigation is used by plants for transpiration and ultimately escapes to the atmosphere as vapor in the process of photosynthesis. Hot weather conditions often create an atmospheric demand for water from plants which is far greater than the amount used for photosynthesis. Water escapes through open stomata as transpiration helps plants to cool which enables the continuation of the photosynthesis process. Extreme heat or high atmospheric demand can shut down the process, and plants temporarily close down the stomata.

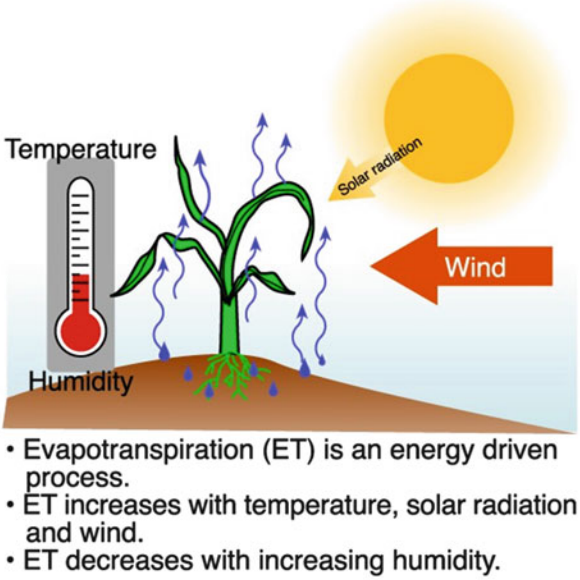
Irrigation researchers have developed empirical relationship of water used by plants in a given day in relation to the weather condition in the form of the evaporative demand of the atmosphere. Water is also evaporated from the soil surface where plants are growing. Evaporation from soil surface and transpiration of leaf through stomata are combined to express the total demand and is called ET or evapotranspiration (Rogers and Alam 2006). Evapotranspiration is energy driven as shown in Fig. 5.5. The ET information is used for irrigation scheduling, which allows the producer to apply water according to crop use or needs and helps eliminate unnecessary irrigation water application.

The relationship of water use by plant in response to the climatic condition helped researchers to develop empirical methods to estimate evapotranspiration from different climatic variables. A large number of such empirical methods were developed to meet the need for irrigation project design and irrigation scheduling plans using available climatic data of the location. In 1970s, the Food and Agriculture Organization (FAO) (Doorenbos and Pruitt 1977) presented four methods to accommodate users with different amount of climatic data availability. These are: (1) the Blaney-Criddle method developed for areas where air temperature was the only available data, (2) the radiation method was suggested for areas where climatic data included measured air temperature and sunshine, (3) the Pan evaporation method also provided acceptable estimate of evapotranspiration adjusted by factors developed for the location, and (4) the modified Penman method was more sophisticated and provided best results, where the model equation used measured air temperature, sunshine, wind speed, and air humidity for a well-watered short cool season grass as a reference crop.

5.1.5.3 Empirical Determination of ET

Empirical methods have been developed to estimate ET. The estimated evapotranspiration value calculated using empirical methods were designated as ET_o. The modified Penman method used cool season grass clipped short and well watered as a reference crop. Crop coefficients were developed to adjust the estimates of ET_o obtained using the empirical model for individual crops according to their growth stages. However, the diffusion of vapor depends on crop height and density. Hence,

Fig. 5.5 Relationship between environmental factors on evapotranspiration (ET)



the aerodynamics of the crop surface due to height of the crop, the density of the crop surface affecting albedo or reflectance of radiation, and the effect of upstream fetch of the wind were studied for further improvements of the empirical models suggested. As a result in 1990s, the Penman–Monteith combination method was developed and was recommended for adoption by a panel of experts under the leadership of FAO (Allen et al. 1998).

The original Penman–Monteith equation and the equations of aerodynamics and the surface resistance were used to come up with the FAO Penman–Monteith equation for reference evapotranspiration ($\mathrm{ET_o}$ shown below) in mm of water per day.

$$\mathrm{ET_o} = \frac{0.408\mathit{\Delta}(R_\mathrm{n} - G) + \gamma\frac{900}{T+0.34}u_2(e_\mathrm{s} - e_\mathrm{a})}{\mathit{\Delta} + \gamma(1 + 0.34u_2)},$$

where

$\mathrm{ET_o}$, reference evapotranspiration (mm day^{-1});
R_n, net radiation at the crop surface (MJ m^{-2} day^{-1});
G, soil heat flux density (MJ m^{-2} day^{-1});
T, mean daily air temperature at 2 m height (°C);
u_2, wind speed at 2 m height (m s^{-1});
e_s, saturation vapour pressure (kPa)
e_a, actual vapour pressure (kPa);
$e_\mathrm{s} - e_\mathrm{a}$, saturation vapour pressure deficit (kPa);
$\mathit{\Delta}$, slope vapour pressure curve (kPa°C^{-1});

γ, psychrometric constant (kPa°C^{-1})

900 in the numerator is a constant for a short reference crop type (height of 0.12 m) for a daily time step.

In 2000, the Environmental and Water Resources Institute of the American Society of Civil Engineers Task Committee on Standardization of Reference Evapotranspiration came up with a standardized equation at the request of Irrigation Association (Allen et al. 2000; EWRI 2001). It has been recommended for use in US and is being followed by many. This helps to calculate ET$_o$ based on a short or tall crop, and most of the crop coefficients developed for modified Penman equation to modify the ET$_o$ to crop evapotranspiration (ET$_c$) are applicable. The standardized (ET$_{sz}$) equation is as follows:

$$\mathrm{ET}_{\mathrm{sz}} = \frac{0.408\,\Delta(R_{\mathrm{n}} - G) + \Upsilon \frac{C_{\mathrm{n}}}{T+273} u_2 (e_{\mathrm{s}} - e_{\mathrm{a}})}{\Delta + \Upsilon(1 + C_{\mathrm{d}} u_2)},$$

where

$\mathrm{ET}_{\mathrm{sz}}$ = standardized reference crop evapotranspiration for short or tall surfaces in mm per day for daily time step or mm per hour for hourly time step;

R_{n} = calculated net radiation at the crop surface (MJ per meter square per day for daily time step or MJ per meter square per hour for hourly time step);

G = soil heat flux density at the soil surface (MJ m^{-2} d^{-1} for daily time step or MJ m^{-2} h^{-1}for hourly time step);

T = mean daily or hourly air temperature at 1.5 to 2.5 m height (°C);

u_2 = mean daily or hourly wind speed at 2 m height (m s^{-1});

e_{s} = saturation vapor pressure at 1.5 m to 2.5 m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum temperature;

e_{a} = mean actual vapor pressure at 1.5 m to 2.5 m height (kPa);

Δ = slope of the saturation vapor pressure–temperature curve (kPa °C^{-1});

Υ = psychrometric constant (kPa °C^{-1}) ;

C_{n} = numerator constant that changes with reference type (short: 900 and tall: 1,600 for daily) or (short: 37 and tall: 66 for hourly) and calculation time step;

C_{d} = denominator constant changes with reference type and calculation time step (short: 0.34 and tall: 0.38 for daily or short: 0.24 and tall: 0.25 for hourly).

5.1.5.4 KanSched

Remote weather stations provide weather data to a central computer system where ET is calculated using a chosen equation by the service provider where the ET values are posted on the Internet. Producers can download the ET information and use this for estimating the water use by the crop. Presently, scheduling has been made easy by developing computer software that can rapidly update soil water status of multitude of fields. One such computer program named KanSched was developed by Kansas State University researchers and being used by Kansas farmers and farm consultants (Rogers and Alam 2007).

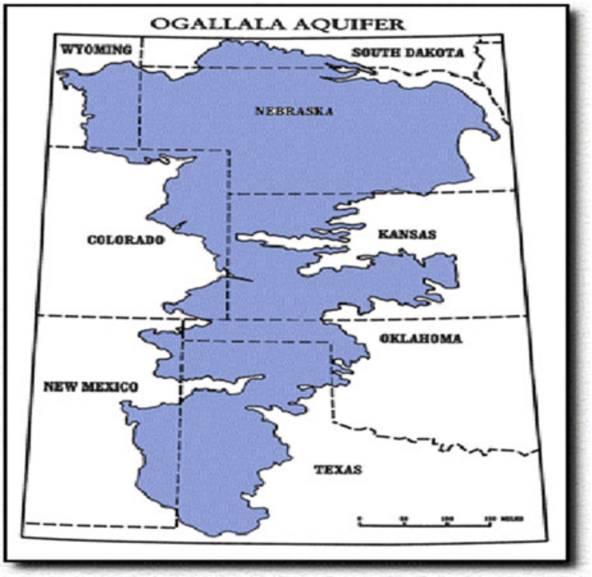
KanSched helps to overcome major obstacles to adoption of on-farm irrigation scheduling, such as time required for gathering and processing soil water status, calculating water use budget, and implementing scheduling on a daily basis during irrigation cycle. The program is designed to help monitor the water balance in the root zone soil profile by tracking input of rain and irrigation and output of crop water use due to evapotranspiration. The upper limit of root zone soil water reserve is determined by the soil water holding capacity or field capacity of the soil within the managed root zone. Any input above this storage capacity of the soil will be drained to lower depth and become unavailable to crop use. The desired lower limit of water reserve for optimal growth can be variable amount depending on the crop, the stage of growth, and management goal. This lower limit also referred to as "management allowable deficit" or MAD is often taken as 50 % of the total available water. The normal goal is to keep track of the amount of water in reserve and help the manager to maintain water balance level above minimum to prevent water stress to the growing crop. Irrigation scheduling tools that can be customized to field characteristics can greatly facilitate the irrigation scheduling process. KanSched will facilitate this process to help eliminate unnecessary irrigation and also avoid crop water stress, where irrigation water is available. One may follow the guidelines for An ET-Based Irrigation Scheduling Tool at: http://www.ksre.ksu.edu/bookstore/pubs/EP129.pdf (Latest Web-Based version is also available).

Kansas experience shows that the shift in irrigation system type from flood irrigation to center pivot irrigation has resulted in improved use of irrigation water. This is indicated by the generally downward trend in irrigation application (Rogers et al. 2008). The reduction in reservoir capacity and lowering of the aquifer level have prompted to adoption of irrigation scheduling technique; conservation tillage and residue management have also contributed to water saving (Klocke et al. 2009). Technological advancement and continued research findings are helping move towards more efficient use of fertilizer and chemicals as well. Producers are striving to reduce production cost whenever and wherever possible to remain profitable, and diesel fuel savings associated with no-till, on top of the water savings, provides clear overhead savings (Songstad 2010a, b). Such examples of overhead reduction by reduced water use will ultimately drive sustainable agriculture by maintaining profitability.

5.1.6 Ogallala Aquifer

In the USA, Kansas has experienced similar events to what are recorded in the history of the development of irrigated agriculture. Although ditch irrigation from the Arkansas River began around 1890, rapid expansion did not occur in Kansas until 1945. After World War II, the technological advancement in engineering

Fig. 5.6 Geographic location of the Ogallala aquifer



made it possible to pump water out of the Ogallala aquifer. The Ogallala aquifer is a confined, almost non-rechargeable aquifer where pumping water is analogous to mining water for irrigation. The Ogallala aquifer extends from the southern boundary of South Dakota to Texas and provides a subterranean source of water for farmers throughout the Great Plains (Fig. 5.6). Irrigated acreage increased to three million acres, and the flood irrigated system gradually changed to center pivot sprinklers. After 50 years of drawing water from the Ogallala, the harsh reality of declining aquifer reserves raised the question of water sustainability.

McGuire (2009) and Sophocleous (2010) described the groundwater level changes for select counties within the Ogallala Aquifer (Fig. 5.7). These findings, which are the culmination of research over several decades, demonstrate the consistent decline in groundwater table within the Ogallala across locations in Kansas and Texas. There are local and regional efforts to manage the Ogallala that are inadequate to meet the future water resource needs from a sustainability standpoint. Therefore, Sophocleous (2010) recommends that the sustainability of the Ogallala can be best addressed by an interstate groundwater commission. This will build upon the efforts and legislation addressing the water supply issues that are described below.

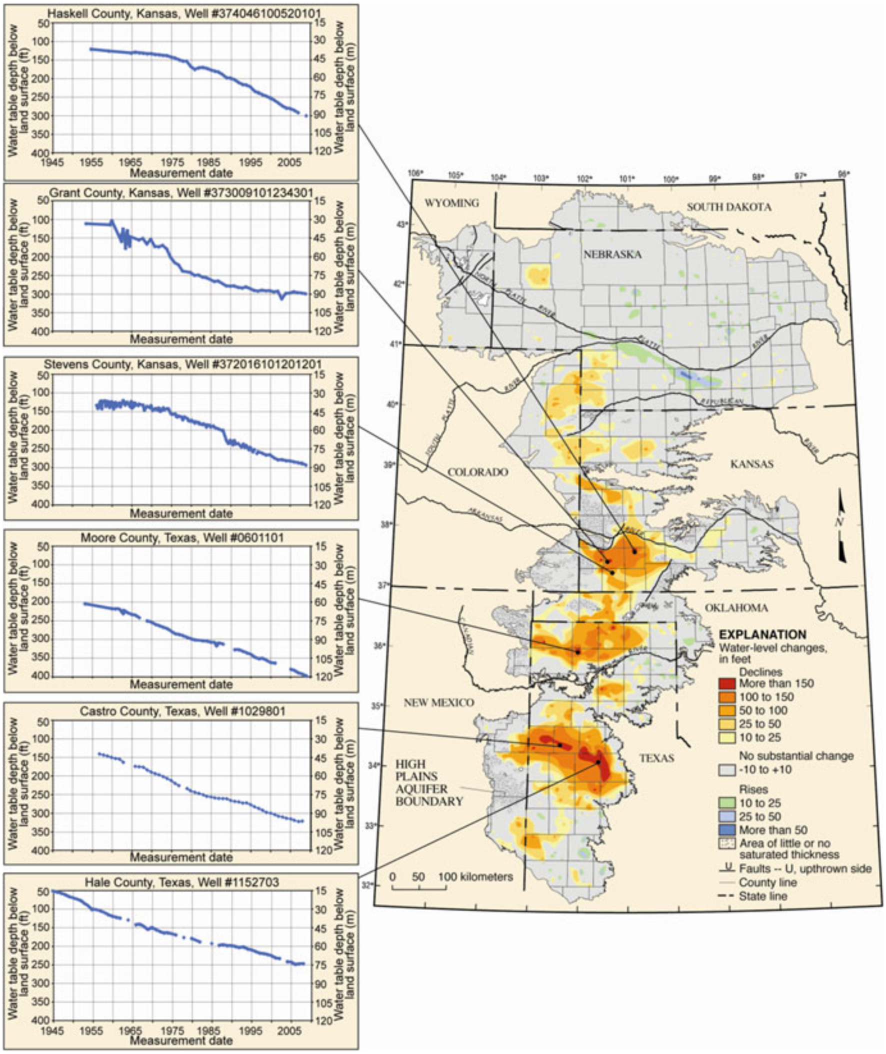


Fig. 5.7 Reduction in water table over time for selected locations supplied by the Ogallala Aquifer. Source: McGuire (2009)

5.2 Plant Breeding, Biotechnology, and Agronomic Practices

5.2.1 History of Production Agriculture and Need for Water

5.2.1.1 Yield Measurement

In the Great Plains of the USA, like many places around the world, water is a valuable and often limiting factor in crop production yields. However, water can be the cause of yield loss in nearly every production system, particularly those that do not have the option of supplemental water through irrigation. In addition to soil, water is the most critical input for global crop production.

Crop production systems in water-limited environments are generally classified as either dryland/rainfed or irrigated. Dryland/rainfed production systems rely solely on the utilization of natural precipitation to supply water to the system to support the crop. Irrigated agriculture utilizes fresh water resources such as lakes, streams, rivers, ponds, or aquifers to supply supplemental water to support crop production. These sources of freshwater as well as ground water are referred to as blue water. Blue water, while used for agriculture, also serves many other purposes to support life on earth. The Water Footprint Network (2013) further defines green water as ground water recharge that is available for plant transpiration and ET (evapotranspiration). ET is the soil available water that either evaporates from the soil surface or is taken up by plants and then transpires.

Starting at the dawn of agriculture, crop yields were looked at on a per plant basis. Early agrarians would keep plants which had high yields to be used for planting in future generations creating selection for crops with high yield potential or a desirable phenotype such as in the development of maize from teosinte (Goodman and Galinat 1988). With the introduction of hybrid corn and advanced crop breeding programs as well as the modernization of agricultural techniques and equipment, mass production of agricultural commodities arose giving way to agriculturalists providing crop production units on a per area basis (i.e., bushels/acre, kilograms/hectare, etc.). As we advance into the next era of agriculture, production of agricultural commodity production will move to efficiencies where yields are measured on a per unit input for water, nutrients, and solar radiation (i.e., inches of water/bushel of grain, cm of water/kilogram of grain, etc.).

5.2.1.2 Systems Approach to Agriculture

As the world population continues to grow towards nine billion people by 2050, it is critical to both maximize production and mitigate yield losses. This is true for both abiotic and biotic stresses, including yield loss due to water deficit. In order to maximize yields and minimize yield losses, producers must consider a variety of options to achieve this goal because it will require a systems-based approach that combines agronomics, breeding, agricultural engineering, and biotechnology.

For water use and management, water production efficiencies can be measured in terms of water applied in irrigation systems, its consumption in terms of plants that perform better under drought conditions, and water use efficiency in terms of the entire crop production system. The need for both understanding and embracing these production standards will be critical to the long-term success and sustainability of crop production, particularly in environments that perennially experience water limitations and/or rely heavily on irrigation to supplement natural rainfall. A systems-based approach to management will be critical to implement these efficiencies and maximize the use of water, a limited resource in many agricultural production systems.

Understanding how the components in a crop production system impact the water requirement of the plant leading to yield stability is critical. Decisions such as what crop to plant, what variety or cultivar that is used, seeding rate, seed bed preparation, nutrient management practices (timing, rate, placement, etc.), timing and amount of supplemental irrigation (if it is available), and even planting date impact the water consumption of crop plants and the water balance. In fact, even pest management timing and pest control have an impact on how efficient the cropping system is at converting water into a crop (Lafond et al. 1992).

In many ways, crop production is the movement of water in the form of energy through the process of photosynthesis. The High Plains region of the USA (western North Dakota, western South Dakota, western Nebraska, western Kansas, western Oklahoma, and northern Texas) has dramatically changed its landscape in the past 40-plus years. There we see movement from grasslands or wheat/fallow rotation to more intensive crop rotations, with crops such as corn and soybean that consume more water (Wright and Wimberly 2013).

5.2.2 Cropping Systems Influence

The production of any crop can be described as the genetic × environment (G × E) interaction. Water is one component of the environmental part of the equation. However, water availability in the environment can be manipulated in different ways and nearly every management decision prior to planting as well as during the course of the crop life cycle have an impact on water availability and crop yields.

5.2.2.1 Residue Management and Tillage

Tillage practice can have a tremendous effect on cropping systems. During the 1930s, particularly 1934 and 1936, drought was severe in the Great Plains region of the USA (Worster 1979). This period, commonly referred to as the Dust Bowl, was known for the wind-borne soil erosion and numerous crop failures. During this period in history, it was thought that “rain followed the plough” and conventional tillage systems including moldboard plowing which buried all crop residue and exposed the soil (Baltensperger 1992). The exposed soil led to high soil erosion and high soil moisture evaporation rates.

The practices of deep tillage led to many benefits including a uniform seed bed, less horsepower needed to seed the crop, and early season weed control, but in the Great Plains region these benefits were vastly outweighed by the water loss. During the 1960s and 1970s, no-tillage production was introduced to cropping systems in the Great Plains. No-tillage production systems allowed for residue from the crop to be left behind, significantly reducing water evaporation from the soil surface. The amount of residue left behind influences the reduction in evaporation of soil moisture. In fact, corn stover and wheat stubble have been shown to have half of the water loss that bare soil has in an irrigated corn crop (Wortmann et al. 2012).

In the mid-1990s the introduction of glyphosate-resistant crops allow for highly effective in-season weed management, addressing one of the major setbacks from the adoption of no tillage systems (Givens et al. 2009). This was addressed in a case study by Fernandez-Cornejo et al. (2012) where herbicide tolerant soybeans is attributed with an increase in no-till acreage (see Lee et al., Chap. 10) from 30 % in 1996 to 63 % in 2006. Having weed-free fields has allowed producers to capture more of the available water within their cropping systems for conversion into yield.

5.2.2.2 Agronomic Inputs and Decisions

In addition to tillage, the producers encounter numerous decisions which will impact water consumption and water availability to the crop. The decision-making process starts with seed selection. In recent years, many companies have developed “water optimized,” “drought tolerant,” “drought resistant,” and “water-use-efficient hybrids,” which will be generically referred to as water-use-efficient hybrids throughout the remainder of this chapter. The development of water-use-efficient corn hybrids and other crops gives producers one more consideration to maximize yields and/or profits in their cropping systems in water-limited environments.

5.2.3 Hybrid or Cultivar Selection

The water-use-efficient corn hybrids have been developed in two different ways, generally defined, by: (1) Traditional trait selection and breeding programs and (2) through use of biotechnology to deliver heterologous water-use efficiency gene (s). The exact details of how either process has been integrated vary greatly based on the objectives of the program. Additionally, there has been outspoken concern by many members in the agricultural community that transgenic and native trait breeding programs will lead to lower yielding or inferior lines under optimal water conditions, but recent findings would suggest that this may not necessarily be the case (Ashraf 2010; Mir et al. 2012; Tester and Langridge 2010). If corn hybrids or other crop varieties can be developed to perform equally well to “race horse” hybrids (high yielding hybrids in optimum performing environments) in well-watered conditions and improved performance to the same “race horse” hybrids in water-limited conditions, producers will see greater yields across multiple growing seasons and yield trends across a wide variety of environmental conditions will have greater sustainability.

5.2.4 Crop Rotation

Another decision that a producer must consider is crop rotation. Crop rotation is linked to the previously discussed input decisions as well as to the input decisions and production practices that follow. Crop rotation decisions are important because each crop has different water consumption requirements to produce yield. Furthermore, yield stability varies by crop rotation, nutrient management strategies, and rainfall environments (Ma et al. 2012). Additionally, choice in crop rotation directly affects the amount of residue after harvest.

Crop rotation is important because of the differences in ET that exists within crop plants (Klein 2008). Figure 5.8 illustrates that greater than 10 cm ET is needed for a wheat crop to produce the first kg of grain. Similarly, sunflower and grain sorghum need greater than 17 cm ET. Lastly, corn and soybean have been reported to need greater than 25 cm of ET to start to produce grain. Regardless of crop, increasing yield requires increased ET, which highlights the critical relationship between water and yield. In the western Great Plains, crop rotation often follows a corn–wheat–fallow rotation, which is implemented to help manage the soil moisture reserves from year to year where, the wheat and fallow years do not have the higher water demand required for corn. Without the fallow period, which is used to increase stored soil moisture, the cropping system would be prone to having frequent crop failures.

Equally important is how the plant converts the available water into yield. The slope of each line in Fig. 5.8 is key because at an ET of 30 cm or greater, corn produces more yield than the other crops. When the ET is less than 30, it is clear from the slope why wheat is grown in the most arid regions of the world. In the Great Plains of the USA, particularly in the past, grain sorghum was often used in rotation with wheat because the water requirements for producing yield are lower than for corn. However, because crop rotation strategies are continuously changing, many hectares of grain sorghum are being replaced with corn. As previously discussed, with improved technology and crop varieties/hybrids, the curves from the ET functions may change. This could lead to additional changes in crop rotation as well as other agronomic practices.

In semi-arid agricultural crop production, it is common to see crops with low soil moisture requirements to produce grain (such as wheat) rotated in with crops that have higher yield potential (such as corn). For example, in the High Plains region of

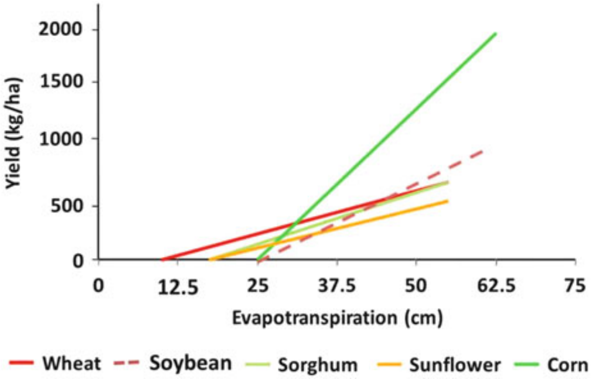


Fig. 5.8 Water consumption of wheat (*Triticum aestivum*), grain sorghum (*Sorghum bicolor*), soybean (*Glycine max*), sunflower (*Helianthus annus*), and corn (*Zea mays*) needed to produce increasing amounts of grain (Klein 2008)

the USA it is common to have a wheat–corn–fallow rotation where the grower is capitalizing from the winter wheat which has a low water requirement to produce grain and from a fallow period (allowing the soil moisture levels to increase). This practice is used in order to store up enough soil moisture to grow corn which is going to require more water to produce grain, but also has the capability to produce significantly more grain than the wheat crop. In some cases, growers who work in arid environments will often tend to be even more conservative in their water use, growing only crops with low water requirements to produce grain or by rotating more fallow periods into their crop rotation.

5.2.5 Planting Arrangement and Plant Population

Planting population density and row spacing within a cropping system have important roles in production and water utilization as well. Dryland crop production in the Great Plains region of the US greatly varies on rainfall, water availability, and soil type, including plant available soil moisture. Work conducted by Lyon et al. (2009) showed that under certain situations, nontraditional planting arrangements could lead to greater yield. In their work, they compared traditional 75 cm row spacing to a 150 cm row spacing, a 75/150/75 cm row spacing, and a 75/225/75 cm row spacing ("skip-row" configurations) across several plant seeding rates. Under most conditions, the traditional 75 cm row spacing was the highest yield. This is not surprising considering that corn breeding programs have been designed to optimize yield in a traditional 75 cm row spacing. However, under extremely dry conditions when other effective agronomic practices for mitigating yield loss from water stress were implemented, the nontraditional row spacing treatments would occasionally out-yield traditional systems. The nontraditional row spacing systems only out-yielded conventional systems where weed populations were strictly managed and there was high residue levels to mitigate surface evaporation.

Cotton showed an even greater advantage to skip-row planting arrangements. Fryrear (1981) demonstrated that cotton yields could be increased as much as 66–79 % by planting in the nontraditional row spacings, but also mentioned the difficulty of maintaining weed management. In their work they included sorghum in the blank rows of some treatments to reduce erosion and minimize weeds, but showed that this negatively impacted yields by 22–38 %.

Like row spacing, plant population density (seeding rates) need to be determined based on a number of other factors (Duvick 2005). Plant population density has a dramatic effect on yield (Duvick et al. 2004). Looking across time, producers have continued to increase plant populations for many crops and many environments. For example, today most corn production in environments where water is not a limiting factor plant in general will plant approximately 80,000 seeds/hectares or more. In environments where water limits product, plant populations need to be reduced. The necessary reduction in population is contingent upon crop, location, and cropping system practices (i.e., tillage, crop rotation).

5.2.6 Weed Control

Having a highly effective and timely weed control program is a necessity for maximizing crop production systems. Weeds compete for resources reducing yield. In water-limited environments, weeds can reduce yields by reducing the availability of water for the crop. Highly effective weed control and timely weed management are necessary to minimize the water consumed by weeds and maximize yields (Ghanbari et al. 2010).

The introduction of glyphosate-resistant crops gave many growers a cost-efficient tool to effectively control a broad spectrum of weeds. The improved crop varieties (such as corn hybrids that perform better in water-limited environments), improved equipment for managing heavy residue environments (i.e., adoption of no-till practices), and better understanding of how to optimize production coupled with the highly effective means for controlling weeds in systems in the absence of tillage have combined to give producers in the Great Plains of the USA and other regions around the world in water-limited environments much greater and more stable yields. Going forward it is going to be critical to continue to develop conservation practices that instill practices and genetics which give us the greatest yields and yield stability across years in these regions of the world if we are to address the needs of a growing population. In addition it will be important for growers to manage their weeds using diversified systems which include the use of other herbicides and/or non-chemical weed control practices in addition to glyphosate. This will be important to retard evolution of resistance to any one herbicide or practice and thus maintain the effectiveness of currently available weed control options.

5.2.7 Breeding and Biotech Traits for Drought Tolerance

5.2.7.1 Breeding for Drought Tolerance

Pioneer Hi-Bred (Johnston, Iowa), founded by Henry Wallace in 1926, has a long history of developing maize hybrids with yield performance, agronomics, and disease resistance for the drought prone environments of the US Corn Belt (Barker et al. 2005; Campos et al. 2006). Long-term genetic improvement for traits contributing to improved yield under drought was initially achieved by breeding and selection for improved yield utilizing wide area testing that sampled many on-farm environmental conditions (Duvick et al. 2004). Water limitations of different intensity are a common feature of on-farm environments throughout the Corn Belt (Löffler et al. 2005). Therefore, through the wide area testing efforts maize hybrids were frequently exposed to a range of drought conditions and the hybrids demonstrating greater yield under the drought conditions sampled and with superior yield under favorable environmental conditions were selected and advanced to commercial status. Targeted efforts focusing on drought tolerance began in the Western region in the 1950s with the opening of the York station by Stan Jensen. With breeding efforts focused on performance under drought conditions, novel elite inbreds and hybrids with improved yield stability for drought were developed and advanced contributing to the long-term genetic gain for yield under drought.

Over the last decade new phenotyping and molecular technologies have provided additional opportunities for breeding maize hybrids with improved performance under drought conditions. The use of key locations (managed environments) in the northern and southern hemisphere, where relevant drought conditions can be uniformly and reliably managed, has enabled two cycles of drought evaluation each year in combination with direct testing of performance in the on-farm conditions of the Corn Belt. With the genotyping of the entries in these breeding experiments connecting the managed environments and the on-farm Corn Belt environments, data are routinely generated on key trait phenotypes. Analysis of these data has enabled detailed mapping of the genetic architecture of drought performance in the elite populations of the breeding program (van Eeuwijk et al. 2010). The results from these experiments have enabled the Pioneer maize breeder to use genetic prediction methodology to complement empirical field evaluation and increase the scale of the breeding programs and accelerate the genetic improvement of yield and agronomics for drought prone environments. In 2011 Pioneer launched the Optimum® AQUAmax™ line of hybrids that were developed for superior performance under drought conditions. The combination of the improved drought tolerant AQUAmax hybrids together with appropriate agronomic management for drought conditions has provided further improvements in the yield performance of maize hybrids for drought prone conditions in the US Corn Belt.

These improvements in hybrid maize drought performance continue the long-term efforts to improve yield of maize for the environmental conditions of the US Corn Belt. Ongoing research efforts continue to evaluate the importance of drought and the impact of further improvements in drought tolerance and the opportunities for utilizing both native and transgenic methodologies. The breeding methodologies developed initially for the US Corn Belt are now being used for drought prone regions globally, and the local breeding programs are supported by a global network of breeding programs that enable germplasm exchange and sharing of the genetic understanding of drought tolerance as it is created from different geographies.

5.2.7.2 Biotechnology

The advent of plant genetic engineering brought in a new means for introducing genetic diversity. The first generation of biotech traits involved resistance to insects and herbicide tolerance. Examples include products from Monsanto such as Roundup Ready Corn (NK603) and Yieldgard (MON810) and the Triple Stack of these two traits along with Yieldgard Rootworm (MON88017). One of the noted benefits of Yieldgard Rootworm is that plants with this trait tend to perform better under water-deficient conditions (Sachs 2012) by protecting roots from insect pressure.

Transgenic maize expressing a transcription factor NF-YB2 demonstrated drought tolerance under water limiting conditions (Nelson et al. 2006). Under these conditions, plants expressing NF-YB2 demonstrated stress adaptation relative to chlorophyll content, stomatal conductance, leaf temperature, reduced wilting, and maintenance of photosynthesis. More recently, Castiglioni et al. (2008) reported the use of a bacterial cold shock protein (cspB) to confer drought tolerance in maize. CspB was isolated from *Bacillus subtilis* and expressed ectopically in maize using the rice actin promoter where it appears to function as a RNA chaperone stabilizing transcripts during drought stress. These transgenic plants showed a 7.5 % significant (0.01 %) yield increase compared to controls under drought stress conditions. The lead cspB event, MON87460, also referred to as "DroughtGard" was planted by 250 farmers in (Monsanto 2012) and also offered for planting in 2013 under a stewardship agreement committing to use the grain as on-farm feed or to sell the grain for domestic use due to pending import approvals in key export markets (Monsanto June 17, 2013 press release). It is expected that plantings in 2014 will increase as pending import requests are approved. MON87460 is also the trait that Monsanto provided to the Public-Private Partnership WEMA (Water Efficient Maize for Africa) which is described by Oikeh et al. in Chap. 13.

5.3 Water Law and Policy

5.3.1 Water Law

Science and technology, along with financial capacity, have crucial roles to play in shaping water security and sustainable water use practices. As discussed, the pressures of population growth on limited freshwater supplies and concerns for the health of the natural environment are resulting in increased competition for water resources (USBR 2012). The rules and regulations governing water use will determine the allocation of water resources across sectors, the nature of conservation programs, and water quality standards. The legislative and regulatory framework for water management will indeed be a critical determinant of future water use and land use going forward. The importance of the governance framework for water use has been recognized worldwide. Efforts such as the 2012 World Water Forum (http://www.worldwaterforum6.org/en), the Groundwater Governance Project (http://www.groundwatergovernance.org), and the Organization for Economic Co-operation and Development's new Initiative on Water Governance, which is an outgrowth of the 2012 World Water Forum (http://www.oecd.org/env/watergovernanceprogramme.htm), are evidence of this recognition. The geographic breadth and high-level nature of these activities demonstrate the importance of interdisciplinary approaches, involving collaboration across the academic and nonacademic communities, to address critical water management issues faced across the globe.

In the USA, the water governance framework reflects water legislation that varies greatly by state and region. Although standards for drinking water quality and for discharges into navigable waters of the U.S. are set by the federal government and there is federal involvement in interstate waters, water quantity regulations are largely the purview of the different states (Megdal 2012a). In effect, U.S. water regulation can be seen as a mosaic of 50 pieces. There are different laws and regulations governing groundwater versus surface water, and the extent to which water is reused and by whom will often depend on a third set of water laws/rules. Approaches to meeting the water needs of people, including their need for food, will reflect policy choices by a multitude of players. To illustrate this diversity in approach, the practices of two states, Kansas and Arizona, are presented. Kansas draws from the Ogallala aquifer and is part of the multi-state High Plains region. Arizona relies heavily on groundwater and surface waters, particularly Colorado River water. Both states are home to major agricultural operations (Megdal et al. 2009).

5.3.1.1 Kansas Water Law

Kansas basic water law was established by enacting the Kansas Water Appropriation Act of 1945, which stated that all water belongs to the people of the state.

Water can be put to beneficial use by individuals who follow appropriation guidelines. This has enabled the state to introduce steps in regulating water use in Kansas.

Water resources development in Kansas was unrestricted prior to 1970, and it was not illegal to divert water without a permit until 1978. The Arthur Stone lawsuit established the legal precedent for requiring a water permit (Rogers et al. 2013). The rapid groundwater level decline in Western Kansas motivated the enactment of Groundwater Management District (GMD) Act in 1972 (KS Statutes:Ch 82a, 1972), which provided local leadership to form a District for a contiguous irrigated area with the purpose of proper management of irrigation. Five districts are now functioning, GMD-1, 3, and 4 are located over the Ogallala Aquifer, and GMD-2 and 5 are located over the High Plains riverine aquifer. The districts are authorized to prepare local water use plan and take steps to implement plans for water conservation. The districts took actions for water metering and reporting, which was made compulsory.

In 1978, the Kansas Legislature amended statutes to enable the state Chief Engineer to designate certain areas as Intensive Groundwater Use Control Areas (IGUCA). This enabled the State Chief Engineer to (1) close an area to further water appropriations, (2) determine the sustainable limit of groundwater withdrawals and apportion that amount among water right holders according to relative dates of priority, and (3) administer the permissible withdrawals of groundwater and protect public interest (KDA – IGUCA 2009).

In 1980, the "safe yield" restriction was first imposed in non-GMD area. Safe yield may be defined as maintenance of long-term balance between the amounts of ground water withdrawn or pumped annually to the amount recharged to the aquifer (Sophocleous 1997). In the unconfined High Plains aquifer, the pumping was restricted to maintain the amount at par with the recharge from precipitation without drying up the natural wetland habitats of Cheyenne Bottoms, which receives stream flow from Wet Walnut creek.

Excessive withdrawal of groundwater threatened to leave Cheyenne Bottoms with no water, which is the largest marsh area in the heartland of the USA. This area has been officially designated as a Wetland of International Importance under the Ramsar Convention. The area serves as the most important habitat for shore bird migration in the western hemisphere (Cheyenne Bottoms 2008). In 1992, an Intensive Groundwater Use Control Area—(IGUCA) was applied in Walnut Creek Valley in Kansas, where Cheyenne Bottoms is located, to address stream flow depletions due to excessive groundwater withdrawals. Kansas water law takes into account that the groundwater and surface water are interconnected. The area receives about 25–30" inches of annual rainfall. The amount of pumping was adjusted to a reasonable amount in accordance with safe yield. This resulted in a pumping reduction of 22–33 % for senior water right holders according to location and about 44 % for the junior water right holders, which was equivalent to 12–14" inches of pumping available for crop production. The original prior appropriation legislative act resulting in the maxim "use it or lose it" was modified to give legal sanction to a 5-year allocation period. The producers could bank their water and use the total allocation over 5 years as needed without fear of forfeiting their water

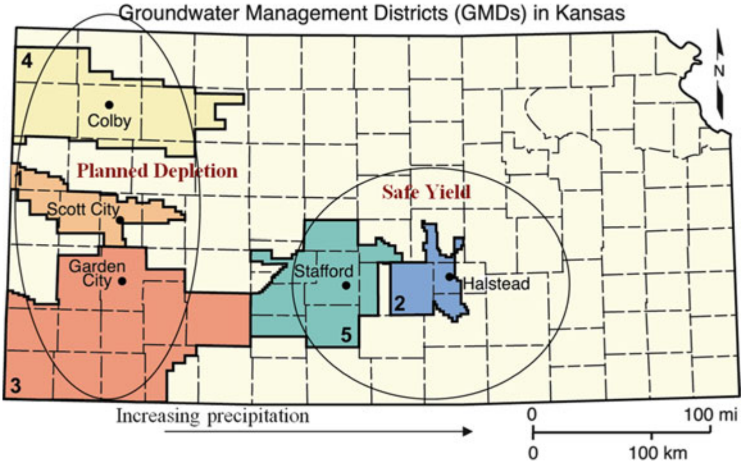


Fig. 5.9 Kansas groundwater management districts with "Safe Yield" and "Planned Depletion" Zones (Sophocleous 2010)

rights. In addition, the IGUCA allowed the marketing or transfer of water right allocations between users. The policy of "Cap and Trade" was designed to facilitate the most profitable use of irrigation water.

The farming area above the confined aquifer area of the Ogallala aquifer had to accept planned depletion as the recharge is minimal, an inch or less per year, whereas the evapotranspiration amounts 22 inches (Sophocleous 2010). GMDs overlying the Ogallala aquifer implemented a minimum two mile radius of distance between wells to avoid direct interference on the cone of depression of the water table around a neighbor's well. The Groundwater Management Districts accepted the idea of planned decline (Fig. 5.9). Penalties were also imposed for noncompliance regarding annual irrigation reporting. At present all new developments of irrigation wells are closed within the state of Kansas, except for some locations within GMD-2 and 5.

Significant new regulations have also been proposed which include closing existing irrigation and returning to dry land farming, limited irrigation, impacts due to tillage, etc. The Ogallala is a confined aquifer with a very minimal recharge. According to the Kansas Geological Survey, the recharge for the Ogallala aquifer is about 0.9 inches per year, whereas the evapotranspiration is 22 inches (Sophocleous 2010). This means that to be sustainable from the recharge of the aquifer section underlying Kansas, it will require an abandonment of 95 % of the irrigated agriculture of today. This would create a devastating impact on the economy, food production, and local communities in the state of Kansas. It is a reality that there will be areas where water will have to be managed with a controlled decline. The areas with a reasonable rainfall will have to accept the policy of safe yield as shown in Fig. 5.9.

The economic impact of the IGUCA on producer return was studied. This included interpreting how IGUCA may help in reducing the depletion of water stored in the underground formation of the Ogallala aquifer referred to as the thickness of the saturated layer. According to Golden and Leatherman (2011), producers were able to mitigate the initial economic losses by maintaining or expanding the production of higher valued crops by adopting more efficient irrigation technologies and practices. The producers also developed strategies based on prior knowledge of water use restrictions to mitigate economic damages. In a separate study to evaluate the economic impact of water use restriction within the Ogallala region, Amosson et al. (2010) found that a one percent annual water restriction produced 12.8 % increase in saturated thickness compared to present decline of the water level of the Ogallala aquifer; however, producer income as well as industry output fell an average of 4.8 % and 1.3 % respectively. Permanently converting 10 % of irrigated land to dry land resulted in increasing the saturated thickness an average of merely 3 % (Amosson et al. 2010). The bottom line is that improving irrigation efficiency to reduce the amount of water withdrawn has a greater impact than taking irrigated lands out of production to conserve water.

5.3.1.2 Arizona Water Law

Arizona's approach to water management largely treats groundwater and surface water as distinct water sources, with effluent considered a third source of water. Pursuant to the 1980 Groundwater Management Act (GMA) (A.R.S. §§ 45-401 et. seq.), groundwater use is regulated in areas of the state designated as Active Management Areas (AMAs), as shown in Fig. 5.10. Enactment of the GMA was driven by aquifer mining or over-drafting in the AMAs, which include Arizona's large population centers and major centers of agricultural activity. Surface water law follows the prior appropriation approach, often referred to as first in time, first in right. Within the surface water category, however, Colorado River water is managed according to what is known as the Law of the River, the broad body of laws and regulations governing the allocation and use of Colorado River water by seven US states and Mexico (Colby and Jacobs 2007). See Fig. 5.11.

Arizona is viewed as a leader in groundwater management. For the AMAs, the GMA quantified groundwater rights, required AMA-developed conservation programs for the municipal, agricultural, and industrial sectors, mandated an assured water supply requirement for new development, and legislatively set a water management goal for each AMA (Colby and Jacobs 2007; Megdal 2012b). A key provision related to agriculture was the limitation on agricultural acreage to those lands that had a history of irrigation during the 1975 to 1979 period. That is, if land had no history of irrigation during that 5-year period, it could not be eligible for rights to groundwater for irrigation purposes. Four of the five AMAs have safe yield as their primary groundwater management goal, where safe yield "means a groundwater management goal which attempts to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawn in an active

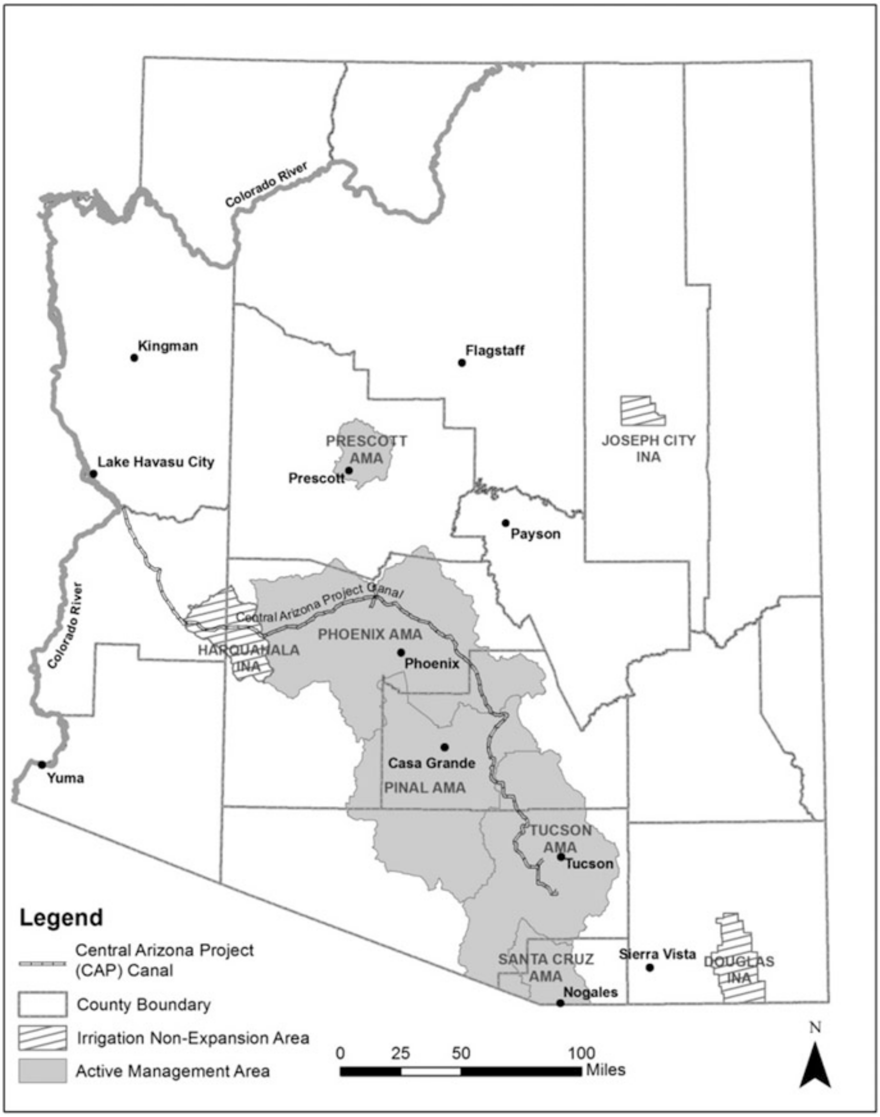


Fig. 5.10 Arizona's active management areas (AMAs) and irrigation non-expansion areas (INAs). Source: Water Resources Research Center (2013)

management area and the annual amount of natural and artificial recharge in the active management area" (A.R.S. § 45-561). The Pinal AMA, where approximately 90 % of the groundwater withdrawn is by the agricultural sector, was granted a different goal, namely to "to allow development of nonirrigation uses and to preserve existing agricultural economies in the active management area for as long as feasible, consistent with the necessity to preserve future water supplies

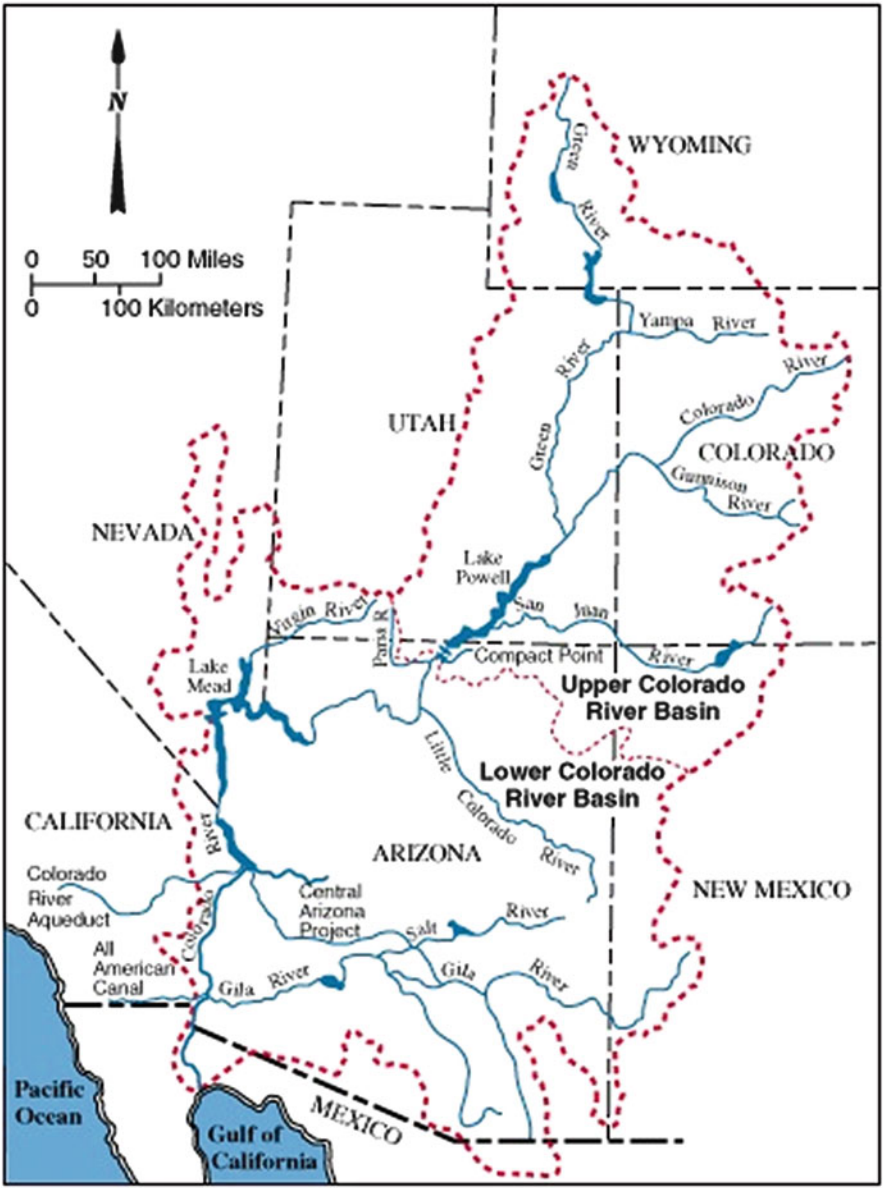


Fig. 5.11 Colorado River Basin in the U.S. and Mexico. Source: U.S. Bureau of Reclamation (2005)

for nonirrigation uses" (A.R.S. § 45-562). It should be noted that state regulations on groundwater use do not apply to Native American Nation lands. Also shown in Fig. 5.10 are the Irrigation Non-expansion Areas (INAs), which are statutorily designated areas in which agricultural acreage cannot expand beyond the 1975–1979 footprint but are otherwise not subject to groundwater regulation. Groundwater use, including that by agriculture, remains largely unregulated in other parts of the state.

The GMA therefore allowed for consideration of local differences in water use to be reflected in water management goals and regulations, but a single state agency, the Arizona Department of Water Resources (ADWR), was established to monitor implementation and enforcement of the GMA and associated regulations. In addition, conservation regulations were developed by sector and could vary by AMA. Separate conservation regulations were established for agriculture by AMA through the legislatively mandated Management Plans. The agricultural conservation regulations in initially focused primarily on an efficiency standard, with later enactment of a Best Management Practices approach (Megdal et al. 2008).

Arizona's large basin and range aquifers in the central part of the state, the availability of Colorado River water through the Central Arizona Project (CAP), and modifications to the GMA allowing for groundwater recharge and banking have provided the state with opportunities to implement innovative recharge programs, including programs that enabled agriculture to substitute Colorado River water for groundwater (Megdal 2012b). Therefore, although Arizona law does not explicitly manage groundwater and surface water conjunctively, its water recharge and banking programs have enabled significant substitution of surface water for groundwater use as well as storage for future shortage conditions along the Colorado River, which are a source of significant concern for Arizona (USBR 2012; Megdal 2013). Arizona water law does not legislatively mandate minimum water availability levels for the water needs of water dependent natural systems (Megdal et al. 2011; WRDC 2011).

Irrigation is required for most of Arizona's agricultural production. Agricultural water diversions and extractions account for approximately 70 % of Arizona's water use (Megdal et al. 2009). Irrigation by Native American Nations both along the Colorado River and in Central Arizona are an important component of Arizona's agricultural water use. The mosaic analogy used to describe the water management situation in the US can likewise be used to describe that in Arizona. The water rights held by agricultural entities differ according to type of water, location of use, and other factors. For example, agricultural water rights held by entities along the Colorado River are senior to all Colorado River water delivered through the CAP, including that delivered to cities and towns. On the other hand, rights to use water delivered through the CAP by non-Indian agricultural users are junior to CAP water delivered to cities and towns. Water delivered to Indian Nations through the CAP is usually of higher priority than water delivered through the CAP to non-Indian agricultural users. The GMA essentially granted in perpetuity groundwater rights for historically irrigated acreage in the AMAs, as long as the groundwater is available. Hence, agriculture has the right to revert to more groundwater use as shortage conditions on the Colorado River impinge on the availability of CAP water to non-Indian agriculture.

Arizona groundwater law established management goals, with safe yield to be achieved by 2025, but the GMA does not include penalties for nonachievement. Forty-five years was thought to provide a long period of time for compliance. There were expectations that agricultural water use would be replaced significantly by municipal use in Central Arizona and that other activities, such as copper mining in the Tucson AMA, would decline. Almost 35 years after enactment, copper mining and agricultural activities, including those of Indian Nations, are robust. Population growth, including communities outside the AMAs, has led to significant growth in municipal demands. These developments have complicated attainment of safe yield in some of the AMAs.

Arizona can be seen as a microcosm of the Colorado River Basin. Water demands are projected to outstrip supplies. As is true across the Basin, as a whole, agricultural water use remains a significant component of Arizona's statewide water use. While irrigators often have senior surface or groundwater rights, they are concerned about the growing demands of the municipal sector and the associated pressures to enter into water transfer transactions that would result in reduced agricultural production. For example, although farmers in the Yuma region in the southwestern corner of Arizona are producers of a significant portion of winter vegetables for the entire US and holders of senior rights to Colorado River water, they are likely targets for voluntary water transfers or fallowing arrangements.

Arizona water users have a history of joining forces to develop solutions to the state's water management challenges. There is much discussion of how to meet future water needs. As a state that values the rights of individual property owners, solutions will likely depend on arrangements with willing partners, including irrigators, and additional investments by municipalities to increase their use of supplies such as treated wastewater and harvested rainwater.

5.3.1.3 Stakeholder Collaboration Is Essential

These brief discussions of water law for two very different states demonstrate that an understanding of the regulations and institutional arrangements of the different states will be necessary in order to address food security and water sustainability. The role of actors from different jurisdictional levels underscores the necessity of active collaboration across geographic location and scale. States have significant authority in water management, although the federal government has a role to play with respect to water quality and interstate waters. The federal government has played an extensive and important role throughout the US, especially in the western US, where the US Bureau of Reclamation has constructed major projects to irrigate lands that are sometimes distant from surface water sources. Reclamation continues to play an important role through its many studies and project partnerships with municipalities, irrigators, and Indian Nations. Potential involvement of the federal government through incentives and other financial assistance could provide a boost to efforts addressing water resource allocation and utilization issues. Though the role of irrigation districts and other substate water management districts and authorities will vary by state and region, it will be essential to involve stakeholders from all levels in efforts to work on legislative and non-legislative approaches to achieve sustainability in agricultural water use.

5.3.2 Whither Federal Water and Food Policy?

Through multiple agencies, most prominently the U.S. Department of Agriculture, the federal government has played a critical role in the development and implementation of sound agricultural water use practices. Sustainability of irrigation is a must to ensure future food need. Presently 40 % of our total food and fiber needs are met by irrigated agriculture (Postel 1999). It is an established fact that crop yield is linearly related to the ET of a crop (Lamm et al. 1995). This requires that the productivity of water used for crop production should not only be maintained, but enhanced, to support the increased food needs of the future. The increased competitive demand for water may be met through water savings from greater efficiencies in agricultural water use, more recycling, and reuse of water enabled by improving technology, application of biotechnology, and financial incentives. Efficiencies that can be gained by other water using sectors should be examined as well. For example, there may be significant water savings associated with water used for aesthetics such as irrigating turf. In the US alone about 4.3 million hectares (10.6 million acres) are in irrigated turf. It is estimated to be three times larger than irrigated corn (Milesi et al. 2005). Turf is the largest single irrigated crop in the US. These turfs are intensively cultivated to achieve a verdant and uniform appearance and, as such, excessive fertilizer and other synthetic chemicals are often used to make them look attractive.

Although the states guard their water management authorities closely, there is much to be gained by a more coordinated discussion of water policy issues. The federal government is in a position to lead this discussion. Given the notable levels of water consumption by irrigated agriculture, an explicit consideration of federal food policy (see Redick, Chap. 3; McWilliams, Chap. 6) would be a relevant component to these discussions. In addition, there is a significant role for federally funded research and policy analysis related to adaptation strategies connected to the impacts of changing climatic conditions.

5.4 Conclusion

This chapter began with a look back to the agricultural practices that predated the technological and scientific advances that have enabled agricultural irrigation and food production to flourish. Nevertheless, in the context of rapidly growing demands for food and energy resulting from population increases and improvements in living standards around the globe, there are worldwide concerns about food security, energy security, and the sustainability of irrigated agriculture. The early twenty-first century may indeed be the demarcation between the technological-scientific era of agriculture to the water scarcity era of agriculture.

Demand for water resources is growing at the same time that climatic factors may be adversely impacting the availability of what had been considered reliable water resources. Fossil water sources are being depleted. The need for more food coincides with greater concerns about the water requirements of natural systems. Solutions to water availability and water quality challenges will require contributions from the research, financial, business, and policy-making communities. Addressing the tradeoffs involving in meeting the water requirements for food production, urban, environmental, recreational, energy, and industrial uses will require policy decisions at various levels of government. It is therefore likely that water legislation, regulation, and policy will play an ever more important role in the future.

Agricultural producers, policy makers, and society will have to develop strategies of adjustment and acceptance of future agricultural water use. Producers will have to increase production efficiencies and conserve water. Irrigation scheduling should be practiced carefully to take advantage of natural precipitation. Tillage practices and crop residue management should encourage absorption of natural precipitation and reduce runoff. It may be necessary to change crop mixture or accept optimal production instead of maximum production. Producers will have to accept reduced yield from limited irrigation strategy where necessary. Agricultural scientists have to work on biotechnology and come up with acceptable new hybrids. They have to work to establish the safety of genetically modified hybrids capable of mitigating the effect of limited water and communicate their findings in a manner understandable to consumers.

It may be that future historians will refer back to the current period of agricultural irrigation as the water scarcity era. Regardless of whether or not of title, these are challenging times for agriculture. The collective actions of many will determine the extent to which we have been successful in managing our water resources and modifying our agricultural practices to achieve food security and agricultural sustainability.

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Part III
Sustainable and Secure Food Production

Chapter 6
Turning the GM Battleship: The Tide of Popular Opinion and the Future of Genetically Modified Foods

James E. McWilliams

6.1 Introduction

The corporate pioneers of transgenic crops must never lose sight of the average consumer. They cannot afford to. Laypeople with minimal scientific literacy but heightened safety concerns wield tremendous cultural and consumer power. And, given that they are routinely asked to swallow a conflicting concoction of questionable information, they are impatient and frustrated. And really, who could blame them?

What is especially unfortunate about this prevalent frustration among consumers is that it stems the progress of an important technology with an impressive array of beneficial applications. Transgenic technology will never become a silver bullet solution to anything, much less a major agricultural problem. But in light of the problems that global agriculture faces in the upcoming decades, it has the potential to play critical roles in nearly every aspect of twenty-first century food production. Critics of industrial agriculture—and, by extension, critics of transgenic technology—have stubbornly refused to confront the most pressing question in agriculture today: how are we going to feed over nine billion people with minimal agricultural expansion? How are we going to achieve a density of production capable of doubling the food supply without destroying rain forests and undermining biodiversity in the process? While supporters of transgenic technology would be amiss to claim that genetically modified crops will in and of themselves solve this global quandary, there is no denying that the traits that this technology brings to the table—insect resistance, drought resistance, herbicide resistance (see Lee et al., Chap. 10; Gianessi and Williams, Chap. 14), nitrogen uptake efficiency, biofortification, and so many other benefits—can play pivotal roles in shaping a future

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agricultural system that is highly productive, profitable, humanitarian, and sustainable (Fedoroff 1999).

But again, from the consumer's perspective mixed messages about GMOs abound. Pro-biotech interests have spent the last decade promoting their products as environmentally beneficial agricultural techniques that will lower food prices, feed the world, and mitigate the negative impacts that climate change is projected to have on the global poor. In a typically salient endorsement, one industry publication explained, "genetically modified plants and animals have the potential to be one of the greatest discoveries in the history of farming" (Rousu et al. 2007). Perhaps. But these optimistic assessments raise hackles of opposition and have been assiduously countered by torrents of negativity. Environmental nongovernmental organizations (NGOs) in particular have persistently impugned genetically modified foods as ecologically destructive, a threat to public health, and sinister tools in the grips of greedy corporations interested in nothing more than the bottom line. Greenpeace, perhaps the most unhinged critic of transgenic technology, deems genetic modification "one of the most dangerous things being done to your food sources today" (Rousu et al. 2007). Extremes and distortions predominate.

Given the heavy cross-currents of information and misinformation that consumers are routinely asked to negotiate, it is perfectly understandable why so many uninformed consumers pursue the path of least resistance and, however dubious their grounds for doing so, reject genetically modified foods. It should come as no surprise that consumers who see no direct benefit in transgenic technology opt to play it safe and keep the technology at arm's length. Even the quickest risk/benefit sketch confirms that, from the consumer's perspective, this choice makes a certain amount of sense. Why take a risk when there is no perceived benefit to be gained in so doing?

But the problem with this widespread popular rejection, and often downright disdain of GM crops, is twofold. First, although there's been hyperbole on both sides, the NGOs have been far more manipulative and propagandistic when it comes to presenting accurate "information" on GMOs. As a result, they have insidiously misinformed consumers under numerous veils of "authority." Second, these distortions are hardly trivial matters—in fact, tremendous humanitarian and environmental advancements are at stake. The future of a sustainable, affordable, and healthy food supply hinges to a large degree on an active public acceptance of agricultural biotechnology. In the end, we are confronting a situation in which the public is being misled, perhaps at times all too willingly, about a potentially powerful humanitarian and environmentally beneficial approach to farming. The court of public opinion, as a result, must be set straight.

This chapter explores how this task might be accomplished. It will primarily evaluate the extent and nature of our entrenched skepticism of GMOs. It will do so, moreover, with an eye toward suggesting exactly what strategies might eventually erode that skepticism and, perhaps, turn the GM battleship in a new direction, one that points to a radical reconceptualization of agricultural biotechnology by mainstream consumers. The first half of my analysis examines why anti-GMO efforts have succeeded as well as they have in swaying public opinion away from transgenic technology. Answering this question requires exploring three themes: the ideological depth and sociological nuance of the anti-GMO critique, the media's frequent complicity in perpetuating negative perceptions, and the underappreciated impact of the local food movement on popular consumer opinions. Building on these mitigating factors, the second half of this essay explores how these seemingly inveterate negative reactions to transgenic technology could realistically yield to a more responsibly presented pro-GMO message, a message marked by credulity and accuracy rather than ideologically charged distortion. Central to this change would be industry's reconsideration of several fundamental issues—issues including labeling, the ideal avenue through which to tell the truth about biotechnology's potential, and the importance of "connecting" with consumers from the "bottom up" through valuable products with which they can identify.

6.2 The Sources of Anti-GMO Outrage

6.2.1 Motivation of Anti-GMO Movement

Understanding the nature of the opposition to biotechnology begins with a simple question: What are opponents of GMOs actually protesting when they protest genetically modified crops? As it turns out, rarely are they protesting genetically modified crops. In fact, rarely are they even talking about science or technology or even agriculture. Indeed, one of the more troubling aspects of the anti-GMO advocates is the assumptions based on a petrified premise mired in anticorporate, antiglobalization, and anti-industrial ideology. This is not to say that it is inherently problematic to critique these complex global trends. There must always be room for healthy debate on such critical issues. But when, in the opposition's condemnation of modernity's defining features, these groups reflexively dismiss a specific technology because of its association with a larger trend of which they disapprove, they are being intellectually deceptive rather than engaging the specific issue on its own terms. As a result, we have every justification to scrutinize the anti-GMO movement's deeper motivations—motivations that, as we will see, have little to do with precise claims against GMOs per se.

In their article "Sustaining Outrage," William A. Munro and Rachel Schurman explore the roots of opposition to GMOs in considerable depth, mining the underlying ideological impulses behind the most fervent opposition to biotechnology. Locating the movement's "motivating sensibilities" in the "new" social movements that developed in the 1970s, they reveal a telling perspective. Passions at that time fomented around a complex set of issues that predated biotechnology—issues such as nuclear power, renewable energy, the military–industrial complex, and toxic waste. These movements gradually cohered into a broader condemnation of corporate consolidation and globalization in general. As it did, a diffuse grassroots movement became poised to (ipso facto) place in its crosshairs any technology prone to corporate consolidation and "neoliberal" application, especially when it came to the global south.

6.2.2 *Prefigured Opposition to Agricultural Biotechnology*

Agricultural biotechnology, as it developed in the early 1980s, happened to fit these prerequisites to a tee. With minimal debate, anti-GMO activists instantly placed biotechnology "under the umbrella of concerns about a potentially apocalyptic and unnecessary technology." In this sense, the direction of popular outrage reflexively followed the same course of protest previously forged by opponents of nuclear proliferation and toxic waste dumping. Again, the point here is not to suggest that biotechnology should have been allowed to slip into the public sphere with a free pass. No technology deployed in a democratic society ever warrants such privileged treatment. The point is simply to show how, in many respects, formal opposition to biotechnology was, in a sense, prefigured. It was set in stone before a fair and open discussion of its comparative merits and drawbacks might have taken place (Munro and Shurman 2008).

The rhetoric of opposition animating the anti-GMO movement clearly betrays this presumption. As Munro and Shurman document, one activist explained that the roots of opposition derived from a desire "to question the whole industrial paradigm." Note that, as this comment reveals, fear was not directed against a questionable scientific or technological danger. Instead, it was pegged to such amorphous phenomenon as "huge systems" and "the dominion of the means of production." Another activist writer described agricultural biotechnology as "an economic race to own the biological and genetic ingredients of agriculture." Yet another based his opposition to GMOs on the general grounds that "any new technology introduced into a society which is not fundamentally just will exacerbate the disparities between rich and poor" (Munro and Shurman 2008).

Munro and Shurman observe that the common thread running through so much of the oppositional camp was not a scientifically grounded critique of GMO safety. Instead, it was a rejection of "the predominant values of late capitalist society." Such a position has a tendency to encourage hysterical commentary, such as when two authors wrote in an academic volume that GMOs would compromise biodiversity to the point that they would cause "the single biggest environmental catastrophe in human history (Munro and Shurman 2008). The last comment notwithstanding, there are perfectly legitimate reasons for being wary of the power structures characterizing "late capitalist society," but those concerns are not enough to forego a balanced discussion of the science and safety of genetic engineering. Still, anti-GMO activists have done a remarkable job of subsuming any factual-based discussions of biotechnology under the emotionally charged rubric of an antiglobalization campaign.

6.2.3 The Media and GMOs

This elision between larger global inequities and a condemnation of GMOs has been especially evident in the fraught relationship between agricultural biotechnology and the popular press. By no means is it the case that "the press" as a whole is categorically skeptical of GMOs. But there is little doubt that, generally speaking, the mainstream media has closely followed public opinion in their failure to evaluate the underlying positive potential of transgenic technology. An important study published in 2006 found that media coverage of GMOs was "intimately associated with other political events of the time, notably the invasion of Iraq" (Cook 2006). While pro-GMO media outlets stressed the issue as a scientific one, the much more influential anti-GMO media response rejected "scientists and companies as unreliable" and cast the issue of GMOs in "a more global frame" (Cook 2006). Many traditional news outlets practice an insidious form of suggestive (and sloppy) journalism, as one article confirmed when, after citing no evidence that GMOs are in any way linked to allergic reactions, noted that "In Britain, the number of children developing potentially fatal allergies to nuts has trebled in the last decade" (Cook 2006). Others redirect concerns from a balanced assessment of GMO's pros and cons to who is most likely to benefit financially from the ongoing adoptions of transgenic crops. As the authors of the 2006 report note, the *Guardian* routinely "emphasized the social and political context of GM knowledge or practices [and] the economic interests of those who fund or support it" (Cook 2006). Conflating transgenic technology with global conflagrations such as international warfare, or with something as universally detestable as corporate greed, far too many press reports "appear to share the view of C. Wright Mills, expressed half a century ago, that a 'power elite' consisting of military, economic, and political leaders, have oligopolistic control over foreign and domestic policy decisions and regard GM as symbolic of this domination" (Cook 2006).

No matter what bias a particular news source might have with respect to agricultural biotechnology, media accounts of GMOs are almost universally marked by overwrought claims and glaring headlines. In a typical case of hyperbolic headlining, the UK's Independent screamed, "Exposed: the great GM crops myth". The piece went on to impugn GM soybeans as causing yield losses. This categorical claim is not only based on one small study, but the article failed to contextualize it in the following necessary points: (a) GM soy is not designed to increase yields but to prevent yield loses; and (b) a number of other studies have found substantial decreases in yield losses. Positive reports err as well in their obsession with the issue of yield. Reporters will often present transgenic technology as integral to solving "the food crisis" without mentioning the numerous other beneficial functions they serve beyond the singular issue of yield. Given that Martin Taylor, chairman of Syngenta, has publicly explained that, "GM won't solve the food crisis, at least not in the short term," media reports have badly distorted the matter by reducing the success or failure of GMOs to the sacred benchmark of yield (Brainard 2008). Perhaps more problematically, such simplistic success-or-failure media treatments of transgenic technology ignore its underlying scientific complexity—a complexity that concerned consumers should be encouraged to negotiate. In so doing, it perpetuates popular distrust of scientists, thereby contributing to the kind of "denialism" that prevents lay consumers from attempting to appreciate the less accessible scientific aspects of transgenic technology (Specter 2009).

A final issue preventing many reporters from delving into the science underscoring transgenic technology involves the pressure to be "objective." Despite the clear biases that many news outlets continually indulge, there is a corresponding effort to mitigate that bias by balancing one opinion against another. For example, a *Chicago Tribune* story ultimately critical of GMOs began with a quote from one food expert explaining, "It is established fact that a number of bio-engineered crops have shown themselves to increase yields through their drought resistance and pest resistance." Then, a few paragraphs later, the story proceeded to quote a representative from the organic lobby, who remarked that "it's pretty obvious at this point that genetically engineered crops…don't increase yields." The writer Seth Mnookin, who has written extensively about public perception of vaccines (and is now a journalism professor at MIT), refers to this balancing act as "manufactured equivalence" (Mnookin 2010).

The juxtaposition of favorable and unfavorable quotes in an objective news story might seem to be a basic tenet of responsible journalism. But there is a bit more to it. Newspaper writers are being pushed to balance out their stories in order to give their work the appearance of judiciousness. But this literal interpretation of fairness—one positive quote for every negative one—ultimately backfires in that it does nothing to advance data-driven conclusions. Instead, it exonerates the reporter from doing what he or she should have been doing all along: researching and reporting on *which* of the conflicting opinions dutifully presented was more accurate. As a writer in the *Columbia Journalism Review* notes, "Too often, science journalists think that adhering to the old norm of 'balance' fulfills their obligation to readers. But two conflicting statements do not enlightenment make." If a position in a debate is so obviously wrong, why should it deserve representation? (Brainard 2008).

6.2.4 The Internet and GMOs

If mainstream print media errs by manufacturing equivalence, the Internet fails by fomenting chaos. Lacking gatekeepers (and, very often, basic decency), web-based sources of information tend to create a toxic informational atmosphere characterized by fear mongering and rhetorical hysteria. In his recent book, *The Panic Virus*, Seth Mnookin explores how the unique connectivity of the Web promotes the unprecedented spread of dangerous misinformation. Although Mnookin is writing about the growing denialist opposition to vaccines, it becomes immediately apparent that an identical Web-induced "panic" has misled consumers about the dangers of transgenic technology. "The anonymity and lack of friction inherent in the online world," writes Mnookin, "means that a small number of committed activists—or even an especially zealous individual—can create the impression that a fringe viewpoint has strong support" (Mnookin 2010).

A case in point with respect to GM seeds would be that of Jeffrey Smith. Smith heads an organization of his own creation called the Institute for Responsible Technology. He has self-published a small shelf of books so packed with innuendo and outright lies about the dangers of GM seeds that Academics Review, an independent organization of scientists dedicated to ferreting out scientific misinformation, maintains a website that systematically debunks Smith's books point by point. Either by taking studies out of context or failing to cite peer-reviewed work at all, Smith has claimed that Bt corn is linked to liver cancer and birth defects while listing 65 specific health problems attributable to GM seeds (Academics Review 2010).

It is important to note that Smith would not be able to make his claims without an unregulated World Wide Web to make them in. He keeps a blog that he routinely updates with unsubstantiated anti-GMO messages alongside conspicuous advertisements for his books. The penultimately revealing thing about Smith is that he has no background in science. Instead, his training is in Maharishi studies and swing dancing. His most notable accomplishment before reinventing himself as an anti-GMO barnburner was to convince thousands of people all over the world to practice a meditation maneuver called the "flying yogic technique" at the same time. Nonetheless, he is often the media's go-to guy for supposedly legitimate information on a technology that he not only fails to understand, but exploits to his professional advantage.

6.2.5 *Food Movement*

Another (but hardly final) factor contributing to public distrust of transgenic technology centers on the popularity of a new but influential Food Movement. Unlike Jeffrey Smith, the Food Movement is a perfectly legitimate endeavor. It just happens to be narrowly focused and deeply opposed to GM seeds. Members of the Food Movement generally seek to eat local, organic, and "all natural" food—food that has preferably not been processed or produced by a multinational company. Underscoring this mission is the idea that the Western diet has become alienated from its subsistence-oriented, pre-industrial roots. People have, in this assessment, lost contact with where the food comes from, who makes it, and why it tastes the way it does. A central mission of the Food Movement is thus to reduce the distance between producer and consumer, going so far as to encourage consumers to be their own producers, or at least become close enough with a local farmer to have a fuller understanding of the methods used to grow local food. Defined by mantras such as "don't eat anything your grandmother didn't eat," (Pollan 2008) this is a movement that has little to no sympathy for (or understanding of) transgenic technology. Efforts to present GM seeds as compatible with organic methods or as just the latest step in a many thousand year history of plant breeding tend to be met with indifference, if not outright hostility from this very influential group (McWilliams 2009; Ronald and Adamchak 2008). The media, one might add, adores virtually everything the Food Movement represents.

6.3 Turning the Battleship

Are there solutions to these problems? In light of the myriad and powerful forces preventing everyday consumers from developing positive assessments of transgenic technology, one would be justified in thinking that pushing public opinion in a more positive direction was a losing proposition. Indeed, when I recently gave a talk at a large seed company with a less than pristine public image, this attitude was certainly in evidence. I was told that a significant portion of the company was simply not interested in continuing its attempt to win the hearts and minds of average consumers. There was too much scientific illiteracy, they claimed, too much muddled skepticism and ideological blindness. I think that this position, while perfectly understandable, is a mistake. Thus this section of this chapter will attempt to argue that, with the right methods and message, public opinion about GM seeds could realistically change for the better.

6.3.1 Voluntary Labeling

First, although this idea sits poorly with the industry, some form of voluntary labeling must be enacted. Currently, the FDA does not require food products to contain any information about GM contents. It is important to understand why this is the case. The FDA currently relies on the principle of “substantial equivalence” as its reason for not requiring GMOs to be labeled. According to this idea (which was formulated by the Organization for Economic Cooperation and Development in 1991), a novel food such as GM food should be evaluated and regulated according to the same standards as its conventional counterpart if its composition and characters are the same. Another reason that the FDA does not require GMO labeling is because, consistent with the Federal Food, Drug, and Cosmetic Act, a whole food—such as corn or soy—is considered GRAS (“generally recognized as safe) and thus does not have to be subjected to the extensive and expensive safety review. It is extremely unlikely that the federal government is going to abandon its adherence to these established and basically effective methods of evaluating the food system.

That said, a voluntarily sought out label would go a long way toward dispelling the popular, albeit paranoid, assumption that a handful of seed companies are surreptitiously trying to conquer or contaminate the world’s food supply. A typical—albeit completely hyperbolic—example of this all-too-popular opinion comes from a commenter to a Huffington Post article who wrote that “One of the reasons so many Americans are overweight is because corporations like Monsanto are sneaking GM foods into our diets.” Sadly, many consumers believe this kind of talk. Labeling products made with GM ingredients would not only directly counter this widespread delusion (one that has done a great deal to foster interest in organic choices), but it would also remind consumers that GM ingredients are integral to our food supply—and have been for 18 years—without a single documented negative side effect. In short, labeling would help earn consumers’ much needed trust in the fact that seed companies have nothing to hide while normalizing the fact that GM ingredients are indeed everywhere. Otherwise, it is simply too easy to portray the Monsantos of the world as being duplicitous and deceptive (Roe and Tiesl 2007).

Labels would not only enable the industry to avoid popular perceptions of duplicity, but it would allow it to present a more accurate message to a more receptive audience. Considerable research suggests that labels—especially those certified by the USDA and FDA—work very well in establishing consumer confidence (Degnan 2000; Pornpitakpan 2004). According to a 2006 study published in Food Policy, consumer credibility is especially strengthened when “genetic modification is mentioned as the means for implementing a more fundamental claim” such as lowered pesticide usage (see Redick, Chap. 3; Lee et al., Chap. 10). As the authors explain, “When the GM claim was expanded to include the reason for the genetic modification respondents’ purchase intent tended to be higher and, in several instances, significantly higher.” When accurate and elaborated labeling was accompanied with a toll-free telephone number and web address for consumers to pursue further questions they might have, labeling credibility increased even further. The potential rise in food prices notwithstanding, these are important findings to consider, especially given the fact that more and more products are being sold with “non-GMO” labels, a development that significantly tips the scales of public opinion against GM foods.

Another reason why accurate labeling is a promising idea centers on an often underappreciated reality: many (if not most) consumers are actually undecided about biotechnology. Indeed, despite the fact that many more people are likely to be overtly opposed rather than overtly supportive of GM seeds, consumers tend to hold, according to the most comprehensive study of public perceptions of biotechnology, “a complex set of beliefs about a range of health, environmental, and social risks and benefits of GM food and crops” (Poortinga and Pidgeon 2007). According to an extensive survey of citizens in the UK, a region that is far more skeptical of GM seeds than the USA, consumers have not become more opposed to transgenic technology over the years, but rather “more undecided about GM food” (Poortinga and Pidgeon 2007). This ambivalence represents an opportunity.

Many of the undecided respondents even leaned in a supportive direction. While people certainly harbor a range of concerns about agricultural biotechnology, the authors note that “a substantial proportion of our sample appreciate the various (potential) benefits of GM food and crops.” The study found, for example, that responders were more than twice as likely to support the claim that “some GM crops could benefit the environment by requiring less pesticides and chemical fertilizers than traditional crops." In the same vein, more respondents agreed than disagreed with the statement that GM crops could "improve the prospects of British farmers by helping them compete with farmers around the world." Only 11 % of those surveyed disagreed with the remark that "some GM non-food crops could have useful medical benefits." Overall, the documented ambivalence over GM crops among a significant portion of the population, in addition to what seems to be an encouraging predisposition toward acceptance, suggests that the time is quite ripe for a carefully considered labeling campaign (Poortinga and Pidgeon 2007).

6.3.2 Third-Party Reviews

A second decision the agricultural biotechnology industry should make to further the process of promoting positive public opinion is also one that it will initially resist: it should stop attempting to be the bearer of its own good news. Companies such as Monsanto and Syngenta need to recognize that their interests are too conflicted to be trusted by the public to provide accurate assessments of its own products. Anyone who has read the science knows that GM seeds will reduce pesticide applications, increase food availability in developing countries, and help confront the world's impending crisis. But the companies that make these seeds must allow other sources of information to convey this information. A number of marketing and economic studies confirm this assessment. For example, in a 2007 study, researchers found that "the perspectives of interested parties are consequential in an auction market setting; pro-biotech information distributed by the biotech industry has significantly negative effects on bid price" (Rousu 2007). However, this is not the case when the positive information comes via a credible third party. As the authors note, "verifiable third-party information in the GM food market has potentially large and statistically significant social value" (Rousu 2007). While the industry's outreach efforts are admirable, its focus should be on transparency (which includes labeling) while allowing a fair-minded third party to present accurate biotech information to the general public.

Such an organization might consist of scientists, environmentalists, and even religious leaders. It should be carefully vetted in order to have no affiliation with any of the interested parties surrounding the issue. It should be nonprofit and have no activist mission. What the involvement of such an agency would mean for the biotech industry is, admittedly, a lessening of control over their message—something no company wants to experience. As the authors of the 2007 assessment note, the optimistic rhetoric behind GM crops would be toned down. For example, the industry has presented the environmental impact of GM plants in these terms: *GM technology has produced new methods of insect control that reduce chemical insecticide application by 50 % or more. This means less environmental damage. GM weed control is providing new methods to control weeds, which are a special problem in no-till farming. Genetic modification of plants has the potential to be one of the most* *environmentally helpful discoveries ever.* But, in the hands of a third party, the same message might read like this: *The effects of genetic modification on the environment are largely unknown. Bioengineered insect resistance has reduced farmers' applications of environmentally hazardous insecticides. More studies are occurring to help assess the impact of bioengineered plants on the environment. One study's reported harm to Monarch butterflies from GM crops, but other scientists were not able to recreate the results. The possibility of insects growing resistant to GM crops is a legitimate concern.*

It is true that the authority consumers might grant to such a statement, as a result of its third party status, means that industry will have to settle with less-than promotional portrayal. But consider a couple of countervailing points. First, even-handed third-party verifications, even if they are not as enthusiastic as the industry might hope, will very likely open up more consumer minds (recall, a large portion of whom do remain genuinely ambivalent about transgenic technology) than would industry's own promotion of its product. Second, the emergence and acceptance of fair-minded third-party assessments would go a long way toward delegitimizing the hysteria that comes from radical anti-GMO groups such as Greenpeace. Consider their statement about the environmental impact of GM seeds: *Genetically modified foods could pose major environmental hazards. Sparse testing of plants for environmental impacts has occurred. One potential hazard could be the impact of GM crops on wildlife. One study showed that one type of GM plant killed Monarch butterflies. Harmful insects and other pests that get exposed to these crops could quickly develop tolerance and wipe out many of the potential advantages of GM pest resistance*. The value of a third-party assessment is that it would correct for this all-too-common brand of propaganda. In the end, industry's decision to allow their products' benefits and drawbacks to be introduced to the public through a credible and responsible third party might have short-term costs, but it promises to pay off in terms of long-term consumer trust of biotechnology (Rousu 2007).

6.3.3 Direct Consumer Benefits

The final way in which biotech can achieve greater consumer support would be to develop and market more products with direct consumer benefits. Reminding the general public that GM seeds will lead to cheaper food, confront starvation in Africa, and even diminish the application of highly toxic pesticides is certainly important, but it ultimately fails to address the "what's in it for me" issue. Because consumers overwhelmingly feel that there's no direct consumer benefit to come from GM seeds, they remain much more open to the suasions of anti-GM activists who portray Monsanto as the avatar of evil and its seeds as the basis of environmental degradation. The only way to stop this cycle of negativity is to appeal directly to the consumer in a way that requires them to reassess risk. And if there's a vulnerable spot in the consumer's armor of suspicion—that is, an area where he or she has historically shown a remarkable willingness to take risks and entertain personal change—it is in the realm of nutrition. Put simply, transgenic technology must initiate and make itself indispensable to a twenty-first century nutritional revolution.

Never before has the timing been better to do this. The future of nutrition is an extremely exciting one. Right now food chemists, nutritionists, and plant biologists are exploring how our food supply—which has been nutritionally depleted over hundreds of years (http://www.scientificamerican.com/article.cfm?id=soil-depletion-and-nutrition-loss)—cannot only be enhanced and biofortified to replenish dozens of lost micronutrients, but possibly even individualized as personal diets based on a person's precise nutritional needs. Nutrigenics, as this new way of thinking about food is called, will happen at the intersection of human genomics, personal nutrition, and biotechnology. Many of you are likely aware that the one area where the public maintains a relatively high regard for biotechnology is in the field of pharmaceuticals. As our quest to optimize the nutritional quality of the human diet beings us closer and closer to designing foods that prevent and fight disease, the potential for nutritionally enhanced GM products—not to mention the companies who make them—to thrive with the utmost public support would very likely skyrocket.

6.3.4 Learning from History

Perhaps the best support for this final argument comes from history. It is worth noting that, a hundred years ago, consumers had to make sense of another controversial and frequently misunderstood technology. So controversial is this technology that, at its inception, critics insisted that it would utterly ruin the global food supply. They worried that real food as we know it would disappear, yielding to a fabricated cornucopia of processed, bad tasting junk. Worse, detractors argued that food would become inherently unsafe with the advent of this invention, that unscrupulous corporations would monopolize and exploit this technology to deceive the general public, and that we'd all succumb to a variety of strange diseases. Advocates of this technology predictably went on and on about how it was going to feed the world and cut food costs, but diehard opponents dismissed such claims as rotten propaganda. Many European countries went so far as to ban this technology altogether. The French, as it happens, led the way.

The technology in question here is *refrigeration* (Friedman 2009). Of course, despite its initial unpopularity, refrigeration went on to become perhaps the most critical technology related to food production and consumption. When I think about the parallels between the refrigeration and GM seeds I'm especially drawn to the post WWI era. It was then that something critical happened in order to radically, and almost immediately, change public opinion about refrigeration. It had nothing to do with the dissemination of information and everything to do with the fact that people could now buy compact refrigerators and put them in their homes. The advent of GE's Monitor Top compact fridge in the 1920s transformed refrigeration from a distant technology that benefitted companies who were transporting perishables to the one that offered a tangible and direct good for the average everyday household. In its 2004 survey, the Pew Charitable Trusts noted that “consumers are most supportive of [the] uses of biotechnology that they feel will directly help them and their families” (Miller 2004). This conclusion applies perfectly to refrigeration. In fact, and somewhat ironically, consumers were so responsive to the obvious conveniences offered by the compact refrigerator that they easily overlooked the fact that the refrigerating medium—sulfur dioxide—was corrosive to the eyes and capable of causing visual impairment and severe burns. It just goes to show: our personal assessment of a technology’s risk is dramatically altered when that technology improves the quality of our lives. Transgenic technology can, and should, do precisely that.

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Chapter 7
Sustainable Production of Omega-3 Fatty Acids

Jay Whelan, Ronald Hardy, Richard S. Wilkes, and Henry E. Valentin

7.1 Introduction

There are two main families of polyunsaturated fatty acids (PUFAs) in the human diet, the *n*-6 and the *n*-3 families, where linoleic acid (LA) with two double bonds and alpha-linolenic acid (ALA) with three double bonds are their respective parent compounds (Fig. 7.1). In 1929 and 1930, Burr and Burr published a series of seminal papers describing a lipid deficiency disease in rodents that was improved with fats containing LA (Burr and Burr 1929, 1930). These initial experiments provided the basis for essentiality of *n*-6 PUFA where the severity of dermatitis, skin barrier dysfunction, and cutaneous inflammation underscored deficiency. The levels of LA in the diet to achieve essentiality have been estimated to be between 0.5 and 2.0 % of energy in infants (Paulsrud et al. 1972; Cuthbertson 1976) and estimated to be approximately 1 % of energy in adults (Calder 2010). Research over the next three decades saw a metabolic relationship between LA and arachidonic

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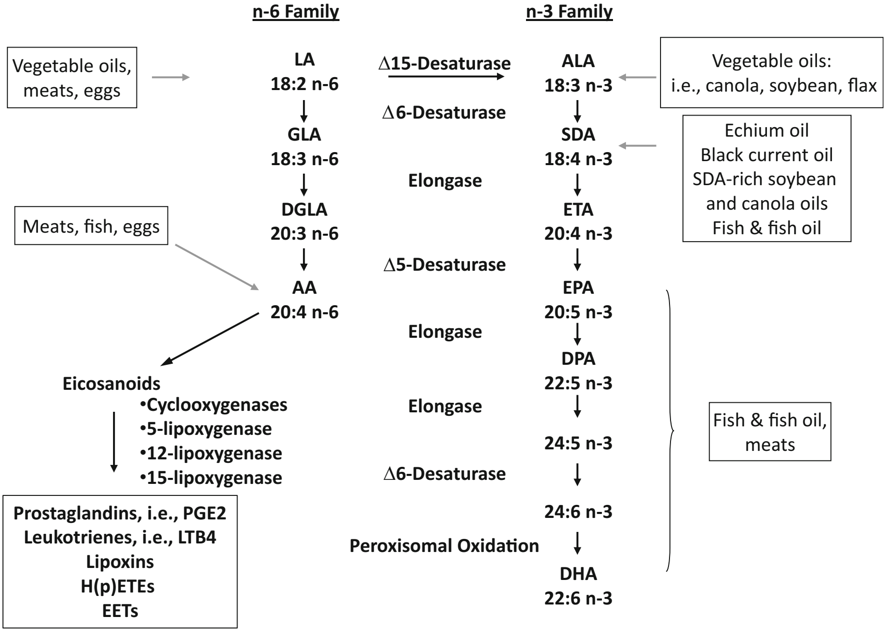

Fig. 7.1 Metabolic pathways for *n*-6 and *n*-3 polyunsaturated fatty acids. *AA* arachidonic acid, *ALA* alpha-linolenic acid, *DGLA* dihomo-gamma-linolenic acid, *DHA* docosahexaenoic acid, *DPA* docosapentaenoic acid, *EPA* eicosapentaenoic acid, *ETA* eicosatetraenoic acid, *LA* linoleic acid, *GLA* gamma linolenic acid, *SDA* stearidonic acid

acid (AA) (Fig. 7.1), the two most prominent *n*-6 PUFAs associated with membrane phospholipids, and it has been reported that tissue levels of AA no longer respond to dietary LA at intakes above 2 % of energy (James et al. 1993).

Evidence for essentiality for ALA was confirmed when episodes of distal numbness, paresthesias, weakness, and visual blurring in a 6-year-old girl on total parental nutrition were successfully treated when a lipid preparation devoid of ALA was replaced with one containing ALA (Holman et al. 1982). The levels of ALA to ameliorate these symptoms were estimated to be 0.54 % of energy. While ALA is considered to be the essential *n*-3 PUFA in the diet (in classical terms for essentiality), its downstream metabolite, docosahexaenoic acid (DHA), is considered to be the biologically essential *n*-3 PUFA because it is found in appreciable amounts in all membranes and it is particularly essential in the retina and brain (as reviewed by Brenna et al. 2009).

ALA is the simplest *n*-3 fatty acid and is the parent compound and metabolic precursor for all other *n*-3 PUFA (Fig. 7.1). When consumed by humans, it is converted to stearidonic acid (SDA) with the addition of a double bond at the C-6 position catalyzed by Δ6-desaturase, the rate-limiting step in this metabolic pathway. Eicosapentaenoic acid (EPA) is formed following the elongation of SDA to eicosatetraenoic acid (20:4 *n*-3) with the addition of a two-carbon unit and the subsequent addition of a double bond by Δ5-desaturase. In humans, EPA is subsequently converted to DHA via a novel set of reactions previously attributed to a putative Δ4-desaturase (Sprecher 1999; Voss et al. 1991), where EPA undergoes two elongation steps [generating DPA and then tetracosapentaenoic acid (24:5 *n*-3)] followed by Δ6-desaturation (addition of a double bond) and peroxisomal β-oxidation (loss of two carbons) (Leonard et al. 2004).

Dietary recommendations for *n*-3 PUFA for Americans are designed to prevent essential fatty acid deficiency so an Adequate Intake (AI) has been established for ALA based on the median intakes in the US population (1.1 and 1.6 g/day for adult women and men, respectively) and EPA and DHA can substitute for up to 10 % of these values (Otten et al. 2006). Several nongovernment organizations including the American Heart Association and the Academy of Nutrition and Dietetics (formerly the American Dietetics Association) recommend consumption of two fatty fish meals per week, providing 450–500 mg EPA/DHA per day for healthy individuals (Kris-Etherton et al. 2002; American Dietetics Association 2007). The current intakes for EPA and DHA are estimated to be 100–200 mg/day in the US population, with DHA intakes in the adult population estimated to be 50–90 and 90–120 mg/day in women and men, respectively (Gebauer et al. 2006; Whelan et al. 2009). An RDA (recommended daily allowance) has yet to be set for any of the *n*-3 PUFA due to inadequate data to establish an estimated average requirement (EAR), the fundamental first step in establishing an RDA. Current estimates for the consumption of highly unsaturated *n*-3 PUFA in other Western countries range between 195 and 298 mg/day in Australia, 215 and 298 mg/day in Germany, and 400 and 497 mg/day in France (women and men, respectively) (Howe et al. 2006; Linseisen et al. 2003; Astorg et al. 2004).

7.2 Dietary Sources of *N*-3 PUFA

Alpha-linolenic acid is the major *n*-3 PUFA in the US diet with daily median intakes estimated to be between 1.1 and 1.6 g for women and men, respectively (Food and Nutrition Board 2005). Plant oils account for the major source in the diet where the levels range from 7 to 65 % of total fatty acids in the richest sources (Table 7.1) (Whelan and Rust 2006). While ALA content in a number of plant oils exceeds 50 % (w/w) (i.e., flax and perilla), soybean oil and canola oil, at 7 and 10 % respectively, provide the bulk of ALA in the US diet. Although there are a number of other sources of ALA in the diet, most of these foods have relatively low levels of ALA and contribute very little to the overall intake (Hunter 1990).

Stearidonic acid (SDA) is formed metabolically from ALA with the addition of a double bond at the Δ6-position and is found almost exclusively in certain plants that are not commonly consumed. Echium oil, at 4–9 % (w/w), is one of the richest sources, followed by black currant seed oil (at ~3.4 %) (Whelan and Rust 2006). Most commonly used vegetable oils do not contain SDA, but novel SDA-containing oils (>20 %) derived from rapeseed and soybean have been developed (Ursin 2003; Froman et al. 2009; Lemke et al. 2010).

Table 7.1 Alpha-Linolenic acid content of selected vegetable oils

Oil	Alpha-linolenic acid content (g/100 g of oil)
Perilla	54–65
Linseed	50–54
Flaxseed	53
Modified Canola	22–44
Cohni	5.9–14.5
Canola	9–11
Wheat germ	6.9
Soybean	6.8

From Whelan and Rust (2006)

7.3 Biochemistry and Nutritional Benefits of Omega-3 Fatty Acids

7.3.1 Biochemistry of Omega-3 Fatty Acids and Effects on Plasma/Serum Phospholipids

In humans dietary *n*-3 PUFAs are primarily stored in the *sn*-2 position of membrane-associated phospholipids. As a metabolic precursor for the more highly unsaturated *n*-3 PUFA, ALA can theoretically modify tissue EPA and DHA levels in these pools. However, within the context of a Western diet, the extent of this conversion appears to be less than robust. Using stable isotopes, the conversion of ALA to DHA in adults appears to be <0.1 % (Brenna 2002) with virtually no changes in DHA levels in plasma/serum phospholipids following supplementation (Brenna et al. 2009). This can be clearly illustrated in Fig. 7.2, where increasing supplemented doses of ALA (0.22–32.2 g/day) to individuals consuming a Western-like background diet does not consistently change DHA content in phospholipids of plasma/serum regardless of intake (Arterburn et al. 2006; etc. Beitz et al. 1981; Brenna et al. 2009; Cunnane et al. 1993; Ezaki et al. 1999; Finnegan et al. 2003; James et al. 2003; Kelley et al. 1993; Layne et al. 1996; Li et al. 1999; Mantzioris et al. 1994; Mest et al. 1983; Seppanen-Laakso et al. 1992; Sinclair et al. 1987; Singer et al. 1986; Thies et al. 2001; Valsta et al. 1996; Wallace et al. 2003). However, dietary ALA can influence tissue levels of EPA, and these effects are more prominent when supplemented at levels of 3 g/day or higher (Fig. 7.3) (Beitz et al. 1981; Cunnane et al. 1993; Ezaki et al. 1999; Finnegan et al. 2003; James et al. 2003; Kelley et al. 1993; Layne et al. 1996; Li et al. 1999; Mantzioris et al. 1994; Mest et al. 1983; Seppanen-Laakso et al. 1992; Sinclair et al. 1987; Singer et al. 1986; Thies et al. 2001; Valsta et al. 1996; Wallace et al. 2003). Although there is some conversion of ALA to other omega-3 fatty acids in humans, the conversion of ALA to SDA and the conversion of EPA to DHA are rate limited by the activity of the Δ6-desaturase (Burdge et al. 2002, 2003; Burdge and Wootton 2002; James et al. 2003; Whelan 2009). It has been estimated

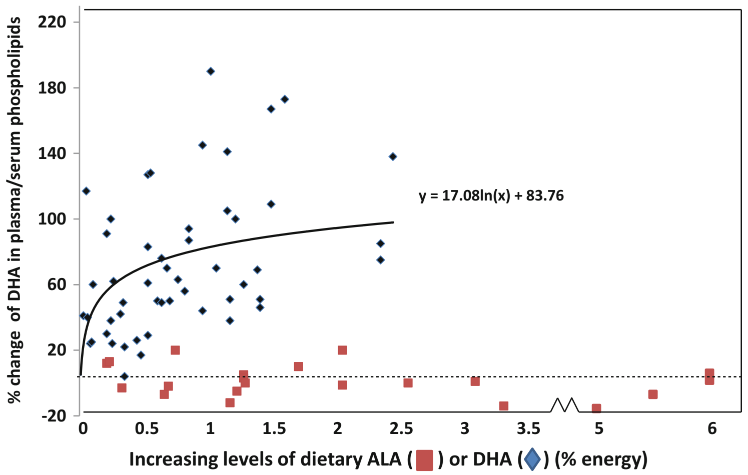

Fig. 7.2 Effect of increasing dietary alpha-linolenic acid (ALA) (*squares*) or docosahexaenoic acid (DHA) (*diamonds*) based on energy (%) on changes (%) in plasma/serum phospholipid levels of DHA. The DHA intake data was plotted based on the calculated amounts of DHA supplied in the diets (Dosing equivalence: 1 % energy = ~2.2 g)

that ALA has an "equivalency factor" of 15:1 with regard to its effects on modifying the *n*-3 PUFA content of plasma/serum phospholipids when compared to EPA (James et al. 2003).

The primary effect of dietary EPA and DHA is selectively modifying their respective pools. When pure EPA is supplemented to subjects consuming a Western diet (0.132–4.84 g/day), dietary EPA increases plasma/serum phospholipid levels of EPA in a dose–response manner, but has no impact on changing DHA content regardless of the level supplemented (Fig. 7.4) (Buckley et al. 2004; Driss et al. 1984; Grimsgaard et al. 1997; James et al. 2003; Jensen et al. 2000; Mori et al. 1999; Thies et al. 2001; Vidgren et al. 1997). Similarly, supplements of DHA (0.154–4.84 g/day) almost exclusively modify DHA levels with some impact on EPA content, particularly at very high doses [possibly via retro conversion (Plourde et al. 2011)] (Fig. 7.4) (Buckley et al. 2004; Driss et al. 1984; Grimsgaard et al. 1997; James et al. 2003; Jensen et al. 2000; Mori et al. 1999; Thies et al. 2001; Vidgren et al. 1997). Therefore, when EPA and DHA are provided in combination (i.e., fish oil), EPA in the diet enriches the EPA pool in plasma/serum phospholipids by as much as 500–600 % (Fig. 7.4). Similarly, dietary DHA can double the levels of DHA in the plasma/serum pool (Fig. 7.4) (Agren et al. 1988, 1991; Blonk et al. 1990; Buckley et al. 2004; Cerbone et al. 1999; Driss et al. 1984; Engstrom et al. 1996, 2003; Finnegan et al. 2003; Ghafoorunissa et. al. 2002; Gibney and Hunter 1993; Grimsgaard et al. 1997; Gronn et al. 1991; Hagve et al. 1993; Hodge et al. 1993; James et al. 2003; Jensen et al. 2000; Katan et al. 1997; Kew et al. 2004; Laidlaw and Holub 2003; Mantzioris et al. 1994; Mori et al. 1999; Palozza et al. 1996; Sanders and Hinds 1992; Sinclair and Mann

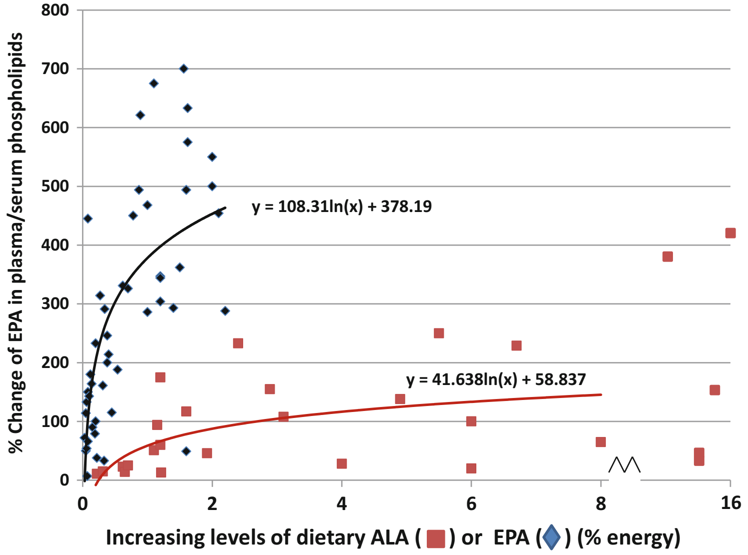

Fig. 7.3 Effect of increasing dietary alpha-linolenic acid (ALA) (*squares*) or eicosapentaenoic acid (EPA) (*diamonds*) based on energy (%) on changes (%) in plasma/serum phospholipid levels of EPA. The EPA intake data was plotted based on the calculated amounts of EPA supplied in the diets (Dosing equivalence: 1 % energy = ~2.2 g)

1996; Sinclair et al. 1987; Stark et al. 2000; Thies et al. 2001; Vidgren et al. 1997; Vognild et al. 1998; Von et al. 1985; Wallace et al. 2003; Wensing et al. 1999).

Bypassing the Δ6-desaturase step appears to facilitate the conversion of 18-carbon *n*-3 PUFA to EPA. When SDA enters the metabolic pathway after this rate-limiting step, it is effectively converted to EPA resulting in the enrichment (up to fivefold) of the EPA pool in a variety of cells and tissues, such as plasma, heart, neutrophils, and erythrocytes (Harris et al. 2007; James et al. 2003; Miles et al. 2004; Surette et al. 2004). When compared to dietary EPA, dietary SDA appears to have ~20–25 % equivalency (5:1) with respect to modifying tissue EPA levels (Lemke et al. 2010; Harris et al. 2008a, b; James et al. 2003) A clinical study performed by Krul et al. (2012) demonstrated that as little as 1.3 g SDA/day resulted in a significant increase in red blood cell EPA levels. However, as observed with ALA and EPA, dietary SDA has little effect on tissue DHA content (James and Ursin 2003; Miles et al. 2004; Surette et al. 2004). This is not surprising since one of the final steps in the formation of DHA involves the rate-limiting step Δ6-desaturase.

Arachidonic acid (AA) is arguably the most important PUFA in membrane phospholipids. When released by a variety of phospholipases, AA can be oxidized to a plethora of bioactive lipids called eicosanoids. When produced in elevated and chronic amounts, these compounds are believed to be involved in contributing to a variety of chronic diseases, such as cardiovascular disease, inflammation, and cancer and it is believed that modulating tissue levels of AA may be important in

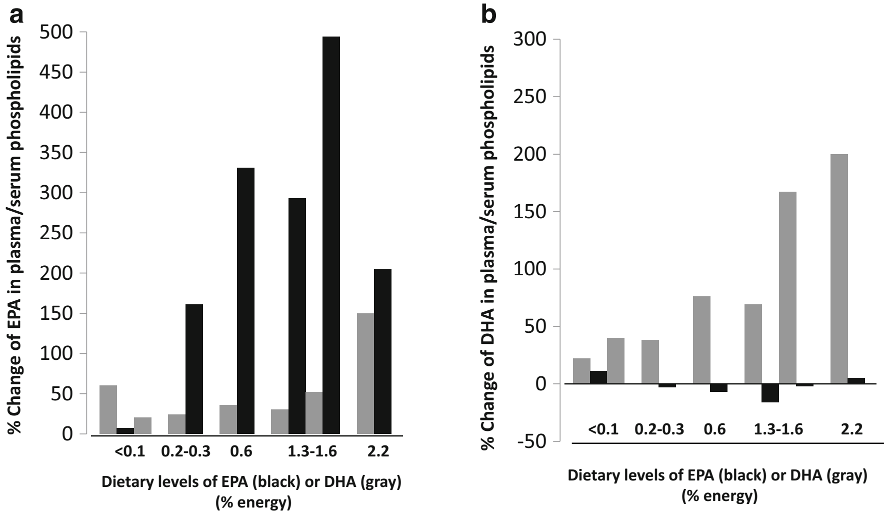

Fig. 7.4 Effect of increasing dietary eicosapentaenoic acid (EPA) (*black bar*) or docosahexaenoic acid (DHA) (*gray bar*) based on energy (%) on changes (%) in plasma/serum phospholipid levels of EPA (**a**) or DHA (**b**). In each case, EPA or DHA was the only *n*-3 PUFA supplemented to individuals (Dosing equivalence: 1 % energy = ~2.2 g)

regulating the formation of these compounds (Whelan and McEntee 2004). Dietary EPA and DHA appear to potently modify tissue levels of AA with equal effectiveness. When supplemented to the diet they can reduce AA content in plasma/serum phospholipids by up to 25 % and these effects are observed at relatively low doses (Fig. 7.5) (Buckley et al. 2004; Cerbone et al. 1999; Engstrom et al. 2003; Finnegan et al. 2003; Gibney and Hunter 1993; Grimsgaard et al. 1997; Gronn et al. 1991; Hodge et al. 1993; Kew et al. 2004; Layne et al. 1996; Mori et al. 2000; Rambjor et al. 1996; Sanders and Hinds 1992; Sinclair et al. 1987; Singer et al. 1986; Stark et al. 2000; Thies et al. 2001; Vidgren et al. 1997; Von et al. 1985; Vognild et al. 1998; Wallace et al. 2003). Similar effects can be observed with dietary ALA, but this usually requires relatively high levels in the diet (Fig. 7.6) (Beitz et al. 1981; Cunnane et al. 1993; Ezaki et al. 1999; Finnegan et al. 2003; James et al. 2003; Kelly et al. 1998; Layne et al. 1996; Li et al. 1999; Mantzioris et al. 1994; Mest et al. 1983; Sanders and Hinds 1992; Seppanen-Laakso et al. 1992, 1993; Singer et al. 1986; Thies et al. 2001; Valsta et al. 1996; Wallace et al. 2003).

7.3.2 *Omega-3 PUFA and Cardiovascular Disease*

Cardiovascular disease, like many chronic diseases, involves multiple steps and is influenced by multiple mechanisms. A key feature in the disease process is the

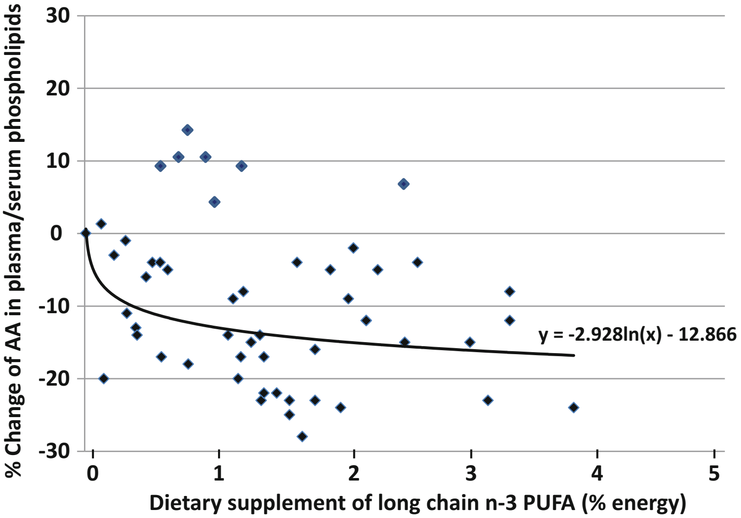

Fig. 7.5 Effect of increasing dietary eicosapentaenoic acid + docosahexaenoic acid (EPA + DHA) based on energy (%) on changes (%) in plasma/serum phospholipid levels of arachidonic acid (AA) (Dosing equivalence: 1 % energy = ~2.2 g)

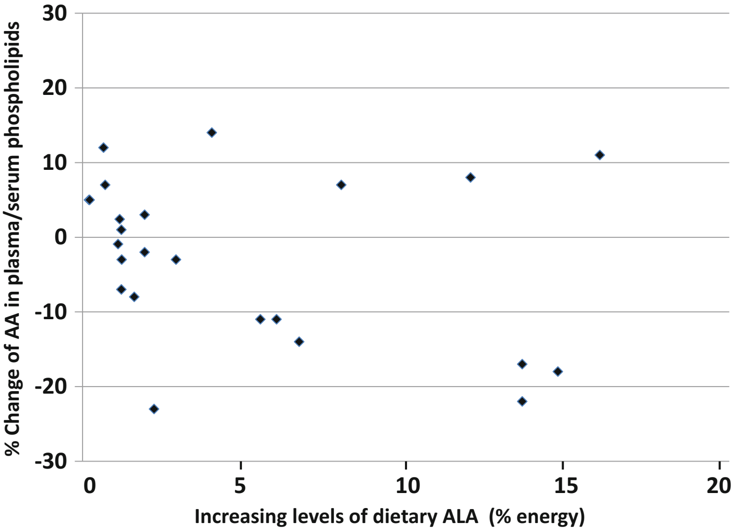

Fig. 7.6 Effect of increasing dietary alpha-linolenic acid (ALA) based on energy (%) on changes (%) in plasma/serum phospholipid levels of arachidonic acid (AA) (Dosing equivalence: 1 % energy = ~2.2 g)

modification of the LDL particle (Steinberg and Witztum 2010), followed by an inflammatory response localized within the intima of blood vessels involving a condominium of activated cells, such as platelets, lymphocytes, leukocytes, and vascular smooth muscle cells (Libby 2008a). The process begins with alterations in endothelial cell function (many times involving elevated LDL cholesterol levels) and the modification of LDL particles which initiates a cascade of events [as reviewed in Libby (2008a) and Libby and Theroux (2005)]. Endothelial cells express cell surface adhesion molecules as mediated by proinflammatory cytokines, and in the presence of a number of chemokines, attract T-cells and monocytes to the intima. Modified LDL is cleared by activated macrophages via a scavenger receptor-mediated process. The localized inflammatory response is believed to lead to the formation of complicated lesions. Smooth muscle cells migrate (influenced by platelet-derived growth factor) from the tunica into the intima producing connective tissue, stabilizing the advanced plaque. Disruption of the protective fibrous cap by a variety of collagenases in the matrix metalloproteinase family can contribute to erosion and cap rupture and thrombosis (Alvarez et al. 2004). Most fatal coronary events involve thrombotic complications associated with plaque disruption, so stabilization of the fibrous cap is critical (Libby 2008b).

Highly unsaturated *n*-3 PUFAs have been shown to be cardioprotective (Breslow 2006). Their mechanisms of action interfere with the atherogenic process and disruption of the fibrous cap (Massaro et al. 2010). *N*-3 PUFA can reduce circulating triglycerides (Balk et al. 2006), a known risk factor for cardiovascular disease (Harchaoui et al. 2009). They are antagonists to the proinflammatory eicosanoids derived from AA by competing with AA for incorporation into membrane phospholipids and subsequent metabolism by cyclooxygenases and lipoxygenases. Their positive effects include inhibition of leukocyte recruitment, platelet activation, smooth muscle cell proliferation, inhibition of proinflammatory cytokines (i.e., IL-6, IL-1Ra, TNF-α, CRP), increases in anti-inflammatory biomarkers (i.e., TGF-β and IL-10) with increases in nitric oxide production, and vasodilatation (Engler and Engler 2006; Farzaneh-Far et al. 2009; Ferrucci et al. 2006). When individuals consumed an *n*-3 PUFA supplement (EPA + DHA), the levels of EPA in plaque were inversely correlated with plaque instability, inflammation, and the number of T-cells. Plaque from patients who received *n*-3 PUFAs had significantly lower levels of mRNA for matrix metalloproteinases, intercellular adhesion molecule-1 (ICAM-1; endothelial cell adhesion molecule), and the cytokine IL-6 (Cawood et al. 2010). Phospholipid EPA content was inversely associated with monocyte-derived TNF-α and IL-1β (Calder 2006). This cardioprotective relationship for EPA was observed in a large-scale clinical trial examining the effects of EPA on risk of coronary heart disease in individuals with hypercholesterolemia (Japan EPA Lipid Intervention Study: JELIS) (Yokoyama et al. 2007). Remarkably, significant reductions in major coronary events occurred in the EPA-supplemented group despite the fact that this was a high fish eating population also receiving statin therapy for their elevated cholesterol levels. These studies demonstrate that cardioprotective effects can be observed with EPA alone, in addition to supplementation of EPA + DHA.

The major cause of death from cardiovascular disease is the result of sudden death. These events are mediated by atherothrombosis, such as myocardial infarction and ischemic stroke, and arrhythmias (Christensen 2003; Kang and Leaf 2000; Leaf et al. 2003a, b; Libby 2008a; Mozaffarian et al. 2004). Proposed mechanisms have involved stabilization of the fibrous cap via downregulation of matrix metalloproteinases and fibrinolysis. Ventricular fibrillation is of particular importance and it has been estimated that for each 1 % rise in the levels of EPA + DHA in red blood cells (as measured by the omega-3 index; see next section) there is a 58 % reduction in the risk of ventricular fibrillation in individuals who had suffered a sudden cardiac event (Aarsetoey et al. 2011). Increasing resting heart rate is also positively associated with sudden death and resting heart rates were significantly reduced in 18 individuals supplemented with 0.8 g/day of EPA + DHA for 4 months (Kannel et al. 1985).

7.3.3 *Omega-3 Index*

It is the level of incorporation of EPA and DHA in tissue phospholipids, along with their competition with AA, that is critical for many of the beneficial effects observed with *n*-3 PUFAs. Those *n*-3 PUFAs with the highest ability to alter tissue levels of EPA and/or DHA (i.e., SDA, EPA, and DHA) are also the most efficacious in driving down AA content and creating a more favorable *n*-3 to *n*-6 ratio of highly unsaturated fatty acids in tissues.

A new important biomarker for cardiovascular disease risk is the omega-3 index, the sum of EPA + DHA in erythrocyte membranes expressed as a percentage of total erythrocyte fatty acids (Harris and Von 2004). The index is inversely correlated with risk of a variety of cardiovascular disease endpoints that is as good as or better than more traditional biomarkers (i.e., C-reactive protein, LDL cholesterol, etc.) and is an important indicator for cardioprotection. Increasing the omega-3 index has been inversely associated with risk of sudden death, primary cardiac arrest (Harris 2010), and ventricular fibrillation (Aarsetoey et al. 2011).

The major dietary fats influencing the omega-3 index are highly unsaturated *n*-3 fatty acids. In side-by-side experiments, evaluating the impact of dietary ALA, SDA, and EPA on the omega-3 index, SDA and EPA were much more effective than ALA, which had no effect (Harris 2008). Relative to EPA, SDA was 17 % as effective in increasing the omega-3 index (Lemke et al. 2010; Harris et al. 2008a, b). Figure 7.7 shows the impact of ALA, EPA, and SDA consumption on the omega-3 index. At a level of 4.2 g SDA supplementation per day the omega-3 index increase observed is statistically equivalent to 1 g EPA supplementation per day. The omega-3 index in the Western population is estimated to be 4.9 % with the desired level of 8.0 % for ideal risk reduction (Aarsetoey et al. 2011; Sands et al. 2005). The American Heart Association recommends the consumption of

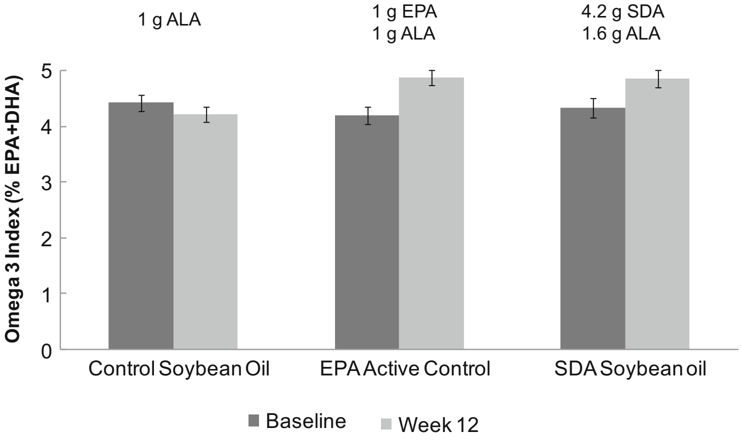

Fig. 7.7 Baseline and posttreatment omega-3 index results for three omega-3 treatments. *Bar graphs* represent the mean (±SEM) for per protocol population of 157 subjects; $*p < 0.001$ compared to soy oil control; SDA and EPA not different $p = 0.585$; ANCOVA (Lemke et al. 2010; Harris et al. 2008a, b)

two servings of fatty fish per week as part of a heart healthy diet (Kris-Etherton et al. 2002). This level would provide an individual ~500 mg of EPA + DHA per day, shifting the omega-3 index above 6.0 (Sands et al. 2005), resulting in an estimated reduction in cardiovascular disease risk of >30 % (Harris et al. 2008a, b).

7.4 Marine Sources of Omega-3 Fatty Acid

7.4.1 Accumulation of Omega-3 Fatty Acids in Fish

Omega-3 fatty acids are normal constituents of all organisms and essential dietary nutrients for fish (NRC 2011). In nature, omega-3 fatty acids are synthesized by algae which are consumed by zooplankton and bioaccumulate through the food chain to fish. Fish cannot synthesize omega-3 fatty acids and must have a dietary source to survive (NRC 2011). Freshwater species and salmonids can convert ALA to long-chain polyunsaturated fatty acids (LC-PUFAs) of the omega-3 family, specifically EPA and DHA, but the efficiency of conversion is relatively low (Tocher 2003). The marine environment is rich in LC-PUFA containing foods and marine ingredients derived from marine resources, such as fish meal, fish oil, or products recovered from seafood processing by-products, are the main sources of LC-PUFAs in feeds for farmed fish. The freshwater environment is also a source of LC-PUFA containing foods, with algae being the primary source. However, the freshwater environment is not as rich in LC-PUFAs as the marine environment. Freshwater fish species, such as carp, tilapia, or catfish, do not require LC-PUFAs in the feed when raised under commercial conditions, although they likely require small amounts of LC-PUFAs in the diet (NRC 2011). This sounds contradictory, but many warmwater fish species are reared in ponds where substantial natural food production occurs. Fish derive some nutrients from pond organisms and this is sufficient to meet their requirements for LC-PUFAs. Salmonids, in contrast, require omega-3 fatty acids in the diet, even in the freshwater phase of their life history. In nature, they derive these nutrients through the food chain down to the ultimate source of omega-3 fatty acids in freshwater, algae. Prey items such as aquatic and terrestrial insects and crustacean (Cladocerans, copepods, and *Daphnia* sp.) are rich sources of EPA for salmonids in freshwater (Higgs et al. 1995). Freshwater culture of salmonids takes place in flowing water, not ponds, and natural food (prey) is essentially absent. Salmonids at this life history stage require 1–1.5 % LC-PUFAs in their feed to prevent clinical deficiency (NRC 2011). However, the dietary amount of LC-PUFAs needed to prevent clinical deficiency signs in farmed salmonids is substantially lower than the amount required to reach LC-PUFA levels typically found in wild salmon. In other words, dietary LC-PUFA levels required to produce fillets containing amounts of EPA and DHA to provide healthful benefits to consumers are much higher than that required to prevent deficiency.

7.4.2 Nutritional Aspects of Ocean vs. Farmed Fish

There are over 1,300 species of fish harvested from the ocean for human consumption and about 250 species of fish produced through aquaculture, of which 180 are marine species (Duarte et al. 2009). There is tremendous diversity among wild species in habitat, prey items, and LC-PUFA levels in various fish tissues. Nevertheless, some generalizations can be made to categorize and predict LC-PUFA levels in edible fish tissues, e.g., fillets. High-value wild-caught marine species are nearly all carnivores whereas freshwater species can be divided into carnivores, or more accurately piscivores, and omnivores. Since farmed species are simply domesticated wild species, the same categorization holds for farmed species. Fish can be further divided into species that store substantial amounts of lipid in fillets (muscle) and those that store lipid in the liver, with relatively low amounts of lipid in fillets. Species that undergo long migrations, such as salmon and tuna, store lipid in muscle. Species that undergo seasonal variability in food supply, such as freshwater fish in temperate or sub-Arctic regions, store more lipid in tissues than do fish living in areas where food abundance is less variable through the seasons. The liver is the main lipid storage depot in many marine fish species. Finally, farmed fish typically contain more lipid than wild fish of the same species because food (feed) is always abundant for farmed fish and they do not have to expend energy searching for food and avoiding predators. Lipid levels in fish tissues are important when comparing omega-3 fatty acid levels among fish species or between wild and farmed fish of the same species because although fatty acid levels are typically expressed on a percentage lipid or tissue basis, consumers eat portions of fish and thus quantities (mg) of omega-3 fatty acids, not percentages.

Another important determinate of lipid and fatty acid levels in fish tissues is the fatty acid profile of food or prey. Both lipid and fatty acid levels of prey items vary with season. The fatty acid profile of fish closely reflects the fatty acid profile of the diet. Some fatty acids are preferentially metabolized for energy while others are preferentially retained in tissues. However, under conditions of food sufficiency where metabolic energy demands are met, the fatty acid profile of fish tissues closely resembles that of their food. This is the case for farmed fish.

Omega-3 fatty acids levels of fish differ among marine carnivorous species, freshwater carnivorous species, and freshwater omnivorous species. Differences are associated with differences in dietary fatty acid intake and also with differences in fatty acid metabolism, e.g., ability to elongate and desaturate ALA to EPA and DHA (Tocher 2003). As mentioned above, marine fish lack this ability. Salmonids (trout and salmon) also have the ability to convert ALA to DHA but not at rates sufficient to meet their needs for maximum growth (Wirth et al. 1997). The biosynthetic pathway for conversion of ALA to EPA and DHA is known and involves the enzymes Δ6 and Δ5-desaturase and elongase (Tocher 2003). Freshwater fish and salmonids consume a variety of insects and plant materials that contain ALA and SDA. The diets of marine fish contain EPA and DHA in abundance. Consequently, marine fish lipids are rich in these fatty acids, in contrast to lipids in freshwater species. Juvenile salmonids are an exception to this generalization; their tissues are relatively rich in LC-PUFAs despite the fact that they live in freshwater.

7.4.3 *Supply Issues of Ocean vs. Farmed Fish: Overfishing of Oceans and Its Affects on Long-Term Sustainability and Food Security of the Global Fishing Industry*

Global marine fish landings increased steadily throughout the period between 1950 and 1990, but have not increased since, holding steady at about 80 million metric tons (mmt) [Food and Agriculture Organization (FAO) (2010)]. During this period, the proportion of marine stocks considered to be underexploited or moderately exploited decreased from over 40 to 15 % while those considered overexploited, depleted, or recovering increased from less than 10 to 32 % (FAO 2010). Stocks considered fully exploited remained constant at about 50 %. Landings comprise food fish (~70 % of total) and industrial fish (~30 % of total), the latter term referring to species of fish that are not consumed directly but rather used to produce industrial products, mainly fish meal and fish oil. Fish oil is a coproduct of fish meal production. The global fish supply was estimated to be 17.2 kg per capita in 2009 from all sources (freshwater and marine capture plus aquaculture), excluding China which was omitted when it was discovered that production from China had been over reported by a significant amount for years (FAO 2010). Removing industrial fish from marine landings left 52.3 mmt for direct human consumption in 2009, plus an additional 10.1 mmt from freshwater landings. Aquaculture, by comparison, produced 55.1 mmt. Given the status of most marine fish stocks, increased production from capture fisheries is unlikely. To maintain per capita fish consumption for the increasing global population, higher production from aquaculture will be required (Duarte et al. 2009).

Global landings of industrial fish have ranged from 27 to 32 mmt since the late mid-1980s, although in El Niño years global landings decline by several mmt and so does production of fish oil and fish meal. About ten marine fish species make up the bulk of industrial fish harvested to produce fish meal and oil. Over the past decade, global fish oil production averaged slightly over 1,000,000 mt per year, ranging from as high as 1,128,000 mt to as low as 810,000 mt in an El Niño year that lowered landings of Peruvian anchovy (*Engraulis ringens*). Collapse of specific fish stocks, such as capelin (*Mallotus villosus*) in the North Atlantic and the Japanese sardine (*Sardinops melanostictus*) in Japan, also affects fish oil production, often for years. The collapse of Japanese sardine stock populations in the late 1990s occurred naturally as a result of changes in oceanic conditions and/or competition with other species that affected spawning and recruitment success (Oozeki 2000). Fishing pressure was not the primary driver of this population crash; the Japanese sardine population experienced a similar crash in the 1930s in the absence of strong fishing pressure. However, sustained overfishing can dramatically reduce stock abundance and subsequent landings. For example, landings of anchovy for reduction to fish oil and fish meal in Peru increased rapidly in the 1980s as a result of investment in fish meal processing, reaching a peak of 10.9 mmt in 1993. This resulted in a decline in population abundance and landings. In the last decade, the Peruvian anchovy fishery has been increasingly regulated to reduce catches to sustainable levels (Hardy and Shephard 2009) and is considered fully exploited (FAO 2010). In recent years, landings have averaged about 6.5 mmt. Peruvian anchovy landings account for about 25 % of global landings of industrial fish, so any change in landings of this species affects total global landings and annual fish oil production accordingly. Historically, industrial fish have been considered unsuitable for human consumption. However, efforts are being made to increase direct consumption of such fish to increase food security in some countries. If this tendency takes hold, the amount available to produce fish oil and fish meal will decrease.

Fish oil is also recovered from seafood processing by-products. In Alaska, for example, landings from wild harvests average 2.43 mmt per year. Of that quantity, approximately 54 % is used to produce food for direct consumption, leaving 46 % or 1.12 mmt of processing by-product (Bimbo 2008). Approximately 22,000 metric tons (mt) of fish oil could be recovered from this material, assuming a 2 % recovery of fish oil. In fact, a proportion of this oil is already recovered. Some is used for direct human consumption (fish oil capsules), some is sold for use in fish feeds, and the rest is actually burned for energy because it is worth more as a fuel source in remote locations than as a feed ingredient. An underutilized potential source of fish oil may be processing by-product from farmed fish. Taking salmon as an example and assuming 45 % of the wet weight of salmon ending up as processing by-product, global production of salmon at 1.56 mmt in 2007 would result in about 0.7 mmt of processing by-product. If 2 % oil was recovered from this material, it would yield 14,041 mt of fish oil. Higher recovery would yield more fish oil. Although this amount of fish oil is small in relation to total global production, recovery from processing by-products of other farmed fish species could contribute more to total available fish oil.

7.4.4 Beneficial Aspects of Aquaculture on Sustainability and Food Security

Aquaculture production, excluding plants, increased from less than 1 mmt in the early 1950s to 52.5 mmt in 2008, an annual growth rate of 6.6 % (FAO 2010). Most production occurs in Asia (89 %), with China the dominant producer (62 %). As mentioned above, aquaculture production must increase to maintain the current per capita fish supply since landings from capture fisheries are unlikely to increase. However, recent growth rates of aquaculture are highly variable among countries, suggesting that future growth of aquaculture faces barriers. In some countries or regions, aquaculture production is increasing (China, the eastern Mediterranean, Africa) while in Europe and North America, annual growth is only 1.2 %. Part of this can be attributed to the high cost of production and to the strict regulatory environment in Europe and North America. Freshwater availability is another potential barrier to increased aquaculture production, making expansion of marine aquaculture the most likely means by which increased production can occur.

Aquaculture has made significant progress in addressing sustainability issues associated with feeds containing high levels of fish meal and fish oil, both finite global resources. Most species of farmed marine fish, including salmonids, are piscivores requiring high dietary protein levels for optimum growth and health. Fish meal provides the ideal amino acid profile for use in fish feeds compared to alternative proteins from grains, oilseeds, or land animal proteins. Until relatively recently, fish meal was the primary protein source used in fish feeds and fish oil was the primary lipid source. Use levels in feeds were high, leading some to predict that by 2010, aquaculture feeds would utilize total annual production of these products (Naylor et al. 2000). However, use levels in feeds have progressively declined over the past decade, primarily due to rising prices for fish meal and fish oil but also due to increased knowledge of the nutritional qualities of alternatives and experience with their use (Naylor et al. 2009). Aquaculture uses a larger percentage of annual fish oil production than fish meal production, making fish oil a more critical ingredient to replace in fish feeds than fish meal. Replacements for fish meal include protein concentrates from grains, oilseeds, and legumes and for fish oil include rapeseed, linseed, soybean, and palm oils. Fish do not have a dietary requirement for fish meal and fish oil, per se, but require the dietary nutrients these ingredients contain (NRC 2011). Thus, as knowledge increases on nutritional requirements of farmed fish species, optimum balances of dietary nutrients, availability of nutrients from alternative ingredients, optimum processing of ingredients and feeds to inactivate antinutrients, dietary supplements to counteract antinutrients and release nutrients from alternative ingredients, and optimum feed formulations to support high fish growth performance, sustainability of aquaculture, at least from the feed input side, will increase further.

7.4.5 Variation in Omega-3 Fatty Acid Levels Across and Within Fish Species

Omega-3 fatty acid levels in fish vary with species, a consequence of diet and fatty acid metabolism, particularly lipid storage. The fatty acid profiles of many marine fish species are relatively constant throughout the year, except after spawning when whole-body lipid levels are generally at their lowest because during maturation, tissue fatty acids are transferred to the developing ovaries. Egg fatty acids are a combination of triglycerides and phospholipids, the latter being higher in omega-3 fatty acids than the former. To protect stocks, fishing is often restricted during spawning. Because fillet quality is low after spawning, fishing focuses on periods when fish have recovered from spawning. The effects of maturation on farmed fish are not a factor driving omega-3 fatty acid levels since fish are harvested before they begin to mature. Omega-3 fatty acid levels in wild-caught species having relatively low lipid levels in fillets, such as Alaska pollock (*Theragra chalcogramma*), are about 0.2–0.3 g omega-3 fatty acids per 100 g serving (Table 7.2). Salmonids, sablefish (*Anoplopoma fimbria*), and members of the tuna family (tunas, albacore, mackerel) are notable exceptions to the general observation that the lipid and omega-3 fatty acid levels in fillets of marine fish are generally below 0.5 g per 100 g serving.

Pacific salmon have an anadromous life history, living in freshwater as fry and juveniles, spending most of their life in the ocean and returning to freshwater to spawn. Pacific salmon undertake lengthy marine migrations, starting at the mouth of their natal river system as juveniles and ending back at the same place as maturing adults, followed by an upstream migration to spawning areas which may be a few miles or over a thousand miles, depending on the river and species and population of salmon (Groot and Margolis 1991). Salmon may spend less than 2 years in the ocean, e.g., pink salmon (*Oncorhynchus gorbuscha*), or up to 6 years for chinook salmon (*O. tshawytscha*). There is a great deal of plasticity in life history of Pacific salmon, except for pink salmon which have a 2-year life cycle. Further, the natural prey of some species of Pacific salmon, e.g., pink and sockeye salmon (*O. nerka*), is mainly zooplankton or krill. Other Pacific salmon species (chinook, coho salmon, *O. kisutch*, and chum salmon, *O. keta*) consume a variety of

Table 7.2 Lipid and omega-3 fatty acid content in fillets of selected marine fish species (wet-weight basis)

Species	Lipid content (%)	Omega-3 fatty acid content (%)
Atlantic cod (*Gadus morhua*)	0.67	0.20
Halibut (*Hippoglossus hippoglossus*)	1.33	0.22
Sea bass (*Lateolabrax japonicus*)	2.00	0.67
Sole (*Bothidae and Pleuronectidae*)	1.93	0.29
Alaska pollock (*Theragra chalcogramma*)	0.41	0.17
Sablefish (*Anoplopoma fimbria*)	15.30	1.56
Bluefin tuna (*Thunnus thynnus*)	4.90	1.30
Skipjack tuna (*Euthynnus pelamis*)	1.01	0.27
Swordfish (*Xiphias gladius*)	6.65	0.90
Mahi-mahi (*Coryphaena hippurus*)	0.7	0.12
Mackerel, Pacific and jack (*Scomber and Trachurus* sp.)	7.89	1.56

US Department of Agriculture, National Nutrient Database http://www.nal.usda.gov/fnic/foodcomp/search/

prey, including krill, shrimp, squid, and small fish. The availability of various prey items varies with season and ocean position during migration, e.g., near-shore areas, continental shelf, or in the open ocean in the Gulf of Alaska. Lipid stores increase greatly toward the end of marine life for salmonids as they prepare for the spawning migration. It is generally at the later stage of marine life or early in the spawning migration when wild salmon are harvested for food.

Lipid and omega-3 fatty acid levels in salmon vary among species and with duration of ocean life, distance of spawning migration, and natural food preference, which is also associated with season and with location (Table 7.3). Chinook salmon migrate the greatest distance upstream of the five salmon species and consequently have the highest lipid content of Pacific salmon, averaging 11.5 % but ranging from 2.2 to 19.0 %. However, not all chinook salmon migrate great distances; this depends on the stock and river system and accounts for the wide variation in total lipid content in this species. Chum salmon, in contrast, spawn in lower tidal reaches of rivers and have the lowest lipid level, averaging 4.3 % (Sidwell et al. 1974). Omega-3 fatty acid levels in Pacific salmon range from 0.3 to 3.1 %, on a wet weight basis (Hardy and King 1989).

Freshwater farmed fish species have relatively low levels of fillet lipid and omega-3 fatty acids. Tilapia, for example, contain only 1.7 % lipid and 0.167 % omega-3 fatty acids in fillets. Catfish have higher fillet lipid levels than tilapia, 5.9 %, but only 0.14 % omega-3 fatty acids. Rainbow trout are an exception among farmed freshwater fish species, having 6.2 % lipid and 0.88 % omega-3 fatty acids which are primarily derived from high fish meal and fish oil levels in feeds. Trout store lipid in muscle tissue similar to salmon, whereas most freshwater fish species store lipid in other body compartments.

Table 7.3 Lipid and omega-3 fatty acid content in salmon fillets

Species	Lipid content (%)	Omega-3 fatty acid content (%)
Atlantic salmon (*Salmo salar*), farmed	13.42	2.5
Chinook salmon (*O. tshawytscha*)	11.5	1.8
Coho salmon (*O. kisutch*)	5.7	1.2
Sockeye salmon (*O. nerka)*	7.5	1.1
Pink salmon (*O. gorbuscha*)	5.3	1.7
Chum salmon (*O. keta*)	4.3	0.8

Source. Hardy and King (1989)

7.4.6 Role of Aquaculture to Improve the Sustainable and Secure Supply of Omega-3 Fatty Acids

Aquaculture is both a net consumer of omega-3 fatty acids derived from fish oil by its use in feeds and the major source of LC-PUFAs in consumers' diets. The other main source of LC-PUFAs for consumers is fish oil capsules. Over the last 40 years, fish oil use has shifted from being used primarily in margarine with minor use in fish feeds to almost exclusive use in fish feeds or direct human consumption. Industrial uses have decreased to less than 4 % of annual production. Several factors are responsible for this shift. First, aquaculture production has increased since 1970 by about 7 % per year. Production of salmon and trout has increased eightfold since 1989 from approximately 250,000 mt per year to over 1,800,000 mt (Tacon and Metian 2008). Salmonids are fed high-energy feeds, with dietary energy supplied by in large part by fat sources, until recently mainly fish oil. Second, salmon and trout feed manufacturing switched in the 1990s from compression pelleting almost exclusively to cooking extrusion, producing pellets that can absorb larger amounts of fat applied after pelleting, as high as 35 % total lipid (Hardy and Barrows 2002). Compressed pellets, being denser than extruded pellets, cannot absorb as much fat or oil, with 18–20 % being the upper limit. Finally, Atlantic salmon (*Salmo salar*) became the dominant species of farmed salmon. Atlantic salmon grow rapidly and do not store large amounts of lipid in the gut when dietary lipid levels are high, in contrast to rainbow trout (*Oncorhynchus mykiss*) or Pacific salmon (*Oncorhynchus* sp.). As a result, fish oil use in feeds increased from approximately 5,000 mt 30 years ago to an estimated 774,000 mt in 2008 (Tacon and Metian 2008). The amount used in 2008 accounted for over 80 % of that year's fish oil production (De Silva et al. 2011), although, as noted above, annual production levels vary considerably and this affects calculations of the percentage of annual production used in fish feeds. However, the use level trend is clear; aquaculture feeds have been consuming a growing proportion of global fish oil production, and without some change in use levels, demand from the aquaculture feed sector will exceed annual global production. As a result, fish oil is the most limiting ingredient used in fish feeds, more so than fish meal (Naylor et al. 2009).

Given the limited world supply of fish oil and the fact that the aquaculture industry uses more than 80 % of annual production, the challenge for the aquaculture industry is to provide healthful products with suitable DHA and EPA levels using the fish oil supplies that exist. This problem is being addressed by reducing the percentage of fish oil in feeds for farmed fish and providing finishing diets high in fish oil during the final stages of production to increase LC-PUFA levels in fillets (Rosenlund et al. 2010). Feeding rainbow trout diets containing plant oils for a portion of their rearing cycle followed by feeding a finishing diet containing fish oil reduced fish oil use by 33 % in one study (Stone et al. 2011). This work confirms earlier work (Bell et al. 2003) with Atlantic salmon. Studies with gilthead seabream (*Sparus aurata*) demonstrate that omega-3 levels in fillets can be predictably restored by feeding diets containing marine oils prior to harvest (Fountoulaki et al. 2009; Izquierdo et al. 2005). There is little turnover of fatty acids in fish tissues under normal rearing practices, so changes of omega-3 levels in fish tissues follow a simple dilution model (Jobling 2003). However, fish oils produced from different species of industrial fish differ in fatty acid profile and LC-PUFA levels (Oliveira et al. 2008).

Alternative sources of LC-PUFAs, e.g., dried marine algae meals, are now too expensive to consider in aquaculture feeds. Efforts to increase LC-PUFA levels in farmed fish fillets by feeding oils rich in ALA, such as linseed, echium, and camelina oils, have resulted in elevated tissue ALA levels but not in substantially higher tissue EPA and DHA levels (Tocher et al. 2010). The first step in converting ALA to EPA in fish species involves desaturation to produce C18:4 *n*-3 (SDA), and this step is generally considered to be the rate-limiting step, similarly to humans. Therefore, supplying SDA to farmed fish should be more effective than supplying ALA as a means to increase tissue EPA levels. SDA-rich oils include those derived from echium, buglossoides oil, and genetically modified soy (Tocher et al. 2010). However, feeding trials with fish so far have shown contradictory results (Bharadwaj et al. 2010; Miller et al. 2008).

Tacon and Metian (2008) estimated that global fish feed production was 34.65 mmt in 2010, and 770,000 mt of fish oil was used in these feeds, an average inclusion of 2.2 %. Carp, catfish, and tilapia feeds contain little if any added lipid, generally less than 2–3 %, and no added fish oil. Salmon feeds, in contrast, range from 18 % to as high as 35 % lipid; high lipid levels are used in feeds for grow-out salmon reared in marine pens. To achieve such high lipid levels requires more than 25 % added oil. Feeds for salmon fry and fingerlings raised in freshwater contain lower levels of total lipid. Total salmon feed production in 2010 was estimated to be 2,226,000 mt (Tacon and Metian 2008). If fish oil had been the sole added lipid source in salmon feeds in 2010, total fish oil use would have been 556,500 mt (Naylor et al. 2000). However, fish oil used in salmon feeds in 2010 was estimated to be 267,100 mt, approximately half of the total lipid added to feeds. Other lipid sources made up the difference. Nevertheless, salmon feed use accounted for over 35 % of total fish oil use in all fish feeds in 2010, despite the fact that salmon production accounted for slightly less than 7 % of total finfish production in the aquaculture sector. Marine fish, shrimp, and trout accounted for 22, 19, and 11 %, respectively.

Retention of dietary omega-3 fatty acids in fillets of farmed salmon-fed diets containing fish oil throughout the rearing cycle is relatively low, about 18 %. Fillet yield for salmon for skinless, boneless fillets is 36 % and this accounts for a significant portion of the yield value loss. Lipid retention in fillets is about 24 %.

7.5 Challenges with Consuming More Omega-3 PUFAs

The Dietary Guidelines for Americans (United States Department of Agriculture/ Health and Human Services 2010) recommend Americans more than double their intake of seafood. While these recommendations appear reasonable, there are several challenges that have to be overcome. In 2004, the Food and Drug Administration (FDA) issued an advisory for women who are, or might, become pregnant, nursing mothers, and young children to consume no more than 12 oz of fish per week (6 oz for albacore tuna). They are to completely avoid shark, swordfish, king mackerel, and tilefish because they contain high levels of mercury (Environmental Protection Agency/Food and Drug Administration 2004). For all other individuals, it has been recommended that the benefits of fish consumption outweigh the risks (Lichtenstein et al. 2006); however, there are additional challenges getting the population to eat more fish, real or imaginary, such as the continuing concern over seafood safety due to exposure to heavy metals and other environmental toxins, shelf life (oxidation), and palatability ("fishy" smell or taste) (Racine and Deckelbaum 2007). One potential solution is increasing the commercial development of commonly consumed foods that are fortified with fish oils (Whelan 2006), but availability could eventually be an issue due to the problem of overfishing (Brunner et al. 2009; McIntyre et al. 2007; Taylor et al. 2006). A potential solution is with aquaculture (farming fish), and while this is a viable alternative, there have been concerns about pollution and the spread of disease to the feral fish population (Krkosek et al. 2007; Marty et al. 2010). In addition fish require LC-PUFAs in their diet. Potentially omega-3-rich algal oils could fill this gap. However algal oils are currently not economically competitive. Generating a land-based plant source rich in highly unsaturated *n*-3 fatty acids could relieve some of the burden placed on the fishing industry. Efforts have been made in this area with the development of SDA-rich soybean and canola oils (Lemke et al. 2010; Ursin 2003) and the production of algal oils rich in DHA. New oils such as SDA soybean oil could overcome shelf life and palatability issues, providing consumers additional means to increase long-chain omega-3 intake.

7.6 Plant Sources of Omega-3 Fatty Acids: Alpha-Linolenic Acid

7.6.1 Flax

Flaxseed is an important oilseed crop because of its high content of ALA, lignans, and fiber. It has been cultivated on over 2.6 million ha with primary growing countries Canada, China, Ethiopia, India, and the United States. Canada is the world's largest producer of flax and accounts for nearly 80 % of the global trade in flaxseed (Singh et al. 2011). With recognition of the importance of dietary omega-3 fatty acids, there is growing use of flaxseed and its oil in food products for humans and animals. Generally, the oil is obtained by cold pressing or by extraction with supercritical carbon dioxide. With its high concentrations of ALA, flax oil readily oxides and polymerizes, and can have flavor and shelf life impact on food made from the oil (Gunstone 2006). Flaxseed typically contains from 35 to 45 % oil, with a typical ALA content of 45–52 % (Singh et al. 2011). This can vary depending on specific cultivars. Commercial supplies of flaxseed oil can contain up to 70 % ALA (Polar Foods 2012).

Flaxseed has been incorporated into diets for many centuries, historically used as a laxative due to its high levels of soluble and insoluble fiber.

In addition to fibers and beneficial fatty acids flax contains lignans, a group of phytochemicals that have been linked to beneficial impacts on various forms of cancer such as breast, colon, and prostate cancer (Landete 2012). Landete (2012) reported there are several possible mechanistic explanations for the observed bioactivities, including involvement in hormonal metabolism or availability, angiogenesis, anti-oxidation, and modulation of gene expression.

7.6.2 Food Application and Sensory Impact of Flax

Flax and other sources of ALA have found increased use in foods as a source of omega-3 fatty acids. However, the high levels of ALA, which is susceptible to oxidation, result in reduced flavor stability. The addition of natural caraway seed and cinnamon essential oils has been reported to improve the oxidative stability of flax oil (Ozola et al. 2010). Oil blends containing 2 % cinnamon oil were considered most acceptable from an oxidation and taste impact perspective.

Bakery products represent a specific area of focus for the addition of whole ground flaxseed. Aliani et al. (2011) reported on the formulation of muffins and snack bars containing milled flaxseed. The muffin samples demonstrated lower sweetness, reduced vanilla taste, and significantly higher grain/flax and bitter attributes compared to the muffin without flax. A gingerbread raisin snack bar was shown to have no substantial taste and flavor differences compared to a raisin bar prepared without flax, showing promise that this recipe could be a flavoring option to mask the flavor differences found when incorporating milled flax. In a follow-up study, Aliani et al. (2012) evaluated the impact of flax incorporation on the flavor profile of bagels. Grain/flax aroma and flavor were significantly higher compared to the non-flax bagel. A cinnamon raisin bagel did not demonstrate the same degree of differences. In terms of consumer acceptability, bagels with flax showed significantly lower means for overall acceptability, flavor acceptability, and frequency of eating compared to bagels without flax. Cinnamon raisin bagels had high consumer acceptance scores.

Flax has been used to increase omega-3 levels in feed for hens. This has enabled the commercial production of omega-3 eggs. Fraeye et al. (2012) conducted a review on the dietary enrichment of eggs with omega-3 fatty acids using feed enriched with omega-3 fatty acids including flax. The data are inconsistent, showing increases in ALA content in the eggs, and in some cases enrichment of DHA. The authors reported that incorporation of more than 10 % flax in the feed resulted in the perception of eggs having fishy off-flavors and that the addition of antioxidants including vitamin E did not reduce the off-flavors originating from flaxseed supplementation.

7.7 Modified Oilseed Sources of Omega-3: Stearidonic Acid

Several efforts have been made to engineer omega-3 fatty acid production in oil seed crops. SDA accumulation was first reported in Canola (Ursin 2003) and in soybean (Clemente et al. 2003). Co-expression of the *Mortierella alpina* Δ6-desaturase and the *Brassica napus* Δ15-desaturase resulted in canola oil that contained up to 23 % SDA. Surprisingly co-expression of these two desaturases together with a third gene, the *M. alpina* Δ12-desaturase, did yield only up to 16 % SDA, suggesting that two desaturases, a Δ6 and a Δ15-desaturase, are sufficient to achieve significant SDA levels in canola oil. In the same year Clemente et al. (2003) reported on soybean expressing the borage Δ6-desaturase under the control of the seed-specific beta-conglycinin promoter. The best performing line in this experiment produced up to 5.1 % SDA. Both papers reported the accumulation of substantial levels of the omega-6 fatty GLA, between approximately 20 and 39.5 %, respectively.

Substantial progress in engineering SDA biosynthesis in soybean was made when Eckert et al. (2006) reported the co-expression of the Borage Δ6-desaturase and the *Arabidopsis thaliana* Δ15-desaturase using the beta-conglycinin promoter to drive expression of both genes. T2 beans of these plants contained up to 29.5 % SDA and 7.2 % GLA.

While SDA oils can be produced on a variety of oilseed crops, historically soybean oil has been the dominant oil for food production in the United States

(Ursin 2003). With processing capabilities and applications optimized for soybean oil, soybean-derived omega-3 oil would be expected to penetrate the market more easily.

7.7.1 Soybean Genetically Modified to Produce SDA Soybean Oil

Recently Monsanto Co. has been developing soybean that accumulates 15–30 % SDA in the oil (Ursin et al. 2005, 2006; Froman et al. 2009; Voelker and Wilkes 2011). These plants have been engineered to target the expression of two microsomal fatty acid desaturases, the *Primula juliae* Δ6-desaturase and the *Neurospora crassa* Δ15-desaturase, to the seed (George and Rogan 2010). A key feature in achieving substantial SDA levels while keeping GLA levels low was obtained through the utilization of the *P. juliae* Δ6-desaturase which prefers ALA over LA as substrate (Ursin et al. 2005; Voelker and Wilkes 2011). Utilization of LA as substrate for the Δ6-desaturase reaction results in the formation of GLA. The *N. crassa* Δ15-desaturase has the capacity to convert GLA to SDA (Fig. 7.1, data not shown). However, the substrate preference of the *P. juliae* Δ6-desaturase for ALA reduces the need for GLA conversion. In this setting the additional expression of the *N. crassa* Δ15-desaturase is needed only to increase the availability of ALA as substrate for SDA biosynthesis.

Soybean with seed-specific expression of *the P. juliae* Δ6-desaturase and the *N. crassa* Δ15-desaturase was obtained by Agrobacterium-mediated transformation of A3525 commercial soybean with a 2-T-DNA binary vector that harbored expression cassettes for the two desaturase genes controlled by the p7Sα and the p7Sα′ seed-enhanced promoters, respectively. Both expression cassettes were located on a marker-free T-DNA (Fig. 7.8) (George and Rogan 2010). Transgenic plants were obtained by selecting for the presence of the CP4 glyphosate resistance marker that was located on the second T-DNA and subsequent screening for unlinked T-DNA inserts, harboring single copy T-DNAs for the desaturase expression cassettes. Thorough molecular and biochemical screens resulted in the identification of a transformation event that contains only one copy of the expression cassette, is free of the synthetic CP4 EPSPS glyphosate tolerance selectable marker, and is free of the vector backbone DNA. This event does not harbor any identifiable genetic elements in the DNA adjacent to the T-DNA insert, and it does not encode any genes in >900 bp of the 5′- and 3′-adjacent genomic soybean DNA.

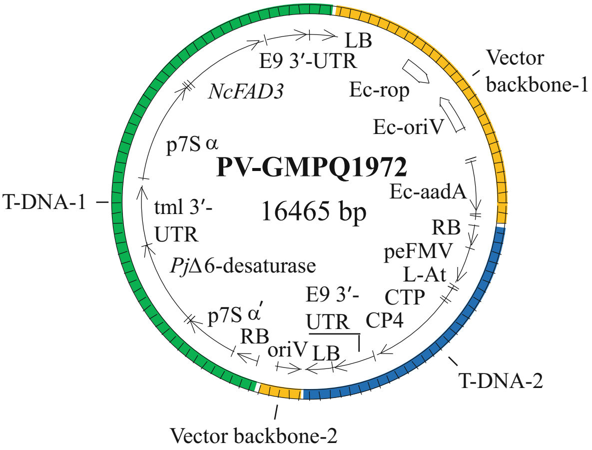

Fig. 7.8 Binary vector used to engineer soybean for SDA biosynthesis. Green and blue colored areas in the vector map define T-DNAs. Yellow areas define the vector backbone. T-DNA I carries the expression cassettes for the two fatty acid desaturases that enable SDA soybean to produce SDA soybean oil. Figure according to George and Rogan (2010)

7.7.2 *Compositional Analysis of SDA Soybean*

Compositional analysis of SDA soybean seed and comparison to the parent line as well as a set of ten commercial soybean varieties revealed no substantial change of seed composition other than the intended changes resulting from the expression of the two fatty acid desaturases (Tables 7.4 and 7.5). Proximates such as fiber, ash, protein, and total oil were comparable to the parent line and fell well within the range of commercial control lines (George and Rogan 2010). The oil composition exhibited the expected shift toward higher polyunsaturation. The levels of LA, which serves as a precursor for GLA and SDA, were reduced while GLA and SDA ranged from 6.07 to 8.03 % and 16.8 to 33.9 %, respectively (Table 7.5).

7.7.3 *Agronomic Performance of SDA Soybean*

Characterization of agronomic performance parameters, such as nodulation, pollen viability and morphology, early stand count, seedling vigor, days to flowering, plant height, lodging, pod shattering, final stand count, seed moisture, 100 seed weight, test weight, and yield (see Stojsin et al. Chap. 9), did not reveal consistent performance changes compared to the parent line and placed the performance of SDA soybean well within the range of conventional soybean lines (George and Rogan 2010). Extensive evaluation of SDA soybean seed yield that was performed in 6 subsequent field seasons and included between 10 and 16 locations in each season exhibited SDA soybean yield on par with the yield of the negative isoline (Ursin et al. unpublished results).

Table 7.4 Compositional analysis of SDA soybean seed

Component (units)	SDA soybean mean	Standard error	A3525 soybean mean	Standard error	Commercial range
Acid detergent fiber (% DW)	16.8	0.42	16.9	0.42	14.6–18.9
Neutral detergent fiber (% DW)	16.8	0.38	17.2	0.38	15.0–18.9
Ash (% DW)	5.72	0.092	5.63	0.092	5.59–6.20
Carbohydrates (% DW)	36.5	0.99	38.7	0.99	33.5–40.2
Moisture (% FW)	7.47	0.17	7.41	0.17	6.68–8.16
Protein (% DW)	41.9	0.27	39.8	0.27	37.5–42.4
Oil (% DW)	15.9	1.05	15.9	1.05	14.0–20.6

From George and Rogan (2010)

Table 7.5 Mean fatty acid composition of SDA soybean compared to the parent line and commercial control lines

Seed fatty acids (% total fatty acids)	SDA soybean	A3525 soybean	Commercial range
Palmitic acid	12.1	11.8	7.28–14.2
Oleic acid	15.2	19.2	12.6–28.0
Linoleic acid (LA)	22.8	54.9	50.5–60.0
Alpha-linolenic acid (ALA)	11.2	9.20	3.72–13.5
Gamma-linolenic acid (GLA)	7.09	n.d.	n.d.
Stearidonic acid (SDA)	26.1	n.d.	n.d.
Arachidonic acid	0.34	0.31	0.20–0.45
Behenic acid	0.29	0.32	0.22–0.49

From George and Rogan (2010)
n.d. not detected

7.7.4 Oxidative Stability of PUFAs

The susceptibility toward oxidation is a major challenge in utilizing omega-3 PUFAs in foods, potentially impacting initial flavor and shelf life. The susceptibility of PUFAs to lipid oxidation greatly increases with the degree of unsaturation due to a reduction in bond strength (Decker et al. 2012). A comparison in the relative oxidation susceptibility of a number of fatty acids as reviewed by Frankel (2005) is shown in Table 7.6.

Lipid oxidation can have significant impact on oil flavor and any food produced from the oil. The oxidation reaction produces low molecular weight volatile compounds of both desirable and undesirable flavors. The total impact on flavor is a function of the volatile concentrations and the detection threshold levels for each individual flavor compound. *Trans, trans*-2,6-nonadienal has a very low flavor threshold and has been found to be a major reaction product in EPA and DHA oxidation and off-flavor development. The high degree of polyunsaturation in EPA and DHA makes them very susceptible to oxidation and off-flavor development.

Table 7.6 Relative susceptibility of fatty acids to oxidation

Fatty acid	Relative oxidative susceptibility
Oleic acid (18:1)	1×
Linoleic acid (LA) (18:2)	10×
Alpha-linolenic acid (ALA) (18:3)	20×
Stearidonic acid (SDA) (18:4)	30×
Eicosapentaenoic acid (EPA) (20:5)	40×
Docosapentaenoic acid (DHA) (22:6)	50×

Adapted from Frankel (2005)

For many sources of fish oil, oxidation can begin in the fish as soon as they are harvested and oxidation continues during rendering. While oil refining removes many volatile compounds, the oil still contains nonvolatile oxidation products called core aldehydes that are not removed by steam distillation. These aldehydes can be potentially toxic and act as pro-oxidatives (Gomes et al. 2011).

SDA soybean oil has better oxidative stability than the more highly unsaturated omega-3 fatty acids, EPA and DHA, due to a lower number of double bonds (Table 7.6). In addition, soybeans contain inherent antioxidant protection systems, such as encapsulated oil bodies, antioxidants including tocopherols, and control of pro-oxidative metals, that can protect fatty acids from oxidation. In the seed the oil is packaged in physical structures known as oil bodies. Gray et al. (2010) found that the oxidative stability of oil in oil bodies was much greater over time than extracted or emulsified oil. Interestingly, while tocopherol levels in SDA soybean oil are within the range of conventional soybean oil, soybean-derived SDA oils contained higher tocopherol levels than primrose, flaxseed, and menhaden oils (Akoh and Vazquez 2011, unpublished).

The fatty acid composition of SDA soybean oil has been reported as follows (as shown in Table 7.7, Vazquez et al. 2012).

Oil stability is measured as the time period until peroxide formation in the head space enters an exponential growth phase. An analytical measure, peroxide value, is commonly used in the fats and oil industry to measure the amount of peroxides formed. Application of common food antioxidant ingredients such as citric acid and *tert*-butylhydroquinone (TBHQ) (commercially available as Tenox-20, Eastman Chemical) delayed the onset of lipid oxidation of SDA soybean oil beyond the induction of lipid oxidation of conventional soybean oil (Fig. 7.9).

With improved oxidative stability, SDA soybean oil may provide a means of providing an omega-3 fatty acid source in a broad range of food products. Table 7.8 provides a list of the types of foods that could be enriched with SDA soybean oil.

7.7.5 Sources of SDA and Regulatory Approvals

SDA can be found in small quantities in borage, black currant, and primrose oil. Recently CRODA Inc. launched Echium oil containing approximately 12 % SDA

Table 7.7 Fatty acid profile of SDA soybean oil

Fatty acid	Wt %
Palmitic (16:0)	12.2
Stearic (18:0)	4.2
Oleic (18:1 *n*-9)	15.9
Linoleic (18:2 *n*-6)	24.5
Gamma-Linolenic (18:3 *n*-6)	7.2
Alpha-Linolenic (18:3 *n*-3)	10.8
Stearidonic (18:4 *n*-3)	23.7

From Vazquez et al. (2012)

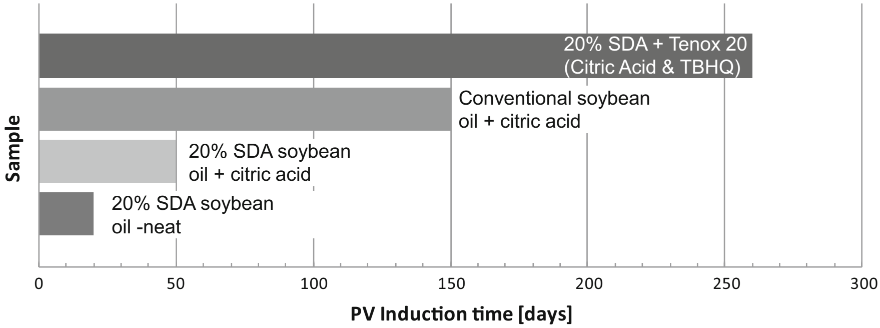

Fig. 7.9 Peroxide value (PV) induction period for SDA soybean oil and commodity soybean oil at 25 °C. Tenox 20, a commercially available food antioxidant ingredient containing citric acid and *tert*-butylhydroquinone (TBHQ) (Eastman Chemical)

Table 7.8 Range of foods which could incorporate SDA soybean oil

Baked goods	*Beverages*	*Oil-based foods*
Baked bars	Dairy drinks	Margarine/spreads
Extruded Bars	Soymilk	Shortenings
Sheet and cut bars	Soy/dairy drinks	Salad dressings
Crackers	Yogurt	Mayonnaise
Tortillas	Smoothies	Fat powders
Bagels	Clinical nutrition	Icings
Bread		
Pastries		
Chocolate compound coatings		
Cookies		
Processed foods	*Processed meats*	
Soups	Frankfurters	
Sauces	Sausages	
Broths	Pepperoni	
Peanut butter	Smoked hams	

as a new food ingredient product. The oil was approved as a new dietary ingredient in the United States in 2007 and received EU novel foods approval in 2008 for use in milk and yogurt-based drinks, cereals, nutrition bars, and food supplements.

SDA Soybean oil was the subject of a Generally Regarded as Safe (GRAS) notification review completed by the US Food and Drug Administration (FDA) in September 2009 (GRN 000283) (http://www.accessdata.fda.gov/scripts/fcn/gras_notices/grn000283.pdf and http://www.accessdata.fda.gov/scripts/fcn/fcnDetail Navigation.cfm?rpt=grasListing&id=283). A biotechnology consultation was completed with FDA for SDA soybeans in July 2012 (FDA BNF 000117) (http://www.fda.gov/Food/Biotechnology/Submissions/ucm314243.htm). SDA soybeans and SDA soybean oil received a positive response from the FDA for the consultation and GRAS notification. The GRAS notice covers intended uses as an ingredient in baked goods and baking mixes, breakfast cereals and grains, cheeses, dairy product analogs, fats and oils, fish products, frozen dairy desserts and mixes, grain products and pastas, gravies and sauces, meat products, milk products, nuts and nut products, poultry products, processed fruit juices, processed vegetable products, puddings and fillings, snack foods, soft candy, and soups and soup mixes, at levels that will provide 375 milligrams (mg) of SDA per serving. Regulatory authorizations on the SDA soybean and associated uses of SDA soybean oil have been completed in the United States, Canada, and Australia/New Zealand. Additional global authorizations are pending.

7.7.6 Application of SDA in Food

With improved oxidative stability and oil flavor more typical of conventional soybean oil, SDA soybean oil can be added to many different foods to provide an improved source for omega-3 fatty acid intake. A range of food product prototypes were prepared to evaluate the impact of SDA soybean oil on flavor, shelf life, and more importantly consumer acceptance. Based on recommended intakes of omega-3 polyunsaturated fatty acids and relative conversion rates of SDA, a target of 375 mg SDA/serving for an individual food product was selected. Consumer acceptance testing was used to evaluate functional and sensory performance. Using untrained consumer panelists, test and control samples were evaluated using a 9-point hedonic or liking scale and analyzed statistically using analysis of variance (ANOVA) and Tukey's significant difference testing. The number of panelists ranged from 30 to 60 depending on the individual test and products were evaluated at an age typical for consumer consumption. No significant differences in overall liking, liking of flavor, texture, and mouthfeel were found across the range of foods including snack bars, mayonnaise, beverages, yogurt, yogurt drinks, margarine spreads, frankfurters, and cream soup (Decker et al. 2012). Figure 7.10 provides a summary of the consumer acceptance testing.

Whittinghill and Welsby (2010) described the addition of SDA soybean oil to a range of bakery applications, either directly in the formula or through the addition of a shortening containing SDA. In one example, apple cinnamon baked cereal bars containing 6 % SDA soybean oil that contained 20 % SDA were manufactured using a typical industrial process and analyzed for flavor and consumer

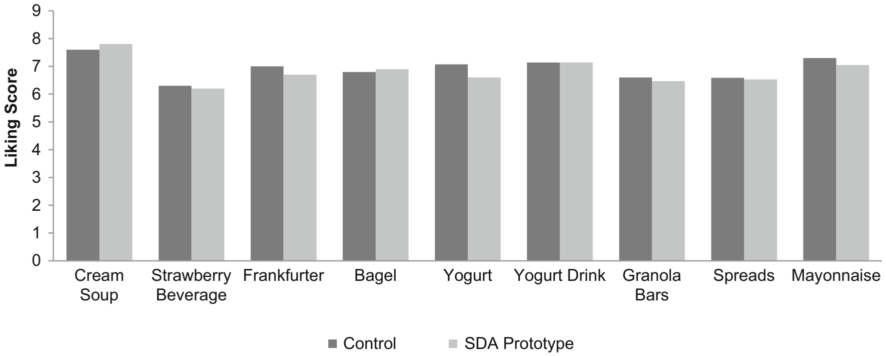

Fig. 7.10 Summary of consumer acceptance testing of SDA-enriched food prototypes compared to control prototypes

acceptability. No differences from a control baked bar using commodity soybean oil were found.

In another example, fruit and nut granola bars were prepared using a range of omega-3 oils. The bars were typical sheet and cut bars prepared from a blend of cereals and dried fruit, mixed together, and blended with binder syrup, which contained the specific omega-3 oil. The mixture was then sheeted, dried and cut, and individually packaged for sensory shelf life studies. Each package was stored for 12 months at room temperature and evaluated by a trained descriptive panel ($n = 5$) using consensus of judgment for key flavor and aroma attributes. Scores were recorded using a 15-point scale. Additionally, a quality change score was determined at 12 months to identify the degree each sample changes. Bars were prepared with the following oils: commodity soybean oil, SDA soybean oil, flaxseed oil, algal oil, fish oil, and encapsulated fish oil. Figure 7.11 shows a spider plot for all flavor attributes for granola bars prepared with conventional soybean oil and SDA soybean oil at the 0- and 12-month evaluation period. The graph shows that only minor differences in taste and flavor were detectable between those two granola bars.

The main concern for the application of omega-3-enriched oils is the development of off-flavors, which impact consumer acceptance and can limit shelf life. Figure 7.12 summarizes the impact of off-flavor development after 12 months storage for granola bars made with different omega-3 oils. The degree of off-flavor development for the SDA prototype was comparable to the commodity soybean oil control. Granola bars prepared with algal and fish oil were significantly higher in off-flavor development with flaxseed oil generating higher off-flavors than the control and SDA oil prototypes, but less off-flavors than the algal and fish oils. Due to the level of off-flavor, the fish and algal oil prototypes were excluded from further tasting past 9 months shelf life.

In addition to the descriptive analysis, the trained panelists also evaluated the cumulative change in quality over the duration of the shelf life study. This approach helps provide feedback on when a product exceeds its shelf life. Typically, a

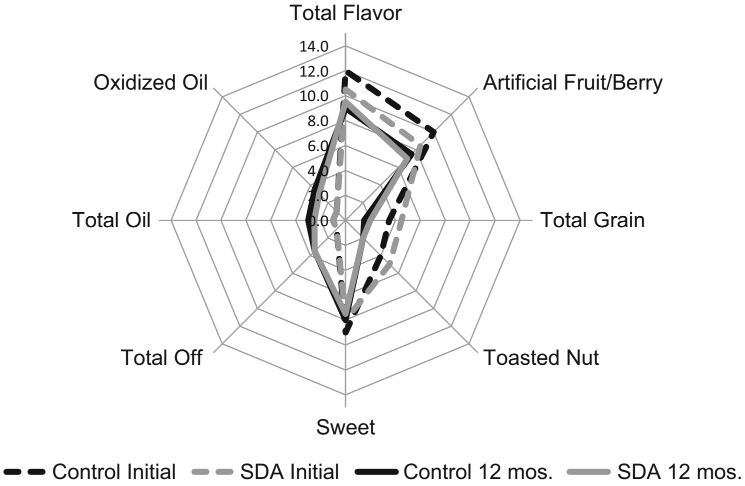

Fig. 7.11 Descriptive flavor analysis for fruit and nut granola bars made with SDA soybean oil and commodity soybean oil (control). Data were collected on fresh material and after 12-month storage at 25 °C according to the Spectrum method as consensus scores obtained from 5 trained panelists on a 15-point scale

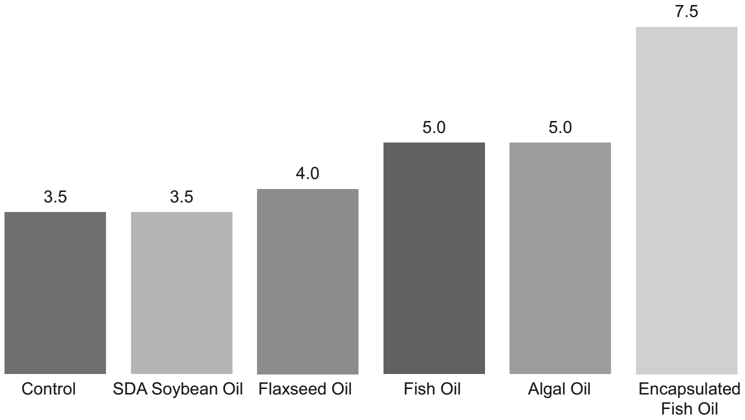

Fig. 7.12 Off-flavor development in prototype fruit and nut granola bars after 12 months storage at 25 °C. Off-flavor ratings for fish, algal, and encapsulated fish oils were reported for the 9-month time point due to the high degree of off-flavors at 12 month. Data were collected according to the Spectrum method as consensus scores obtained from 5 trained panelists on a 15-point scale

product exceeding 40 % change from the initial time evaluation result is considered unacceptable and out of the shelf life. For this study, the degree of change in the SDA sample was considered borderline at 12 months, indicating that the product achieved a typical shelf life for these bars. The alternative omega-3 sources were all unacceptable at 12-month shelf life Fig. 7.13.

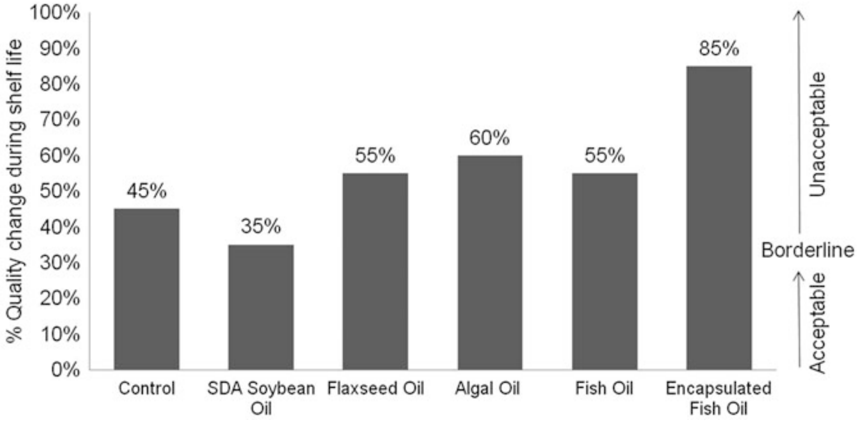

Fig. 7.13 Quality change for fruit and nut granola bars after 12 months storage at 25 °C (Wilkes unpublished)

7.8 Soybean Modified to Produce EPA and Other LC-PUFAs

A number of recent studies have provided evidence for the potential of genetically engineered oil seed crops to produce EPA and DHA (reviewed in Ruiz-Lopez et al. 2012). These studies describe the application of two principally different approaches toward engineering PUFA biosynthesis in plants. One approach builds on the plant internal fatty acid biosynthetic pathway and utilizes LA or ALA as precursor molecules that are converted to EPA and/or DHA by the action of various fatty acid desaturases and fatty acid elongases (Fig. 7.1). The fatty acid desaturases used in the initial attempts to engineer LC-PUFA biosynthesis in plants required phosphatidylcholine-bound fatty acids as substrates, while the elongases require Coenzyme A (CoA)-bound fatty acids as substrates. The resulting transgenic pathway requires extensive back and forth shuttling of the fatty acid substrate between these two substrate pools. This mechanism has been discussed as a potential bottleneck for PUFA biosynthesis in transgenic plants and can in part be overcome by the use of fatty acid desaturases that utilize CoA-bound fatty acids as substrates. Such enzymes are found in some lower fungi.

An alternative pathway utilizes polyketide synthases (PKS) to produce LC-PUFAs from acetyl-CoA and malony-CoA (Metz et al. 2001). The PKS approach provides the advantage of minimizing interaction of the transgenic biosynthetic pathway with other cellular metabolic pathways and has the potential to produce oils that contain only minimal impurities of intermediate fatty acids. However it requires the expression, activation, and proper targeting of several unusually large proteins and has so far only been used to produce small amounts of docosapentaenoic acid (DPA) and DHA (<5 % of total fatty acids) in Arabidopsis seed (Metz et al. 2006).

While considerable progress has been made in engineering LC-PUFA biosynthesis in crop plants, all of these efforts still represent proof-of-concept experiments, and several investigators continue to work in model systems such as Arabidopsis, soybean somatic embryos, tobacco seed or leaves. In addition none of the researchers has reported on field performance of the oil seed crops that have been engineered for LC-PUFA biosynthesis. The extensive screening and testing required to develop a commercially viable genetically engineered product followed by the in-depth characterization and safety assessment necessary to gain regulatory authorizations suggest that any EPA or DHA producing oil seed crops are at least 5 years, more likely 8–10 years away from commercialization.

7.9 Conclusion

The health benefits of omega-3 PUFAs for human nutrition have been extensively studied and reported. However, despite their benefits, the inclusion rate of these fatty acids in the average Western diet is still low. There are many reasons behind this shortfall. ALA, the predominant omega-3 fatty acid in the Western diet, is not converted efficiently to the biological active omega-3 fatty acids EPA and DHA. Direct inclusion of EPA and DHA into the Western diet is limited due to undesirable flavor components derived from these fatty acids due to their susceptibility to lipid oxidation and due to dietary preferences. SDA soybean oil has the potential to provide a land-based, sustainable omega-3 fatty acid source that is much more efficiently converted to LC-PUFAs than ALA, while providing a substantially more stable omega-3 fatty acid source than fish or algal oils. The improved stability reduces the challenges of inclusion into human foods due to an improved taste and flavor profile. In fact the established use of soybean oil for the production of functional foods in the food industry allows for a seamless integration of this novel omega-3 fatty acid source into the food supply and will provide the consumer with a much more diverse array of omega-3 fatty acid sources than has ever been available for human consumption.

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Part IV
Agronomic Implications

Chapter 8
Achieving Sustainable Agriculture: Overview of Current and Future Agronomic Best Practices

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8.1 Introduction

With global population expected to grow by 30 % over the next few decades, agriculture needs to become more productive and more sustainable. By some estimates, we will need to grow as much food in the next 50 years as in the past 10,000 years combined (People and the Planet 2012). Compounding this challenge is the fact that water, land, and energy resources are becoming more limited (see Buchanan and Orbach 2014). Increased attention is being given globally to the impact of ecology on agriculture and vice versa. Global climate change and other ecological phenomena are affecting the direction and economics of agriculture (Schmidhuber and Tubiello 2007; FAO 2008). At the same time, agriculture has the potential to mitigate many of the deleterious effects of global ecological changes.

Land, water, labor, and other resources have always been critical success factors for agriculture. Elevated constraints on these resources, combined with global climate change, have generated intense interest in best management practices to utilize resources while maintaining a robust agricultural industry that can provide the necessary food, feed, and fiber for the increasing global population (e.g., EPA 2012).

Sustainable agriculture is at the core of the challenge and its solutions. Agricultural companies, Monsanto among them, have made commitments to develop technologies that will enable farmers to produce more while conserving more of the natural resources essential to farmers' success. For example, Monsanto's

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sustainable agriculture objectives include the following goals to be achieved by 2030: (1) developing improved seeds that help farmers double yields from 2000 levels for corn, soybeans, cotton, and spring-planted canola, with a $10 million grant pledged to improve wheat and rice yields through Monsanto's Beachell Borlaug International Scholars Program; (2) conserving resources through developing seeds that use one-third fewer key resources per unit of output to grow crops, while working to lessen habitat loss and improve water quality; and (3) helping improve the lives of farmers and the people who depend on them, including an additional five million people in resource-poor farm families by 2020 (Monsanto 2010).

Such sustainable agriculture goals are attainable only through a combination of advanced plant breeding, biotechnology, and improved systems-based integrated farm management practices. This chapter is a result of the deliberations of a group of about 20 prominent academic, US federal government, and industry scientists who convened for a 2-day workshop in St. Louis, Missouri on August 16 and 17, 2010 (see Acknowledgments). These deliberations centered around identifying agronomic best management practices for the next two decades with the objective of developing consensus around future management practices and their contribution towards sustainable agriculture in the areas of Producing More (Sect. 8.2), Conserving More (Sect. 8.3), and Improving Lives (Sect. 8.4). The workshop also included Development of Best Practices and Barriers to Adoption (Sect. 8.5), Grower Awareness and Education Needs (Sect. 8.6), and Further Research and Data Needs (Sect. 8.7).

8.2 Producing More

In the year 2000, about 10.6 % (~1.38 billion ha) of the total land area in the world was under cultivation (FAO 2010). Although new area was brought under cultivation and some of the existing area was removed from cultivation, the percentage of total land area under cultivation was the same in 2008 (FAO 2010). During the same period, world population increased by more than 500 million (FAO 2010). To meet the increased demand for food production for the next two decades, it is essential that improvements be made in productivity rather than by increasing arable land (Burney et al. 2010; Foley et al. 2011). Bringing native land into production agriculture would take it out of its current natural state and potentially decrease diversity, which would be undesirable (Foley et al. 2011). Productivity gains over the next 20 years will likely be obtained through several means. While improvements in traditional breeding (genetic gain) and biotechnology will be two important contributors, improved agronomics will no doubt play a vital role in increasing the productivity of row crops (Foley et al. 2011). Improvements in efficiency of farming practices ranging from land and soil preparation to harvest and residue management warrant further research. The reminder of this section is devoted to discussion on how these farming practices can contribute to *producing more*.

8.2.1 Soil Preparation, Tillage, and Planting

Tillage influences soil and crop productivity in numerous ways (reviewed in El Titi 2003; see Hatfield, Chap. 4). A tillage system combines aspects of soil preparation, planting, cultivation practices, and residue management during a growing season. The most commonly recognized function of tillage is seed placement. Even in no-till crop production systems, the soil must be disturbed to some extent to place the seed. Tillage also releases nutrients from the soil by accelerating mineralization of organic matter and incorporate nutrients found in crop residues, applied fertilizers, and manures. The soil environment that the seed is placed in plays a major role in plant growth and development. In particular, seeds have an optimum temperature, moisture content, and nutrient regime that determine the vigor of emergence from the soil. Numerous studies and reports have documented the benefits and drawbacks of different tillage systems with respect to soil and crop productivity (e.g., Phillips and Young 1973; Phillips and Phillips 1984; Vetsch et al. 2007).

One of the most important soil physical properties that is influenced by tillage is soil compaction, which reduces soil porosity and infiltration (reviewed by Hamza and Anderson 2005). Strip-tillage is a relatively new practice that has been popularized in some geographical regions. It involves tilling a small strip of soil directly in front of the planter (usually less than 30 % of the surface area) and leaving the remainder of the soil surface and crop residue undisturbed. This practice has been implemented to improve yield while also conserving soil and moisture. Tilling the soil in the row opens up the soil to allow sunlight and wind currents to dry and warm the soil faster. Strip-tillage (and similar tillage systems) provides a uniform seedbed that allows rapid and uniform emergence. Several benefits of strip-tillage are worth mentioning. One is that nutrients can be placed with global positioning system (GPS) guidance in a precise band within the tilled strip and within easy access of the planted seed. Manure from livestock operations can be injected with precision near the rows (Al-Kaisi and Hanna 2008). Another is that, with the availability of advanced GPS guidance, farmers can plant their next year's crop between the rows of the previous year's decaying plant stalk and root (Nowatzki et al. 2011). This will increase soil organic matter because the old root system is not disturbed and is a primary source for organic matter accumulation (Overstreet and DeJong-Hughes 2009). The untilled soil between the rows will reduce water evaporation and be less prone to erosion (see Alam et al. Chap. 5). Practices such as strip-tillage are very site-specific: what may work well in a certain cropping system in a particular geographic area may not work in another, so there is a need for similar tillage equipment breakthroughs that could bring similar benefits to other areas. One possible downside to strip-tillage is that because the nutrients are usually placed in a strip directly beneath the corn plants, the funneling effect of water by the corn plant to the roots (Parkin and Codling 1990; Logsdon et al. 2010) might be expected to leach nutrients to a greater degree than if fertilizer is broadcast, but at least some research shows a benefit for banded fertilizer placement (e.g., Fernández and White 2012).

Some US growers are using a type of tillage called “vertical tillage.” This type of tillage lightly tills and mixes the soil while also cutting up residue to enhance decomposition. This tillage occurs before planting and is not as energy-intensive as other forms of tillage, but can generally cover a large number of acres per hour.

Depending on location, climate, crop, and economic factors, farmers are using the full spectrum of tillage options. While some growers do not till the soil before planting, others use several tillage tools to bring their soil to a finely worked, loose soil bed. Many times, a soil in the same geography with the same intended crop is handled much differently by two different growers. These issues raise several questions that need further investigation:

- What is driving these disparate practices?
- Have we done sufficient research to help growers make the best decisions?
- What are the long-term benefits and drawbacks of each tillage system as it relates to the particular cropping system?

Selection of the tillage system to use is not an independent decision. Like all other practices, tillage selection is a part of a management system. Changing one practice often requires adjustment of other practices. Some changes also require time—sometimes several years—for the biological and chemical environment in the soil to reach a new state of equilibrium. The evaluation of the entire system is the key to defining sustainability. The goal is to define a system of best management practices (BMPs) that best meets the farmer’s objectives.

Many farmers around the world have short period of time to plant their crop and still achieve optimum yields. As farms have become larger, the need to plant many acres of a crop per day has increased greatly. For any new agronomic practice, farmers will demand capacity, speed, and ease of adoption.

8.2.2 Planting Density

Optimizing plant arrangement/spacing involves maximizing the space between adjacent plants in the same row while reducing the space between rows, leading to higher planting density. Precise placement of seeds within a row has been shown in some studies to improve corn yields (e.g., Doerge et al. 2002) and would be expected to be beneficial in drought-prone and low-yield environments. More research is needed on the development of “smart” planters with expert guidance systems that can self-adjust to soil moisture, soil texture, elevation, and other surrogate data layers. A crucial component to the adoption of such technology would be the concurrent research and development of equipment designs that can bring higher efficiency than current two-pass systems, yet maintain the higher productivity that some growers see with full soil tillage.

Row spacing for corn has changed over time from 38 in. during the 1970s and 1980s to 30 in. or less since the 1990s. Concurrently with improved genetics and the introduction of agronomic traits, seeding rates have been increasing from an average of 18,000 seeds acre^{-1} to over 40,000 seeds acre^{-1} depending on the yield environment. In corn, the popular belief is that growers will need to increase plant populations to achieve the 2030 yield goals (e.g., Gentry and Below 2011). This increase in planting population can only be achieved by decreasing the row spacing and/or by decreasing the intra-row plant-to-plant spacing and by development of new traits tolerant to abiotic stress. The benefits of higher planting population can only be realized if those higher populations are managed appropriately for fertility and other production practices such as disease, insect, and weed management. Further research is needed on how to manage these higher population under strip-tillage conditions so as to improve the productivity. Research by the USDA-ARS in the Atlantic coastal plain area has indicated that yield advantages of narrow rows can be obtained by twin-row corn planting configuration compared to traditional 36-in. row spacing corn (Karlen and Camp 1985). Similar research conducted in central Illinois has shown that corn populations will need to be in the mid-40,000 range to achieve consistent 300 bu acre^{-1} yield opportunity (Below and Henninger 2010). Choice of hybrid and the growing season climatic conditions had a greater effect on grain moisture content at harvest, test weight, and ear length than row width or plant population. Research in the northern US Corn Belt has shown a yield advantage for narrowing row widths from 30 to 20 or 10 in., and that in some years maximum yields were obtained at harvest plant populations substantially higher than a population of 26,400 plants acre^{-1} (Porter et al. 1997).

8.2.3 Nutrient Management

Key nutrients for crop growth include nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and zinc (Zn). Each of the 17 essential nutrients is needed at a different critical concentration to maintain optimum plant health and growth (Kochian 2000). Fertilizer/nutrient placement and delivery are key to efficient fertilizer and nutrient use (see Reetz, Chap. 15). Immobile nutrients such as P need to be in the right location (placement of fertilizer) so that roots can intercept the nutrients from early vegetative growth stages to grain filling time in corn. Nutrient management should be focused more towards synchronizing the crop need and soil availability through technologies such as slow-release fertilizers. The ideal location for nutrient placement is probably different for each nutrient and each crop, and it can be influenced by factors such as tillage. Based on current knowledge, there is a need for future research to refine placement of specific nutrients relative to the plant, to optimize yields. For example, N might have a different optimum placement than phosphorous, and so on. With the adoption of new cropping systems, such as higher population densities, concurrent improvements will be needed to adjust other components, such as fertility and water management regimes. An integrated approach might include combining planting and fertilizer placement. However, there needs to be a tremendous improvement in the equipment to support this strategy.

Precision planting and precise nutrient application hold promise for increasing yields while maximizing the efficiency of nutrient inputs. Real-time kinematic (RTK) precision will become the norm in the future and be much less expensive. Nitrogen management through improved formulations, time-released fertilizers, and improved mechanical equipment will be needed in the future. A big challenge is supplying nutrients to crops in the just the right amounts at all growth stages. Many nutrients are mobile, so providing all the nutrients early in the season risks losing nutrients such as N to leaching and denitrification. Adding nutrients during the growing season can improve the fertilizer use efficiency though it involves the risk of not being able make the fertilizer application due to unfavorable weather. Nutrient management could be enhanced by sensing systems that give real-time analysis of fertility levels and plant requirements, perhaps by probing the plant and/or the soil for available nutrients. Aerial and satellite imagery could provide growers near-real-time information to respond to various agronomic issues in a site-specific manner (e.g., NASA 2002; Franzen 2008).

Yield losses due to lack of N and waterlogged soils are observed in some areas every year and can be widespread in years with significantly greater precipitation than average. In such environments N losses due to denitrification can be very high. Managing this issue would be an opportunity for increasing yield. It may be possible to develop drainage management systems to preserve and recover the nutrients removed from drained water.

Seed products change on a regular basis; it is a challenge to provide nutrient recommendations that are product specific. Recommendations based on family lineage might be more practical and beneficial to growers. Below and Henninger (2010) showed that improvements in corn hybrids due to high adoption of Bt (insect resistance) technology can increase a hybrid's ability to tolerate higher plant populations. He theorized that with "anti-ethylene" characteristics, plants of the future could be tricked into accepting close neighbor plants while still growing well (Below and Uribelarrea 2008, 2009). With the development of fast and deep rooting systems in the current hybrids, attention must be given to the changes in nutrient concentration below the plow layer (Haegele and Below 2013).

Although soils can provide nutrients to plants during the early growing stages, many growers plant when soil temperatures are suboptimal. These cooler soils do not release nutrients to plants as quickly as when soils are warmer (Pregitzer and King 2005). Early planting might require supplementing the plant with nutrients during the critical early growing stages.

8.2.4 Water Management

The water-holding capacity of a soil has a tremendous influence on crop productivity. Soil water-holding capacity and/or plant-available water can be enhanced by improving management practices with regard to conservation tillage, crop residue, and irrigation management (Bot and Benites 2005). This would reduce the need for irrigation. Internal soil drainage through tile would be key to using irrigation on slower-draining soils. Some modern drainage systems have the ability to hold water in the field during dry periods and supply nutrients through the same tubes that drain water during wet periods. Inadequate drainage results in soil anoxia, which can weaken plants. Poor drainage also is a catalyst for denitrification, nutrient loss, and soil salinity. Strip-tillage in the Red River Valley has improved drainage and increased evaporation in the row, while the residue-covered area is more porous and will hold water better when the plants require it.

Corn plants can be considered as natural funnels. Leaves channel water toward the stalk which can flow down towards the roots (Parkin and Codling 1990). With the right spatial arrangement, a field of corn might be able to channel even more water directly to the roots of the plant. However, this would need further investigation under different row spacing and planting population combinations. This might reduce the total amount of rainfall needed to reach optimum yields. Drought-tolerant crops produced through biotechnology could also play an important role in mitigating water-stress conditions (NRC 2010).

Subsurface drip irrigation has been considered as a way of improving irrigation water-use efficiency and nutrient management. Semi-permanent drip tubes could be placed into the soil using GPS and then future traffic and tillage could be managed using GPS to maintain the integrity of the drip system. These systems are currently used for high-value crops and could become a good investment with higher yield potential and precision equipment. The ability to supply water to double-crop soybeans and the development of soybeans with improved drought and stress tolerance could allow wider success with this double-crop system.

8.2.5 Integrated Pest Management

Effective integrated pest management (IPM) is important to maintain the viability of genetically modified (GM) crops (see Lee et al. Chap. 10). In the case of weeds, exclusive use of glyphosate in the South and other areas has brought weed resistance that has the potential to lower yields. Rotating crops, rotating herbicides, tillage methods, etc., can slow the development of weed resistance (reviewed in Beckie 2006).

In the case of insects and diseases, IPM involves monitoring pest levels and then treating when pest populations exceed a given threshold limit and with multiple modes of action. Achieving higher yields on a sustainable basis involves keeping disease and insect damage below threshold levels. A program of sentinel plots to monitor insect and disease levels across the United States could give growers more lead time to initiate control methods when these issues arise. Transgenic insect-resistant crops and insecticide seed treatments should be considered as a part of insect resistance management, even though they are prophylactics. The concept is very similar to plant breeders developing host-plant resistance. Controlling major pests allows growers to focus their IPM efforts on other targeted pests.

8.2.6 Crop Residue Management

With higher and higher yielding crop varieties being available, the need for on-farm crop residue management is becoming increasingly important. One option to deal with large amounts of plant residue would be to harvest some of the residue for other purposes, such as ethanol production. For example, stover can be incorporated into distillers dried grains (DDGs) to provide some of the carbohydrates in cattle feed (Loy 2008). However, the use of crop residues for animal feed and potential development of cellulosic-based ethanol production can have long-term effects on crop productivity and soil quality (Wilhelm et al. 2007). Thus, there is a need for research on an integrated systems-based approach to residue management and its effect on soil and crop productivity along with a balanced approach to bioenergy demands. Another area of research is for bioenergy crops suitable for a range of diverse landscapes to produce fuel for societal needs.

Increased yields from insect-resistant GM crops have brought about increased plant residue that remains on the soil after harvest. Laboratory results suggest that the residue from Bt crops breaks down more slowly than residue from non-Bt crops (Flores et al. 2005), although several field studies have shown no difference between Bt and conventional hybrids (Tarkalson et al. 2008; Lehman et al. 2010). Lignin is a plant component that adds rigidity to plant stems and stalks. Focused research on the heritability of lignin in plants is needed.

8.2.7 Crop Rotation

Crop rotations reduce disease, insect, and weed pests. Prior to 1900s this was the primary approach to provide nutrients and control pests. The benefits from crop rotations are likely to be different for each crop. Additional progress could be made by developing crops properties useful in rotation systems. For example, double-cropping wheat and soybeans in more northern US areas might require earlier wheat varieties. Spring wheat varieties with more cold tolerance would allow growers to choose fuller-season varieties that might have higher yield potential. Double-cropping on a consistent basis in the Midwest and Upper Midwest would require crops with maturities that are unavailable today, such as corn with 60-day relative maturity. Government farm programs have a large impact on crop rotations in the United States (e.g., Karlen et al. 2006). While a crop rotation involving three or four plant species might be ideal from the standpoint of sustainability, growers in some areas are struggling to grow more than corn. Soybean yields need to be improved in certain geographies so that they can compete well with corn production.

8.2.8 Farming Practices

New crops may not be needed, but farmers need the genetics, resources, and know-how to consistently raise the yields of current crops. As discussed in Sect. 8.3.2, there are interactions among all of these factors that will need to be taken into account. For example, some agronomic recommendations will need to be hybrid- and variety-specific to optimize yields. For instance, two hybrids might have 250-bu acre^{-1} yield potential, but one reaches this peak at a 40,000 bu acre^{-1} planting population, while the other reaches optimum conditions at 34,000 bu acre^{-1}. Response to nutrients could diverge in a similar fashion.

On farms with livestock, proper management and utilization of animal manure is key for returning nutrients to the soil. Integrated farming systems that include crop production and livestock can be very beneficial. The manure from livestock is placed back into the cropping system; it brings carbon and inorganic nutrients back into the system (Russelle et al. 2007).

Equipment traffic in the field for tillage, planting, and other operations can affect the rooting environment for a plant and thus should be properly managed for high productivity. The tire spacing and configuration between tillage, spraying, and harvesting equipment is often not aligned, thus increasing the area subject to soil compaction. Wide-bed systems in Australia and England used controlled traffic, minimizing the field area subject to compaction.

Diverse landscapes (soil types, slopes) are often managed as if they are the same. They usually are planted to one crop, given the same fertilizer, and planted to the same population density. This tends to lead to diminished yields and indicates that further research is needed on optimizing farm economics using specific crops and management techniques on each landscape.

8.2.9 Cover Crops

Cover crops can provide a residue base to improve precipitation water-use efficiency as well as to dry the soil enough to plant seed in the spring. The residue from cover crops provides a source of slow-release nutrients during the growing season, but the growing season after the harvest of corn and soybeans is too short to support cover crop establishment in many areas. One alternative that is being explored involves planting a crop after soybeans that is harvested early the next spring, followed by a shorter-season soybean variety. Inter-seeding cover crops into corn or soybeans would be necessary in many areas of the Corn Belt to establish these crops. Cover crops following wheat are well suited for N fixation, green manure, or winter grazing purposes. As discussed in Sect. 8.2, the needed increases in crop productivity must not come at the cost of increased damage to the environment (Foley et al. 2011). The next section discusses ways in which agriculture can contribute to *conserving more*.

8.3 Conserving More

8.3.1 Conservation Objectives

Few would argue against the need to conserve resources, such as water, fertilizer, and soil, that are critical to growers' success (see Hatfield, Chap. 4; Alam et al., Chap 5 and Reetz, Chap. 15). However, the challenge presented to agriculture both historically and especially in the coming decades is to conserve those resources while maintaining productivity sufficient to meet global demands for food, feed, fiber, and fuel. To that end, an appropriate objective for resource conservation in agriculture is increasing the efficiency of production, i.e., reducing units of inputs required per unit of output. This goal can best be met with a multidisciplinary approach across agricultural technologies and partnerships with growers. Seeds can be improved through both plant breeding and genetic modification methods to utilize water and nutrients more efficiently. Agricultural equipment can be improved to more effectively and precisely apply water, fertilizer, and crop protection products (Sect. 8.2.3). Chemistry and formulations can be improved to make fertilizers, plant health, and crop protection products more effective, thus affording the opportunity to optimize quantities applied to each acre. There are also improved management practices that growers can adopt to conserve resources, such as reduced tillage practices (discussed in Sect. 8.2.1).

Advances in agricultural technologies are needed to achieve the objective of resource conservation. However, these technologies can only deliver their benefits if growers and land owners are educated in these technologies, adopt best practices for their production systems, and have a strong commitment to increasing their resource-use efficiency over the long term.

8.3.2 Optimizing Technology Development Through a Systems Approach

For farmers to simultaneously maximize their productivity and resource-use efficiency, they require technologies that enable both goals. Thus, a systems-based approach should be applied to technology research and development.

Karlen et al. (1994) describe the differences between a systems approach to the traditional research method, which uses a reductionist approach. In the reductionist approach, scientific problems are broken down into discrete units, and research tends to fall neatly into a particular discipline. The reductionist approach has and will continue to be the source of critical discoveries, but it does not take into account the interactions between different parts of a system, such as a cropping system. In contrast, systems research considers how changes made in one part of a system lead to changes in another. For example, Lewis et al. (1997) describes pest management as a science requiring a systems approach: a pesticide is chosen because of its effectiveness in isolation, but other parts of the system (the pest) change to overcome it. As another example, narrow rows require tires that have less floatation and potentially higher compaction; thus, a factor intended to increase yields (narrow rows) might have a drawback (compaction) that can influence long-term yield opportunity unless it is recognized and addressed (e.g., No-till Farmer 2012). As Karlen et al. (1994) noted, systems-based approaches will identify some questions best answered through a reductionist approach; in turn, the answers produced by reductionist science need to be considered and applied in light of the whole system.

Applying a systems approach to the needs of sustainable agriculture, new technologies would be evaluated under variable conditions to determine the optimal combination of technologies and practices that growers could implement to efficiently manage resources while maintaining productivity. For example, a new corn hybrid containing a biotechnology trait providing improved N-use efficiency (NUE) would be evaluated under different tillage practices, planting densities, row spacing, N regimes, crop protection options, and potential environmental limitations such as water availability. A systems approach to new technology development ensures effectiveness of the new technologies under a production system optimized for resource-use efficiency. A significant benefit of systems-based research and technology development is the data generated, which can be utilized in economic analyses of different production systems to demonstrate profitability. This information is essential for growers to help drive their adoption of new seed and input technologies, equipment, and practices supporting resource-use efficiency.

8.3.3 Land Management with a Focus on Efficiency and Conservation

Agriculture may be best served by working to increase productivity while maximizing resource-use efficiency in the best-producing land and increasing conservation practices in high-risk, lower productivity land to ensure that the land can support future production. Increasing inputs on the best acres can maximize the impact of a region while allowing more ecologically sensitive areas to remain undeveloped.

There is a strong relationship between soil quality, water quality, and productivity that should be considered in key management decisions (NRC 1993). For example, focusing soil measurements on the land closest to rivers can minimize the impact of N contamination of water. Analyzing yield maps across a historical series can help to identify parts of the landscape that are wetter or dryer, where production could be intensified and where it should not. It can also identify areas where soil function has been lost and allow growers to concentrate conservation efforts on these areas. System-level thinking and applying the appropriate practices to different fields/areas will support efficient land management and long-term productivity. An initial focus on resource management in land areas that can benefit most can lead to adoption of similar management practices on other, less critical acres. Growers should be educated on the importance and contribution of properly managing the high-risk areas on their farm.

8.3.3.1 Conservation Tillage and Carbon Sequestration

In 1965, less than 3 % of US cropland was managed using conservation tillage (Walters and Jasa 2000). This percentage increased to 16 % by 1979 but remained relatively flat until the passage of the Food Security Act in 1985, which was intended to discourage crop production on highly erodible land. By 1998, 37 % of US farmland was under conservation tillage (tillage and planting system that covers 30 % or more of the soil surface with crop residue, after planting, to reduce soil erosion by water), with an additional 26 % under reduced tillage (tillage system that leaves 15–30 % residue cover after planting) (Walters and Jasa 2000). The motivations for conservation tillage have varied somewhat over time; in the 1970s and early 1980s, fuel savings motivated interest in conservation tillage, whereas in the 1990s, it was used increasingly because of its conservation benefits (Harper 1996). Ding and colleagues examined the effects of weather extremes on adoption of conservation tillage and found that recent drought conditions increase conservation tillage adoption (Ding et al. 2009).

As awareness about climate change heightens, basic research is being conducted examining agriculture's opportunities for carbon sequestration (Lal 2004; Eagle et al. 2012). In particular, tillage releases carbon from the soil; thus, conservation tillage practices are beneficial for retaining carbon in the soil (Overstreet and DeJong-Hughes 2009).

8.3.3.2 In-Field Management Practices to Better Utilize Resources

There are numerous opportunities to improve the efficiency (including time) and effectiveness of in-field management practices. For example, multiple activities could be combined into one pass of equipment across the field, such as combining application of fertilizer and water in the form of fertigation. Additionally, equipment and practices could be improved to expedite in-field activities such as planting, spraying, and harvesting. Reducing time spent in field management could potentially reduce overall fuel and labor requirements.

Controlled-traffic farming is one example of a practice that can help expedite field management while also improving the effectiveness of conservation tillage practices. It involves confining all field vehicles to the least possible area of permanent traffic lanes. Current practices which do not limit traffic to specific areas in the field can lead to widespread soil compaction, especially when combined with conservation tillage practices. Research has demonstrated that soil compaction can result in yield losses, reduced water infiltration, and impaired root development (covered in Sect. 8.2.1). Controlled-traffic farming utilizes new technologies such as GPS with RTK signal correction and auto-steering capabilities of equipment to ensure that the same wheel tracks are utilized for every in-field operation, helping to minimize soil compaction (Watson and Lowenberg-DeBoer 2004; Wolkowski and Lowery 2008).

8.3.4 Precision Nutrient Management

Although incremental inputs may be needed in order to generate the higher productivity levels necessary to meet future demands, resource savings can come from precision placement and timing and “protection” techniques to avoid environmental losses of those applied inputs (Sect. 8.2.3). With its ability to provide ±1 in. farm vehicle operation, the technologies of RTK-based precision farming can enable precise application placement and timing of nutrients and crop protection products. The development and adoption of tools such as dry spreaders, which allow precision and flexibility in concentration and placement of fertilizers, are other examples. Controlled-release and other enhanced-efficiency fertilizers could further enable efficient use of nutrients. Additionally, sensors can be incorporated into equipment to enable precision application of inputs.

Historically, equipment trends have favored large equipment to help improve efficiency of field management. It is possible that in specific environments and with certain crops, smaller machinery will be required for precision management. More flexible machinery that can be modified or adapted to serve different purposes should be developed to help both small and large grower operations to maximize their efficiency of resource management. Driverless robotic units and unmanned miniature aircraft currently under development may offer some new approaches to equipment size and design for more flexibility for certain field operations.

Nitrogen management is already a primary focus of agronomic practices concerned with productivity and efficiency. But with increasing concern for the greenhouse gas profile of agriculture, N management is becoming more important than carbon management because nitrous oxide, which is a major greenhouse gas, is produced by agricultural soil management, animal manure management, sewage treatment, and mobile and stationary combustion of fossil fuels. Nitrous oxide has a larger effect on the accumulation of greenhouse gases in the atmosphere than carbon dioxide. However, significantly more research should be dedicated to the issues of soil fertility and fertilizers in general, and N in particular. In some cases, the fundamental understanding of nutrient availability and utilization requires updating. Today's soil fertility recommendations are based on data that are 40–60 years old. As our agronomic systems evolve to use nutrients with increasing efficiency, we need to develop new recommendations that take into account these new practices. As such, current research should consider futuristic scenarios in order to test potential new recommendations.

8.3.5 Pest Management Practices: Long-Term Sustainability of Systems

Pest management practices have been dramatically changed by the introduction of GM insect-resistant crops. The reduction of insecticide use in cotton in 2010 was estimated to be 23 % on an active ingredient (ai) basis in the United States and 34 % in GM cotton-adopting countries worldwide (Brookes and Barfoot 2012). Regarding corn, insecticide use targeted to corn-boring and rootworm pests was reduced by 84 % in the USA in 2010 (Brookes and Barfoot 2012). This technology could offer similar benefits if adopted in other crops. For example, in 2010, pesticides used on fruits and vegetables represented 45 % of the total agricultural pesticide expenditures worldwide (Shelton 2012), representing significant opportunity for pesticide reduction through the addition of GM insect-resistance traits.

Pest management practices will continue to face challenges such as the threat of insect resistance and climate change impacts, and thus need to continue to evolve to ensure long-term sustainability. Like any insect-control technology, GM insect-resistance traits in crops should be used wisely to avoid the development of pest resistance (Sect. 8.2.5); however, we need to include biotechnology in the broader set of tools for IPM to decrease the opportunity for development of pest resistance. Climate change is expected to increase the geographical areas where certain insects and diseases impact crops. As such, new transgenic approaches will be needed to continue to reduce pest damages to crops and minimize the need for insecticides.

8.3.6 Promoting Conservation Practices for Long-Term Sustainability

8.3.6.1 Considerations for Land Owners, Managers, and Renters

In many areas of the United States, agricultural lands are increasingly being farmed by renters rather than the land owners themselves (e.g., Duffy and Smith 2008), although this trend does not hold nationwide (Nickerson et al. 2012). In the case of rented land, many land owners may not even reside near their acres and thus have very little contact with their land (Arbuckle 2011). In most cases there is not a strong, short-term incentive for these land owners to promote conservation practices with their renters or invest in their own land management practices or improvements to support resource conservation. If land owners do not promote the adoption of these practices or financially support a renter's choice to adopt them, it may be difficult for the grower renting the land to take actions related to its long-term sustainability.

Similar situations exist for other entities, i.e., farm management companies and crop consultants. Farm management companies and crop consultants manage a large proportion of productive land. In general, they tend to make decisions primarily on economic terms. These decisions may not necessarily best support the long-term sustainability of the farm, the farmer, the land owner, or the environment.

Another dimension of the land ownership issue is that some land is been passed from generation to generation, but with land owners living longer, the transfer of management of farms is delayed. For example, a 60-year-old son or daughter who inherits the farm from an 80-year-old parent may not have had the opportunity to make major decisions regarding practices that enable productivity and resource conservation.

8.3.6.2 Policy Changes and Key Influencers

One approach to increasing adoption of resource conservation practices would be to invest in research that develops economically and environmentally sustainable systems leading to the development of policies that would mandate their use; another is to provide incentives for voluntary compliance. Examples of potential policies that could support resource-use efficiency include subsidies for production profiles that favor low environmental footprints (although carbon should not be the only measurement considered) and providing incentives to companies to produce "green" products from renewable agricultural resources.

However, policies arise from the perceptions of their key influencers such as legislators and their advisors. These perceptions of key influencers need to be understood by scientists and other stakeholders. For example, there is a perception that organic methods for producing crops are inefficient compared to producing crops through current conventional methods (CAST 2009). Other perceptions may also need to be challenged, e.g., the perception that farmers who are efficient and profitable are "bad" farmers that neglect the environment.

Unfortunately, many key influencers of agricultural policy in government are not well educated on agricultural issues. Most senators, representatives, and their aides have very little agricultural experience and increasingly represent constituents who have no connection to agriculture. The result can be that policies impacting issues with both rural and urban consequences, such as land-use and water-use efficiency, will be addressed from an urban-needs perspective, ignoring the needs and concerns of agriculture.

Agricultural organizations (commodity groups, etc.) and environmental organizations have powerful lobbying groups and work to impact agricultural policy. There is a spectrum of environmental groups, some that are unwilling to work with the agricultural sector and others that are. The Nature Conservancy is a good example of an environmental nongovernmental organization (NGO) that is active in agriculture scientific societies and their meetings offer opportunities for scientists to converge across disciplines and discuss policy issues.

Given that many of the key influencers of agricultural policy have diminishing contact with and knowledge of agriculture, it is likely advantageous for farmers to make changes themselves to their management practices, adopt more precise recommendations with the help of practitioners and companies, and make progress in resource-use efficiency to limit the need for policies mandating these practices. It is also important for farmers and their advisers to carefully document the changes they make in practices and the resulting impact of those changes. Good baseline data and good monitoring of effects of change are critical.

8.4 Improving Lives

As discussed earlier, Monsanto has committed to "helping improve the lives of farmers and the people who depend on them, including an additional five million people in resource-poor farm families by 2020" (Monsanto 2010). Many other companies throughout the agricultural supply chain have made similar commitments to improving lives through sustainable practices (e.g., DuPont 2012; Syngenta 2006; Field to Market 2012). The steps discussed in Sects. 8.2 and 8.3 can contribute to improving the lives of farm families and their communities by increasing farm productivity, increasing and stabilizing farm income, preserving farm value, and improving environmental quality.

Because of the great diversity in agriculture worldwide, the needs of farmers in different world areas and even different parts of the United States may be vastly different; thus, practices and technologies should be appropriate to the needs of individual farmers and regions.

8.5 Development of Best Practices and Barriers to Adoption

The development of best management practices to improve crop and soil productivity is a continuous learning process for the academic and industry groups within the agricultural sector. Although different groups within the agricultural production sector have been working on developing new more efficient technologies for improving crop and soil productivity, there is a definite gap in the dissemination of existing knowledge to the ultimate customer (growers) and adoption of improved farming technologies (e.g., Kitchen et al. 2002). Some of the possible reasons for the lack of adoption of enhanced practices by farmers could be issues related to costs and ease of implementation, access to training and troubleshooting help, perceived and demonstrated benefits (both economic and environmental), or the need for further refinement of new technologies before they can be exploited by farmers. Many of the current agronomic tools and practices are modifications of decades-old technology that have delivered a certain increase in crop productivity. Because of the challenges in transferring new technologies to growers and the urgency in doing so, there appears to be a need to develop entirely new methods to promote the implementation and adoption of these technologies.

There are also new technologies that have not yet transitioned from basic to applied research, but will be applicable to the farm during the next 20 years. One example of such a technology is variable-rate fertility and irrigation management. There has been abundant research on the basics and methodologies for developing variable-rate fertility and irrigation management, but very little on the practical implementation of these technologies. Improvements in both fertility and irrigation management will undoubtedly contribute to increasing future farm productivity.

8.6 Grower Awareness and Education Needs

There is a shortage of trained agronomists that can help growers take all of the various techniques and inputs to help craft systems that will work for that farmer in his or her local area. Training at the farm level will be necessary to transfer the necessary knowledge to integrate these advanced, complex processes and systems. Popular press articles are very important for grower education because they are usually short and easy to comprehend. Technical expertise and grower education will enable all the science and engineering breakthroughs that will occur in the next 20 years to be brought to growers.

Today’s farm communities are dealing with a smaller work force and loss of farming expertise. Producers are looking for ways to minimize labor, but the people that do the labor need to have a higher skill set than in past years. Today’s technology is more sophisticated than ever, and the people necessary to run the equipment need to be highly trained. On the other hand, labor for minor crops is much more intense. The major concern of these growers is having enough labor to harvest the necessary crops. Labor issues are absolutely critical in production of high-value vegetables and fruits.

How do we produce agronomists that are not raised on the farm? One way is to change our educational approach to account for the fact that many students with an interest in agriculture do not have farm experience and give these students the opportunity to learn the basics of farming. Our educational system does not currently give students those practical opportunities. It is also important to engage the next generation of farmers and crop advisors while they are still young and considering possible career choices. The message we want to convey is that production agriculture is an important and challenging profession that is key to many goals that young people really believe in, such as national security, food availability, community development, and environmental understanding.

The site-specific nature of implementing many new BMPs requires local testing of the practices within local management systems and local resources. On-farm demonstrations or research plots can be useful both in showing farmers the benefits of new practices and in teaching the farmer and his advisers how to best implement the practices on their own farms.

At the workshop, it was proposed that agribusiness companies should fund fellowships in basic agronomic sciences. The problem is with the pipeline—getting students interested in agriculture at a young age. We must educate not only the agronomists and managers but also the general public, about agriculture and agricultural biotechnology. It was also proposed that agricultural corporations should develop GM traits that directly benefit the public, which would lead to better public understanding and acceptance of the technology (see McWilliams, Chap. 6).

8.7 Further Research and Data Needs

To reach 300 bu acre^{-1} average corn yields in the United States, yields in the most productive regions will need to hit 400 bu acre^{-1}. To reach this level in corn and make similar progress in other crops, basic research over the next 10–20 years will need to deliver additional breakthrough advancements with focus on both long-term economic returns and short-term returns.

For example, research is needed to establish whether the limiting factor in crop production is the light-energy capacity of the system. Research on nutrients and other crop inputs needs to be conducted in a systematic and quantitative manner to identify the limiting factors. Industry, government, and academic partnerships can promote technology and influence policy through a foundation approach to find answers to these sustainability issues. The government is better suited to do long-term experiments. Academic institutions have shorter-term grants but train the students. A solution that would allow academic researchers to engage in longer term experiments would be to create a foundation that holds the money for a longer term before the study is done; this would ensure that funding for long-term research is not pulled at the convenience of the funder or after the completion of a short-term study.

8.8 Conclusions

The concept of sustainability is not new, but the effects of global climate change and rapid population growth have brought it to the forefront. Agriculture faces major challenges as more food must be produced with fewer resources and a smaller environmental impact. Monsanto's sustainable agriculture commitments are aligned around the goals of Producing More, Conserving More, and Improving Lives, though these three areas are interconnected in numerous ways. From the literature and the discussions of the workshop participants, some basic conclusions can be drawn.

- Most crop production increases will need to come from increasing productivity on currently cultivated land area rather than from increasing the amount of cultivated land.
- Higher plant populations are necessary but not sufficient to achieve this goal, as they will require appropriate management to meet their full yield potential.
- Genetic improvement through both plant breeding and biotechnology will also contribute to preserving and improving yields.
- A wide range of tillage practices are currently used on US farms, and the best practice for one farm might be very different from that for another. In addition to improving water quality and soil structure, reduced tillage retains carbon in the soil, a benefit that has received increased attention with the current focus on global climate change.
- Precision agriculture has the potential to increase productivity while reducing inputs, and the available tools continue to be refined.
- Water-retaining production practices and drought-tolerance traits are needed to grow crops in areas where water is scarce at some time during the growing season. Although water deficit is the usual concern and a severe problem in many areas, waterlogging is a problem in others and may be mitigated by novel drainage solutions. Any considerations of water for agriculture must take into account water quality (before and after use) as well as quantity.
- Technology improvements must be complemented by effective means of technology transfer and grower education and support. New approaches are also needed for training the next generation of growers and farm advisors, many of whom will not have a farm background.
- Systems-based approaches, which account for the interaction effects of one factor (e.g., a cropping system) on another (e.g., an environmental factor), are required to achieve the necessary balance between production and conservation and to minimize unintended consequences.

- The steps that lead to producing more and conserving more can also contribute to improving lives. The lives of growers, their families, and their communities benefit when farm incomes and productivity increase, fewer field operations are required, and the values of land and water are preserved. Growers can and must take an active role in the management of farm resources to ensure long-term sustainability.

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Chapter 9
Sustainable Agriculture and Soybean Breeding: Contribution of Soybean Yield Increase to Sustainable Agriculture

Duška Stojšin, Kevin W. Matson, and Richard A. Leitz

9.1 Introduction

Continual human population growth has driven the need for increased food production worldwide. Greater food production was initially accomplished by increasing the area under cultivation. According to USDA statistical data (USDA-NASS 2011), farmland for soybean production increased almost 50-fold from 1924 to 2010 in the USA. This increase allowed for greater food and feed production, but it has also been associated with land degradation. More than 70 million cropland hectares eroded at rates higher than recommended for sustainable production (Hargrove et al. 1988). The limitation of land suitable for agricultural use, as well as farmland degradation due to misuse or overuse, made it necessary to focus on growing higher yielding crops on available crop land to lessen the demand to clear forested area for crop cultivation. Norman Borlaug estimated that if American farmers did not grow the high yielding crops available in recent decades, all the forest east of the Mississippi river would have to be cleared in order to produce the current food supply (Avery 1998). Globally, total area saved by modern agricultural systems was estimated to be almost 20 million square miles (Avery 1998). In this context, growing higher yielding crops is the most effective environmental conservation effort.

The major factors contributing to soybean yield increases in the USA have been: genetic improvement of soybean varieties, optimization of agronomic practices, market trends, and government policies. Genetic improvement was estimated to

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have contributed 45–50 % to the realized yield gain for soybean (Luedders 1977; Specht and Williams 1984). Most genetic changes contributed to improved pest resistance (Hartwig 1973; Riggs 2004; Parrott et al. 2008), alteration of plant morphology (Specht and Williams 1984; Boerma 1979), changes in plant physiology (Specht et al. 1999; Morrison et al. 2000; De Bruin and Pedersen 2009), or introduction of herbicide-tolerant varieties (Fernandez-Cornejo and Caswell 2006). These higher yielding varieties contributed to environmental protection not only via preservation of land needed for soybean production but also by reducing the need for chemical pest control (due to introduction of disease-resistance, insect-resistance or herbicide-tolerance genes).

Optimization of agronomic practices was mostly due to improvement of agricultural mechanization (Specht et al. 1999), application of chemical pesticides and fertilizers (Aldrich 1983; Luedders 1977), use of crop rotation (Luedders 1977; Riggs 2004), and improvement of tillage systems (Specht et al. 1999). The extent of erosion of USA soils in the 1930s emphasized the need for optimizing tillage systems that would ensure high yielding crops as well as preserve farm soil (Power and Doran 1988). Development of chemical herbicides and herbicide-tolerant varieties (Fernandez-Cornejo and Caswell 2006) allowed for an increase in conservation tillage because much of the tillage during soybean production is associated with weed control management (Buhler and Hartzler 2004). Conservation tillage contributed to a reduction of soil erosion by water and wind, soil degradation, and water or chemical runoff (Unger et al. 1988).

Government policies regarding intellectual property protection (Sleper and Shannon 2003; Kesan and Gallo 2005; Lesser 2005) or environmental protection (Reeder 2000) significantly influenced investment in and direction of soybean research and production, and consequently contributed to increased yield. The objective of this chapter was to identify and discuss the major factors influencing soybean production and yield increases as important contributors to sustainable agriculture.

9.2 Materials and Methods

The National Agricultural Statistical Services (USDA-NASS 2011) data were used to obtain information about soybean yield, grain production, planted area, and harvested area for the period covering 1924–2010 in the USA. The English units used in this database were converted to the SI system. For soybean yield, the conversion was from bushels per acre (bu ac^{-1}) to kilograms per hectare (kg ha^{-1}), for grain production from bushels (bu) to kilograms (kg), and the land area under soybean production was converted from acres (ac) to hectares (ha).

Linear regression analysis was performed for yield, planted area, and grain production with year as the independent variable. The slopes from the regression lines were interpreted as average rates of change for grain yield (kg ha^{-1} year^{-1}), planted area (ha year^{-1}), and grain production (kg year^{-1}) between 1924 and 2010.

Additionally, segmented linear regression models were applied to evaluate changes within each soybean production period (1924–1942, 1943–1977, 1978–1998, and 1999–2010). The breakpoints between segments were modeled at the three midpoints between adjacent periods. Slope coefficients and error variances were estimated separately for each of the four production periods, but only one intercept term was included so that the resulting model would be a continuous function with respect to time. The main purpose of the segmented models was to estimate an average annual rate of change during each period. The PROC REG function in SAS (SAS Institute Inc. 2002–2008) was used for the overall regression lines, and PROC NL MIXED was used to obtain estimates for the segmented linear regression models.

9.3 Results and Discussion

9.3.1 Soybean Production in the USA

According to USDA statistical records (USDA-NASS 2011), USA soybean production increased steadily from 1924 to 2010 (Fig. 9.1). Two major factors contributed to this trend: more farmland utilized for soybean production (Fig. 9.2) and greater soybean yield per unit area (Fig. 9.3). During this 87-year period, there have been four distinct eras that impacted soybean production and were based on type of varieties grown by farmers:

Soybean introductions prior to 1942
Public sector varieties from 1943 to 1977
Private sector varieties from 1978 to 1998
Biotechnology varieties from 1999 through present time

9.3.1.1 Soybean Introductions Prior to 1942

The early records of soybean introduction into North America date back to the eighteenth century (Riggs 2004) when soybean was grown mostly as a novelty plant species. By the end of the nineteenth century, soybean was used predominantly as a forage or silage crop. At the beginning of the twentieth century, exploration trips to China, Japan, and Korea resulted in several thousand soybean land races introduced to the USA (Riggs 2004). These land races were used primarily as a forage crop for hay production (Sleper and Shannon 2003). Some introductions from 1935 to 1940 were large seeded, but low yielding genotypes that were utilized as a vegetable crop (Specht and Williams 1984). Prior to 1943, most cultivars grown by farmers were plant introductions with limited or no breeding effort (Specht et al. 1999). Specht and Williams (1984) showed a nonsignificant genetic yield gain for cultivars released from 1902 to the 1940s. This indicates that breeding did not contribute

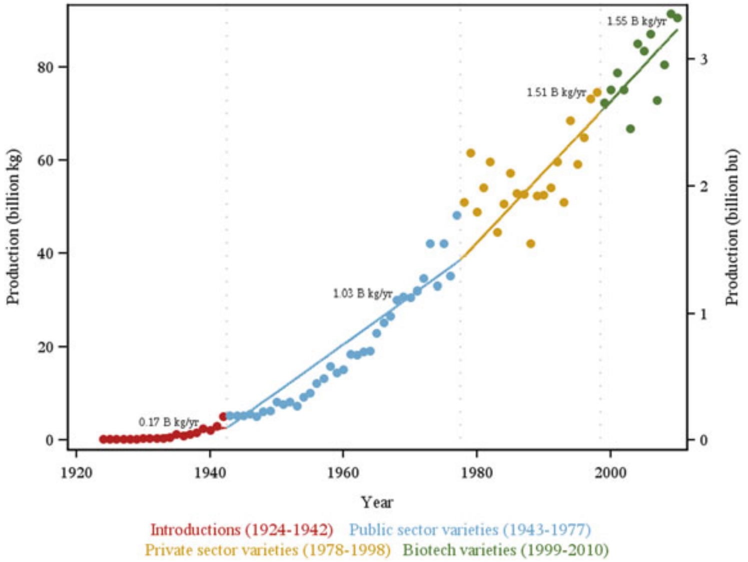

Fig. 9.1 Soybean production (billion kg and billion bu) in the USA for the four eras from 1924 to 2010

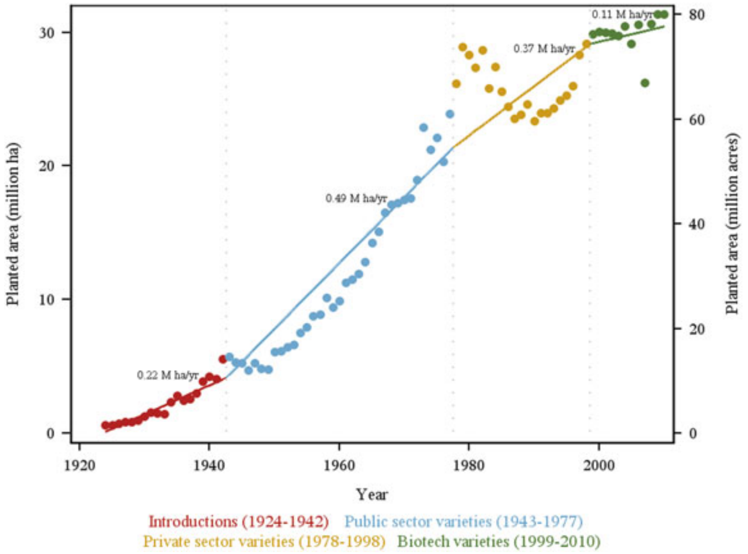

Fig. 9.2 Area under soybean production (million ha and million ac) in the USA for the four eras from 1924 to 2010

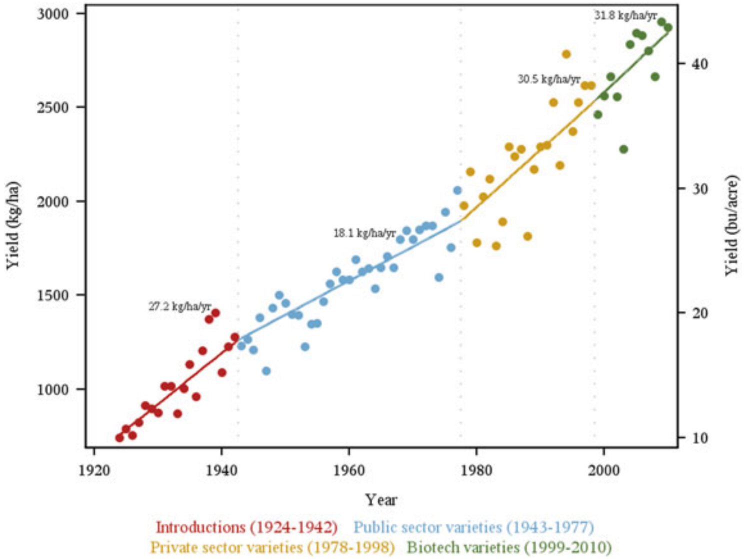

Fig. 9.3 Soybean yield (kg ha^{-1} and bu ac^{-1}) in the USA for the four eras from 1924 to 2010

to yield increase during this period, although some changes were observed, such as increase in seed weight and seed quality, or decrease in plant height and lodging (Specht and Williams 1984). The adaptation of the introduced varieties, optimization of agricultural practices, and a shift in soybean utilization in the USA contributed to the realized yield gain of 27.2 kg ha^{-1} $year^{-1}$ (Table 9.1, Fig. 9.3). The area planted with soybean increased almost ninefold from 1924 to 1942 (Fig. 9.2). Interestingly, for the same period, the harvested area increased 22-fold (USDA-NASS 2011). Only 28.6 % of planted soybeans were harvested in 1924 (probably for grain), whereas 72.2 % of planted soybeans acres were harvested in 1942. This is likely due to the change in soybean usage from a forage to a grain crop, as well as to reduced crop losses. The factors that contributed to reduced grain losses were better adaptation of introduced land races, farmers with more soybean growing experience, introduction of *Rhizobia* to the USA soils, and/or improved agronomic practices.

9.3.1.2 Public Sector Varieties from 1943 to 1977

More focused breeding of the soybean introductions started after the establishment of the USA Regional Soybean Industrial Products Laboratory in 1936 (Sleper and Shannon 2003). Breeders started making crosses between different land races from Asia and initiated selection for better yielding lines that were offered to farmers in the 1940s (Wilcox et al. 1979; Specht and Williams 1984). Soybean varieties released in this period resulted from breeding conducted in the public sector:

Table 9.1 Average annual rate of change[a] for grain production (billion kg year^{-1}), planted area (million ha year^{-1}) and yield (kg ha^{-1} year^{-1}), and the ratio of harvested (H) and planted (P) area for each production era for 1924–2010 period in the USA[b]

Years	Era	Grain production (billion kg year^{-1})	Planted area (million ha year^{-1})	Yield (kg ha^{-1} year^{-1})	H/P (%)
1924–1942	Introductions	0.17	0.22	27.2	36.7
1943–1977	Public sector varieties	1.03	0.49	18.1	93.5
1978–1998	Private sector varieties	1.51	0.37	30.5	97.9
1999–2010	Biotechnology varieties	1.55	0.11	31.8	98.5
1924–2010	Overall	1.10	0.41	23.4	82.7

[a] Regression coefficient
[b] *Source*. USDA-NASS (2011)

State Agricultural Experiment Stations (SAES) and the Agricultural Research Service, a subdivision of United States Department of Agriculture (USDA ARS) (Sleper and Shannon 2003). The average annual genetic gain for this period was estimated to be 12.5–13.7 kg ha^{-1} year^{-1} (Specht and Williams 1984; Boerma 1979), which was a major contributor to the realized yield gain (18.1 kg ha^{-1} year^{-1}) observed for this era (Table 9.1, Fig. 9.3). Estimated genetic yield increase for this period was 15–26 % greater compared to the introductions from the previous era (Luedders 1977; Wilcox et al. 1979; Specht and Williams 1984). This step change in yield increase was due to better gene combinations that resulted from hybridization followed by selection of lines with superior yield. This trend is similar to the one that occurred in corn when the hybrid production system replaced open-pollinated varieties (Specht and Williams 1984). The soybean yield increase was achieved by introducing and combining genes that contributed to better *Phytophthora* root rot resistance (Hartwig 1973), increased nitrogen content, greater nitrogen fixation (Specht et al. 1999), heavier seeds, better quality grain, shorter plants, and reduced plant lodging (Specht and Williams 1984). The area planted with soybeans expanded at the fastest rate during the 1943–1977 period (Fig. 9.2). An average of 0.49 million hectares under soybean production were added annually during this 35-year period, compared to an average increase of 0.22 million hectare per year for the previous period (Table 9.1). With this large increase in area, many soybeans were grown on farms with marginal soil conditions or inadequate management practices (Luedders 1977). However, a much greater percentage of planted acres were harvested for grain for the 1943–1977 period when compared to the average for the previous era (93.5 % vs. 36.7 %).

9.3.1.3 Private Sector Varieties from 1978 to 1998

The private sector started to invest significantly in soybean breeding after the passage of the Plant Variety Protection Act (PVP) in 1970. This act allowed for intellectual property protection of released varieties (Sleper and Shannon 2003). A total of 2,242 soybean cultivars were registered from 1970 to 2008, and 80 % of them were developed through private sector programs (Mikel et al. 2010). Almost four times as many employees devoted to soybean breeding were working in private seed companies compared to the public sector (82 vs. 22, respectively) in 1994 (Frey 1996). By the end of this era, approximately 90 % of soybean acres in the USA were planted with varieties developed in the private sector (Sleper and Shannon 2003). The estimated annual genetic gain for commercialized proprietary varieties in maturity groups 2 and 3 was 25–30 kg ha^{-1} $year^{-1}$ (Specht et al. 1999). This rate of gain is greater than the estimate by Specht and Williams (1984) for pre-1977 commercial releases (18.8 kg ha^{-1} $year^{-1}$). The genetic gain represents a major portion of the 30.5 kg ha^{-1} $year^{-1}$ realized yield gain for this era (Table 9.1, Fig. 9.3). Varieties from this period generally had a greater dry matter accumulation rate during the seed filling period (Specht et al. 1999), improved nitrogen content (Specht et al. 1999), better tolerance for higher plant density (Specht et al. 1999), and better soybean cyst nematode (SCN) resistance (Riggs 2004). The area under soybean production was variable from year to year for this period (Fig. 9.2). This fluctuation might have been influenced by factors associated with demand, market prices, and farm program policies for soybean in comparison to other crops. For example, the 1996 legislation on the ratio of soybean to corn loan rates resulted in an increase in soybean hectares (Sonka et al. 2004).

9.3.1.4 Biotechnology Varieties from 1999 Through Present Time

Herbicide-tolerant soybean varieties were introduced to farmers in 1996 and by 1999 over 50 % of the soybean acres in the USA had this biotechnology trait (Fernandez-Cornejo and Caswell 2006). Such a rapid adoption can be explained by the benefits of this new technology to farmers. Surveys have shown that 63 % of farmers preferred herbicide-tolerant soybean varieties because of higher yields, 17 % of growers liked the reduction of pesticide input cost, and 17 % indicated time saving and ease of management (Fernandez-Cornejo and Caswell 2006). The increased soybean yields that farmers observed with herbicide-tolerant soybeans can be attributed to several factors. In weed-free fields, soybean plants do not need to compete with weeds for water and nutrients (Buhler and Hartzler 2004; see Lee et al., Chap. 10). Weed control also contributes to reducing those pests that use weeds as hosts, such as root-knot nematode (*Meloidogyne* spp.) (Niblack et al. 2004) or soybean cyst nematode (*Heterodera glycines*, Ichinohe) (Riggs 2004). Furthermore, biotechnology utilization in agriculture resulted in more investment in soybean breeding and associated research and development. The realized yield gain for this era is higher (31.8 kg ha^{-1} year^{-1}) compared to the previous three periods (Table 9.1, Fig. 9.3). This estimate might be affected by the fact that this is also the shortest of the four eras; more years are needed to confirm this trend. Subsequent generations of traits resulting from biotechnology will continue to provide farmers with soybean varieties that have higher yield, increased pest resistance, healthier oils, and/or contribute to longer shelf life of soybean products. The area planted with soybean for this period has been relatively flat (Fig. 9.3), whereas total soybean production has increased at the greatest rate during this period compared to the previous three eras (Table 9.1, Fig. 9.1). This is a different trend compared to previous periods, as the increase in total soybean production in the USA was achieved mostly by yield increase rather than by both greater yields and land expansion (Table 9.1).

9.3.2 Factors Contributing to Soybean Yield Increase

The increase in soybean yield (23.4 kg ha^{-1} year^{-1}) has been a consistent contributor to greater grain production across all four eras with the highest rate estimated for the 1999–2010 era and the lowest observed for the 1943–1977 period (Table 9.1). There are several factors that influenced the increase in soybean yield per unit area over the 87-year period with three major ones being:

Genetic improvement of soybean varieties
Optimization of agronomic practices
Market trends and government policies

9.3.2.1 Genetic Improvement of Soybean Varieties

Soybean yield increases per unit area have been achieved by continual development of varieties with better agronomic performance and greater yield performance. From the beginning of the twentieth century to the 1970s, annual genetic gain has been estimated as 11.7–18.8 kg ha^{-1} year^{-1} (Luedders 1977; Boerma 1979; Wilcox et al. 1979; Specht and Williams 1984) which represents 45–50 % of the realized yield gain for that period (Luedders 1977; Specht and Williams 1984). Breeding for higher yielding varieties resulted in changes associated with plant architecture, seed properties, disease resistance, and plant physiology. Average plant height of modern soybean cultivars decreased compared to the soybean introductions grown at the beginning of the twentieth century (Specht and Williams 1984; Boerma 1979). This was achieved mostly by shortening of the internodes rather than reducing their number. Several studies reported improved lodging resistance (Luedders 1977; Wilcox et al. 1979; Voldeng et al. 1997), which made harvesting easier and contributed to reduced harvest losses (Luedders 1977). Some researchers observed that the yield increase was associated with more pods per plant (Boerma 1979), others that it is due to more seeds per plant (Morrison et al. 2000; De Bruin and Pedersen 2009). Increased dry matter accumulation during the seed filing period (Specht et al. 1999; De Bruin and Pedersen 2009; Kumudini et al. 2001) resulted in heavier seeds (Specht and Williams 1984; Kumudini et al. 2001). Seed quality generally improved across maturity groups (Specht and Williams 1984). Seed shattering reduced (Mikel et al. 2010) and integrity of the seed coat was improved. Several studies observed a reduction in protein and an increase in oil (Wilcox et al. 1979; Voldeng et al. 1997; Mikel et al. 2010). In contrast, Yaklich et al. (2002) showed a decrease in oil since 1974. De Bruin and Pedersen (2009) showed that new soybean cultivars have an increased growth rate compared to older varieties. Identification of pest-resistant cultivars and their use in breeding programs contributed to development of varieties that can more reliably realize their yield potential. Morrison et al. (2000) observed a decrease in foliar disease rating when comparing early maturing varieties that represent seven decades of soybean breeding from 1934 to 1992. Since the late 1930s, selection for pubescence practically eliminated potato leafhopper (*Empoasca fabae*, Harris) as a soybean pest (Parrott et al. 2008). Introgression of genes for *Phytophthora* root rot resistance (Hartwig 1973) greatly improved plant health. Several soybean cyst nematode varieties such as Pickett, Bedford, Forest, or Fayette were introduced since the late 1960s (Riggs 2004). It has been estimated that an average yield increase of 2–5 % can be attributed to SCN resistance (Monson and Schmitt 2004), and that the yield advantage can be much greater (18 %) under increased SCN pressure (De Bruin and Pedersen 2009). Healthier plants associated with resistant varieties contributed to increased leaf area later in the season (Specht et al. 1999; Kumudini et al. 2001) and greater photosynthetic rate (Morrison et al. 2000). Higher yielding cultivars also had greater nitrogen fixation and accumulation rates (Specht et al. 1999). In the northern regions modern varieties were bred to have more cold tolerance (Voldeng et al. 1997). Newer soybean cultivars tend to yield more under higher plant density when compared to older cultivars (Specht et al. 1999). In recent years the introduction of herbicide tolerance genes also contributed to yield increases in soybean (Fernandez-Cornejo and Caswell 2006).

9.3.2.2 Optimization of Agronomic Practices

Several agronomic and management practices contributed to the greater soybean yields. Introduction of nitrogen-fixing *Rhizobia* to USA soils resulted in better nitrogen utilization. For soybean grower, this translated into much reduced need for nitrogen fertilizers which are considered the significant contaminators of surface and groundwater in the USA (Hargrove et al. 1988). Continual improvement of agricultural machinery such as planters and combines allowed for earlier planting and reduced harvest losses (Specht et al. 1999)—both contributing to greater yields of soybean. Reduction of harvest losses can be seen when comparing the three eras during which soybeans were grown predominantly for grain (1943–2010). The percent of harvested vs. planted area for the three eras steadily increased (93.5, 97.9, and 98.5 %) over this 68-year period (Table 9.1). Growers made the transition from planting wider to planting narrower rows (Specht et al. 1999) which resulted in a greater number of plants grown per unit area. Soybean farmers started implementing crop rotation in order to manage diseases like soybean cyst nematode (Riggs 2004) or root-knot nematode (Niblack et al. 2004), as well as controlling weeds and insects that can be favored by monoculture (Hargrove et al. 1988). Studies showed yield benefits of a soybean—corn rotation system compared to continuous soybean across different tillage practices (Pierce and Rice 1988). Advances in agricultural chemicals contributed to more intensive agriculture and greater yielding crops (Luedders 1977). Use of chemical fertilizers increased over time. From 1968 to 1977 fertilizer use increased 55 % across crops grown on the USA farms (Aldrich 1983). Development of chemical herbicides and herbicide-tolerant varieties contributed to better weed control in soybean fields and facilitated tillage reduction (Duncan 1969; Specht et al. 1999; Fernandez-Cornejo and Caswell 2006). In the 1960s, Duncan (1969) noted considerable interest in a new "cultural method called no-tillage." During the 1980s, with widespread use of chemical herbicides, a reduced or no-till production system was used on 25–40 million hectares across crops in the USA (Power and Doran 1988). In the 1990s, the introduction of herbicide-tolerant soybean varieties further facilitated conservation tillage. By the late 1990s, about 60 % of the area planted with herbicide-tolerant varieties was under conservation tillage compared to 40 % of the area planted with conventional soybeans. Similarly, 40 % of hectares planted with herbicide-tolerant soybean were under no-till, compared to only 20 % of hectares planted with conventional varieties (Fernandez-Cornejo and Caswell 2006). It has been estimated that due to no-till practices facilitated by herbicide-tolerant soybean varieties, 37 million tons of soil will be saved from erosion by 2020 (Parrott and Clemente 2004). Additional benefits of reduced tillage are an increased amounts of plant debris in the field that result in greater water retention of farmland (Unger et al. 1988; Power and Doran 1988), reduction in losses of soil organic nitrogen through erosion (Power and Doran 1988), increased nitrogen uptake (Power and Doran 1988), and a decrease of SCN population density both in rotational soils (Niblack et al. 2004; Westphal et al. 2009) and under continuous soybean production (Barker et al. 2004)—all contributing to greater yields.

9.3.2.3 Market Trends and Government Policies

Market trends and governmental policies in the USA have been influencing the effort invested into soybeans from research to soybean production and utilization. In the 1920s, several Illinois farm groups guaranteed market prices for soybean grown in Illinois in order to encourage farmers to grow the new crop (Riggs 2004). The price of soybean compared to corn is another factor determining the interest of farmers to grow one or the other crop (Specht et al. 1999). Farm program policies, especially the ratio of soybean to corn loan rates in the 1996 legislation influenced an increase in soybean hectares compared to other crops (Sonka et al. 2004). Once the government subsidies for corn were phased out, investing in soybeans became more attractive for the industry (Specht et al. 1999). Increased protection of Breeder's rights has influenced crop production as it increased the seed sale prices, thereby increasing investment in research and variety development, and consequently contributing to increases in yield (Kesan and Gallo 2005). The Plant Variety Protection Act of 1970 was associated with intellectual protection of novel varieties (Kesan and Gallo 2005; Lesser 2005) and was followed by the 1980 US Supreme Court ruling on patenting of living matter (Sleper and Shannon 2003). These events gave incentives to the private sector increase investment in soybean breeding. With advances in biotechnology in the 1990s, the use of soybean patents was associated with development and commercialization of biotechnology varieties (Lesser 2005). The incentive to develop agricultural pesticides has been influenced by the regulatory approval process, namely the extent of required testing, the time from application to approval, and restrictions or bans on pesticide uses (Aldrich 1983). Generally, the number of new pesticides increased from the 1930s to the 1960s, but declined from the 1960s to the 1970s with increased regulatory requirements (Aldrich 1983).

The use of soybean has changed over time in the USA. Since the 1940s soybean has been grown for grain to be used as food (soybean oil) and feed (soybean meal). In the future, industrial and energy uses of soybean may increase, especially if mandated by legislators for political and/or environmental reasons (Sonka et al. 2004; see Redick Chap. 3). For example, the 2002 Farm Bill encouraged expansion of biodiesel (see Hughes et al. Chap. 2) use of soybean (Schmitt et al. 2004). If more of the soybean crop is grown for fuel production, then less may be available for feeding the growing human population in a sustainable manner (Egli 2008). Since 1994, federal legislation has required farmers to implement conservation management on highly erodible land (HEL) in order to receive US Department of Agriculture program benefits (Reeder 2000). This measure stimulated changes in management practices and as a result, several years later, about 55 % of soybeans were grown under conservation tillage (Reeder 2000). The 2002 Farm Bill also includes more funding for soybean farmers who use conservation practices (Schmitt et al. 2004).

9.4 Conclusions

From the beginning of the twentieth century until the present time, four distinct eras have been identified for their association with soybean production in the USA. The general trend has been a steady increase in soybean grain production. For the first two eras, this was achieved by significant expansion of land used to grow soybean and yield increases per unit area. The third era was characterized by large fluctuations of soybean hectares and steady yield increases. For the period after 1999, increases in overall soybean production have been primarily achieved by yield increases per unit area. These advancements in soybean yield were driven primarily by genetic improvements (adaptation, breeding, and advances in biotechnology), optimization of agronomic practices (mechanization, application of *Rhizobia*, disease, insect and weed control, and tillage system improvements), and by government policies (environmental and intellectual property protection). The fourfold increase in yield from 1924 to 2010 contributed to slowing the expansion in farmland usage for soybean production. With limited farmland available, new soybean varieties will need to continue to have high yield potential and perform well under reduced input. This is no small task, and if we are to be successful, continual innovations and modernization of agriculture are a priority. Considering the estimated increase in human population and its environmental impact worldwide, it is very important for the general public, environmental groups, seed industry, and policy makers to carefully evaluate the risks associated with each of their initiatives and decisions so that innovation and technology development can help to meet our future needs.

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Chapter 10
Impact of Herbicide Tolerant Crops on Soil Health and Sustainable Agriculture Crop Production

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10.1 Introduction

Genetically modified (GM) crops are developed when genetic material from a different or closely related organism is inserted into a plant's genome. Specific transgene addition in a species expands the gene base and has been used to confer herbicide tolerance, pest resistance, or other desired traits into crop plants. By expanding the gene base, it is hoped that genetically modified crops will increase food security (see Buchanan and Orbach, Chap. 1) by increasing yields (or reducing losses) while reducing carbon, energy, environment, and water footprints. Genetically modified crops offer just one of the many important agronomic tools and management methods that can be used to stabilize crop production, reduce energy use, and decrease the risk of crop failure.

This chapter reviews the published literature and conducts a meta-analysis of available data to determine the impact of GM herbicide tolerant crops and conservation tillage adoption on economic returns and environmental quality. Until the development of GM herbicide tolerant crops, herbicides could be applied only to a relatively narrow list of species that were tolerant to a specific herbicide. Today, GM technology enables crops that normally would not survive exposures to specific herbicides to grow and thrive after the application (NRC 2010). Genetically modified crops are then developed into commercial varieties using conventional breeding methods. This approach is somewhat different than using traditional crop breeding techniques, where desirable traits from within the same species were selected, and multiple crosses performed to obtain expression of the desired traits.

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Modern breeding methods that include the use of genetic modifications have increased our ability to control weeds using herbicides that would kill or severely injure a non-GM variety (Table 10.1). Herbicide tolerant cultivars are available for a wide variety of herbicides in many plants including canola (*Brassica napus* L.), corn (*Zea mays*), cotton (*Gossypium* spp.), rice (*Oryza sativa*), soybean (*Glycine max*), sunflower (*Helianthus annuus*), and sugar beets (*Beta vulgaris*). The development and adoption of GM crops has generated scientific debate and public concern (Singh et al. 2005) around national regulatory frameworks for risk assessment and management. The impact of GM crops on crop production, conservation tillage adoption, and the environment, however, are the focus of this chapter.

10.2 Crop Production Impacts

From 1996 through 2011, GM crop use increased 94-fold in hectares (ha) worldwide (James 2011). In 2011, GM soybean occupied 75.4 million ha of the global GM area of 160 million ha, followed by 51 million corn ha, 24.7 million cotton ha, and 8.2 million canola ha (Fig. 10.1). It is predicted that by 2015, the total area of GM crops planted in 40 countries will reach 200 million ha. In 2011 the United States planted GM crops on 69 million ha which accounted for 43 % of global GM area. In 2011, 93 % of US soybean, 78 % of cotton, and 70 % of corn acreage were planted to GM crops. Brazil and Argentina ranked second and third with planting 30.3 and 23.7 million ha that together accounted for 34 % of the worldwide area. In developing counties, GM crop use has been increasing rapidly (Fig. 10.1).

10.2.1 Genetically Modified Crops and Associated Management Impact on Yield

For many producers, the most important factors for adopting new farm management practices are increased yield, ease of implementation, higher profit, and minimizing labor requirements. Genetically modified crops can have direct and indirect impacts on yield. Direct impacts include improved pest control and/or higher yield potential, while indirect impacts are associated with changes in agricultural practices. In many situations, farm management and genetics are linked, with one technology facilitating the adoption of the other. Weeds and insects are a major source of yield losses for agricultural crops worldwide. In non-GM cropping systems, tillage and application of preemergent herbicides are commonly used for weed control. However, in GM cropping systems, the application of glyphosate after crop emergence can control weeds, reducing the need for cultivation and the number of weeds that mature to produce seeds (Marra et al. 2004).

Table 10.1 Selected herbicide tolerant crops that have been marketed, are available, or are currently under development

Herbicide/ chemical family	Tolerant crop designation	Tolerance mechanism	Notes
Glyphosate	Roundup Ready®	Glyphosate binds to the EPSP gene in susceptible plants and stops aromatic amino acid production. The RR or RR2 trait provides resistance to glyphosate through addition of an EPSP gene selected from an *Agrobacterium* strain that prevents glyphosate from binding to the site thereby conveying resistance to transformed plants	Roundup Ready® popularity is associated with a wide application window, ability to control a wide variety of weeds including those that are resistant to other herbicide classes, and lack of yield drag. Available for corn, soybean, and cotton
	Optimum GAT®	Provides protection against glyphosate and selected ALS (sulfonylurea and imidazolinone) herbicide injury. An enzyme transforms glyphosate into a nontoxic metabolite.	Not currently available and eventually may be available for corn, soybean, and other crops.
Glufosinate-ammonia	LibertyLink®	Glufonsinate interferes with glutamine synthase that stops the production of glutamate from glutamine and results in buildup of toxic levels of ammonia. The resistance gene, phosphinothricin acetyl transferase (pat), was isolated from strains of Streptomyces and, in transformed plants, metabolizes the herbicide to nonphytotoxic products	Liberty® and Ignite® are post-emergent herbicides that provide broad-spectrum control of annual broadleaf and grasses. Available in canola, corn, and cotton (Duke and Cerdeira 2005)
Imidazolinone family	Imidazolinone resistant (IR) corn hybrids. Clearfield® hybrids	This herbicide family controls weeds by inhibiting the acetohydroxy acid synthase (AHAS)/ acetolactate synthase (ALS) enzyme that stops branched chain amino acid production. Genes conferring imidazolinone tolerance were discovered through mutagenesis	Herbicides for use on IR corn include Pursuit® (imazethapyr) and Lightning® (Pursuit® + imazapyr). These herbicides control a broad spectrum of grass and broadleaf weeds. These genes also have been inserted into corn,

(continued)

Table 10.1 (continued)

Herbicide/ chemical family	Tolerant crop designation	Tolerance mechanism	Notes
		and integrated into crops through breeding and plant selection	wheat, rice, canola, and sunflower varieties
Sethoxydim	SR corn hybrids	Sethoxydim kills grasses by preventing the synthesis of lipids by inhibiting the acetyl coenzyme A carboxylase (ACCase) enzyme. Resistance is provided through an altered ACCase enzyme that is not inhibited at normal application rates	Poast and Poast Plus are post-emergence grass herbicides. Allows for application in corn after emergence of both crop and weed
Sulfonylurea family	STS soybeans	This herbicide family controls weeds by inhibiting the acetohydroxy acid synthase (AHAS)/ acetolactate synthase (ALS) enzyme that stops branched chain amino acid production. STS soybeans have an ALS 1 gene which enhances tolerance to some, but not all, sulfonylurea herbicides	Synchrony STS® is a 3:1 premix of chlorimuron (Classic®) plus thifensulfuron (Harmony GT®) for use only on STS soybeans®
Dicamba[a]	Presently in development	Gene that metabolizes dicamba was isolated from soil bacteria and inserted into the susceptible soybean genome. The gene confers at least 10× resistance to dicamba compared to non-transformed plants	Dicamba (Banvel® and Clarity®) is a post-emergent herbicide used for broadleaf weed control. Resistant soybean varieties are currently in development

[a] Not available in US markets as of 2/2011

To determine if yields have been influenced by GM crop varieties, a meta-data analysis of studies that compared yields across conventional vs. GM varieties was conducted, building on findings previously reported by Carpenter (2010). Studies were selected for inclusion in our meta-data set if they included field data comparisons of yield between a GM isoline and their conventional counterpart (near-isoline) cultivars (Table 10.2). Each observation was calculated as a response ratio (yield of GM cultivar/yield of conventional non-GM cultivar). A value of one indicated that GM and non-GM cultivars had identical yields, and the 95 % confidence interval of relative values across all entries was determined.

	2010		2011		Change	
	Area	%	Area	%	Area	%
	Million ha		Million ha		Million ha	
By Country						
USA	66.8	45	69.0	43	2.2	9
Brazil	25.4	17	30.3	19	4.9	19
Argentina	22.9	15	23.7	15	0.8	3
India	9.4	6	10.6	7	1.2	13
Canada	8.8	6	10.4	7	1.6	18
China	3.5	2	3.9	2	0.4	11
Paraguay	2.6	2	2.8	2	0.2	8
Pakistan	2.4	2	2.6	2	0.2	8
South Africa	2.2	1	2.3	1	0.1	5
Uruguay	1.1	1	1.3	1	0.2	18
Bolivia	0.9	1	0.9	1	0.0	0
Other	2.0	1	2.2	1	0.2	10
Total	148		160		12	8
By Trait						
Herbicide tolerant (HT)	89.3	61	93.9	59	4.6	8
Insect resistant (IR)	26.3	17	23.9	15	-2.4	-9
HT + IR	32.3	22	42.2	26	9.9	31
By Crop						
Soybean	73.3	50	75.4	47	2.1	3
Corn	46.8	31	51.0	32	4.2	9
Cotton	21.0	14	24.7	15	3.7	18
Canola	7.0	5	8.2	5	1.2	17

By Year	Worldwide	Industrial Country	Developing Country	Industrial Country	Developing Country
	million ha			%	
1996	1.7	1.5	0.2	88	12
1997	11.0	9.5	1.5	86	14
1998	27.8	23.4	4.4	84	16
1999	39.9	32.8	7.1	82	18
2000	44.2	33.5	10.7	76	24
2001	52.6	39.1	13.5	74	26
2002	58.7	42.7	16.0	73	27
2003	67.7	47.3	20.4	70	30
2004	81.0	53.4	27.6	66	34
2005	90.0	56.1	33.9	62	38
2006	102.0	61.1	40.9	60	40
2007	114.3	64.9	49.4	57	43
2008	125.0	70.3	54.4	56	44
2009	134.0	72.5	61.5	54	46
2010	148.0	76.3	71.7	52	48
2011	160.0	80.2	79.8	50	50

Fig. 10.1 Worldwide production areas of genetically modified crops: by country, by trait, by crop, by year. *Source*. James (2011)

10.2.1.1 Herbicide Tolerance Impact on Soybean Yields

Direct comparisons between GM and non-GM glyphosate tolerant soybeans and their conventional counterparts had mixed results. Yield potential was evaluated in two ways. The first analysis separated soybean yield results into two groups, yields less than and greater than 2,500 kg grain ha^{-1}. The second analysis examined GM release date (i.e., varieties released during the first few years of introduction

Table 10.2 Studies used in meta-data analysis

References	Crop	Trait	Location	Year
Bertram and Pedersen (2004)	Soybean	HT	USA	1997–1999
Burke et al. (2008)	Corn	HT	USA	2003
Culpepper and York (1999)	Cotton	HT	USA	1996–1997
Elmore et al. (2001)	Soybean	HT	USA	1998–1999
Heatherly et al. (2002)	Soybean	HT	USA	1996–1999
Heatherly et al. (2003)	Soybean	HT	USA	1999–2001
Heatherly et al. (2005)	Soybean	HT	USA	2000–2003
Loecker et al. (2010)	Soybean	HT	USA	2006–2008
Nelson and Renner (2001)	Soybean	HT	USA	1997–1998
Shaw et al. (2001)	Soybean	HT	USA	1997

HT indicates herbicide tolerance

vs. later released varieties) by using data in studies published prior to 2000 vs. data in studies published after this date.

The first analysis that used yield as a separating factor indicated that the ratios between GM and non-GM isolines in the less than 2,500 and greater than 2,500 kg grain ha^{-1} groups were 1.00 (±0.06) and 0.97 (±0.023), respectively. These results suggest that yield groups had minimal impact on the relative response (Fig. 10.2). However, if low yields are caused by increased weed pressure, then different results would be expected. A regression analysis was conducted to determine the relationship between relative pest pressure [RP = (GM yield – (conventional yield)/GM yield)] and yields in studies that started after 1999. The resulting equation was

$$\begin{gathered}\text{GM yield}\left(\text{kg}\,\text{ha}^{-1}\right) = 84.9 + 2{,}637[\text{RP}] + 0.97(\text{conventional yield}),\\ R^2 = 0.99 **\end{gathered} \tag{10.1}$$

This equation suggests that relative pest pressure (higher RP value) can impact the relative response from the GM crop. In about half of the studies, the RP value was negative which suggested that the GM crop had a lower yield. Lower yields in GM soybean may be attributed to many factors including reduced microbial activity and N_2 fixation, increased Mn and Fe deficiencies, and reduced weed and disease control. Based on the reported data, it is difficult to quantify why yields were reduced. For example, in many of the early comparisons glyphosate may have been applied only once, resulting in weeds being present during the critical weed-free period. Additionally, glyphosate may have soil-specific impacts on N fixation or mycorrhizae populations or changed the susceptibility of the plant to diseases and/or Mn and Fe deficiencies (Feng et al. 2005; Reddy and Zablotowicz 2003; Savin et al. 2006). In the other half of the studies, the RP value was positive, which suggests that the GM crop has a higher yield. Higher yields most likely are attributed to improved pest management.

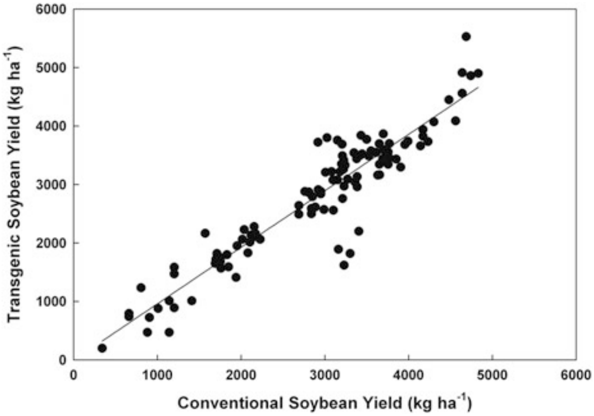

Fig. 10.2 A yield comparison between genetically modified herbicide tolerant and conventional soybean cultivar

The results of meta-analysis of published yield data showed that the GM yield expectations are based on the GM variety's release date. Studies published prior to 2000, on average, reported that glyphosate tolerant soybean had 8 % lower yields (GM/non-GM ratio = 0.92 ± 0.063) than non-GM isolines. Possible causes of these differences are discussed above. With time, this yield reduction has decreased, and in studies initiated after 1999, average yields in GM and non-GM isolines were similar (i.e., ratio = 1). These findings suggest that the yield drag associated with early GM soybean varieties has been addressed. Based on the meta-analysis, it is impossible to identify specific reason(s) why the yield reduction seen in early varieties is no longer evident.

Depending on the specific study, higher, lower, or similar yields based on GM trait have been reported. For example, Brookes (2003) reported that in Romania, the adoption of glyphosate tolerant soybean increased yields 31 %, whereas Oplinger et al. (1998) and Elmore et al. (2001) reported that the glyphosate tolerant soybean adoption reduced yields. Others have reported that glyphosate tolerant and conventional soybean had similar yields (Bertram and Pedersen 2004; Burke et al. 2008; Ferrell and Witt 2002; Hofer et al. 1998; Thomas et al. 2007). Differences among the studies may be due to different responses in low and high yield environments and/or that the responses are cultivar, climate, or soil specific.

Soybean yield comparisons (see Stojšin et al., Chap. 9) between glyphosate tolerant and conventional cultivars suggest that yield enhancements are dependent on growing conditions (Bertram and Pedersen 2004; Elmore et al. 2001; Heatherly et al. 2002, 2003; Shaw et al. 2001). For example, Bertram and Pedersen (2004) found that yields of GM and conventional soybean cultivars were similar when grown in environments that had below normal (i.e., cool) temperatures. However, when temperatures were normal (high yielding condition), GM soybeans had 6 % lower yield than conventional cultivars. A field study conducted in Mississippi also showed that glyphosate tolerant soybeans produced greater yields and net returns under drought stress condition, but conventional cultivars generally produced greater yield and net return than GM cultivars in an irrigated environment (Heatherly et al. 2002, 2003).

Ease of implementation for using GM soybean also has influenced producer adoption of this technology. For example, during the early years of glyphosate tolerant soybean introduction, nine different herbicides with different active ingredients were listed as important in South Dakota (SD) soybean production (South Dakota Agriculture 1998), and 47 % of the acreage was treated with glyphosate. Depending on which weeds were expected to be problematic, products often were not used alone, but applied as two or three ingredient tank mixes, or in sequential early and later season applications, again with two or more ingredients recommended at each application date (e.g., Sims and Guethie 1992). Prior to 1996, the use amounts of the nine chemistries used in SD ranged in total active ingredient for a specific chemistry from about 1,200 kg (rimsulfuron) to about 1.8 million kg (EPTC) (see South Dakota Agriculture reports prior to 1996). In 2002, after widespread GM soybean adoption, only two active ingredients (glyphosate and treflan) were listed (South Dakota Agriculture 2004) and in 2006, four active ingredients were listed for SD soybean production, with glyphosate applied to over 97 % of the soybean acres (South Dakota Agriculture 2010). These findings indicate that the adoption of glyphosate tolerant soybean has changed weed management practices and maintained yield (Brookes and Barfoot 2011; Shaw et al. 2001). This interpretation is generally in agreement with others (Elmore et al. 2001; Fernandez-Cornejo et al. 2002; Heatherly et al. 2002, 2003; Loecker et al. 2010; Meyer et al. 2006; Raymer and Grey 2003; Shaw et al. 2001).

Others have reported that in soybean, profitability was enhanced due to increased yields and reduced herbicide costs. For example, a Romanian study reported that the adoption of GM glyphosate tolerant soybeans increased the net gross margin by \$59 per ha in 2006 (an average of \$105 per ha during 1999–2006), which was primarily derived from higher yields (3–3.5 Mg ha^{-1} for glyphosate tolerant soybeans vs. 2 Mg ha^{-1} for the conventional cultivars) and reduced herbicide ingredient and application costs (1.9 treatments applied to glyphosate tolerant soybeans vs. 4.3 treatments to conventional cultivars) (Brookes and Barfoot 2011; Otiman et al. 2008).

10.2.1.2 Herbicide Tolerance Impact on Corn and Cotton Yields

Due to the limited number of studies that have investigated the impact of herbicide tolerance on corn and cotton yields, a meta-analysis of several data sets could not be conducted. However, Burke et al. (2008) did compare corn yields of cultivars that had different GM herbicide traits (glyphosate, glufosinate, and imidazolinone tolerance). They reported that corn yields of GM cultivars and conventional cultivars were 9,603 and 8,460 kg grain ha^{-1}, respectively.

The yield analysis for cotton is discussed as early vs. current cultivars, similar to the soybean analysis. In the early glyphosate tolerant cotton cultivars, the labels specified that glyphosate should be applied at or before the fourth leaf growth stage.

By following this restriction, boll abscission and the number of weed control options were reduced. In early comparisons, Culpepper and York (1999) investigated cotton yields between glyphosate tolerant cotton and a conventional cultivar. In their study, the average yield in GM and non-GM cotton cultivars was 1,318 and 1,340 kg ha^{-1}, respectively. They concluded that yield and net profits were similar when bromoxynil tolerant, glyphosate tolerant, and conventional cotton managements were used. These results suggest that initially weed resistance in cotton had a minimal yield advantage. More recent cotton cultivars have reduced the impacts of glyphosate on cotton boll abscission (Mills et al. 2008; Pline et al. 2003). Currently, glyphosate is registered for use on GM herbicide tolerant cotton for most of the growing season (until 60 % open bolls) (Joy et al. 2008). May et al. (2004) evaluated these cultivars at nine US locations. Findings from this study indicate that the new genetic constructs may overcome problems associated with the initial releases.

10.2.2 *Correlation of GM Crops and Conservation Tillage Adoption*

Many areas with high GM crop adoption have also had high adoption rates of conservation tillage. To explore the potential linkages between these technologies, a better understanding of each technology is needed (Triplett and Dick 2008). Civilization, as we know it, has required the development of efficient techniques to plant seeds and control weeds. Over 10,000 years ago ancient Babylonians used simple tools to place and cover seeds. Over time, seeding and seedbed preparation techniques were slowly improved. The introduction of the moldboard plow in England during the eighteenth century revolutionized farming by decreasing the time and labor needed for seedbed preparation and increasing the amount of land a grower could farm. This technology resulted in both positive and negative impacts on crop production and the environment. In the 1950s other equipments, such as plows, disk-harrows, and cultivators, were widely used to create seedbeds and control weeds. A disadvantage with using plow-type technology is that it can increase soil erosion due to wind and water (see Hatfield, Chap. 4 and Alam et al., Chap. 5).

Improvements in planting equipment, such as no-till drills, as well as the development of pest resistant cultivars and herbicides that can be applied post-emergent rather than preplant have made many tillage practices unnecessary. This section explores the evidence supporting the hypothesis that the development and use of GM crops has increased the simultaneous adoption of conservation tillage practices.

Conservation tillage and GM crop development are two technologies where significant advances have occurred over the past 30 years. The adoption of both technologies is dependent on: (1) management and labor requirements; (2) farmer profits and flexibility requirements; (3) the ability of the technologies to overcome management and production barriers; (4) the ability of the new technology to be easily integrated into current production systems (Carpenter 2010; Fernandez-Cornejo and Caswell 2006); and (5) synergistic relationships between conservation tillage and GM crop adoption (ASA 2001; Brookes and Barfoot 2011; Frisvold et al. 2007; Givens et al. 2009; Mensah 2007a, b; Pekrun et al. 2005; Young 2006). To explore these relationships, we will use examples from five different areas of the world.

The first example is from South America where Argentina increased the hectares in no-tillage from 300,000 to over 9 million ha from 1990 to 2000 (Trigo et al. 2003). Associated with this increase was the release of GM crops. Trigo et al. (2003) and Smyth et al. (2011) explored these technologies, and their findings suggest that rapid no-tillage adoption was enabled by the release of herbicide tolerant soybean and canola.

In the second example, Givens et al. (2009) conducted a survey from producers located in the central United States (Illinois, Indiana, Iowa, Mississippi, Nebraska, and North Carolina). Results of the survey indicated that the adoption of glyphosate tolerant crops increased the adoption of reduced tillage systems and tillage intensity declined more in the states with a lower adoption of conservation tillage. Mensah (2007a) reported that producers who adopted no-tillage were more likely to plant herbicide tolerant soybean.

In a third example, Roberts et al. (2006) investigated linkages between GM cotton and conservation tillage adoption in southern United States. They reported that the probability of a cotton producer to adopt conservation tillage increased if they planted GM cultivars. Fernandez-Cornejo and McBride (2002) had slightly different results in that simultaneous adoption was important for no-tillage adoption but not for seed use decisions. Kalaitzandonakes and Suntornpithug (2003) reported that the adoption of herbicide tolerance and stacked cotton traits increased conservation tillage adoption. Frisvold et al. (2007) had similar results and found that the adoption of conservation tillage and GM cotton were linked.

The fourth example compares conservation and GM crop adoption in Europe and the United States. In Europe, no-tillage practices and GM crop use are very low (Fig. 10.1), while in the United States no-tillage practices and GM crop use are relatively high (Brookes and Barfoot 2010; Derpsch et al. 2010). Relatively low no-tillage adoption rates in Europe may be related to the reliance on cultivators and plows to manage crop residues and control pests (Anderson and Jackson 2006). US farmers also relied heavily on these same technologies prior to wide scale adoption of GM crops. However, in the United States, the adoption of both technologies appears to be linked. For example, associated with an increase in full season conservation tillage adoption for soybean from 11.6 in 1995 to 17.2 million ha in 2008 was the wide scale adoption of GM soybeans (CTIC 2008; Uri 1999). For cotton, the conservation tillage adoption increased from 0.65 in 1995 to 13.5 million ha in 2008, while for corn the increase was from 11.86 in 1995 to 13.5 million ha in 2008. Different results were observed for the non-GM spring wheat, where no-tillage adoption decreased from 4.5 in 1995 to 4.3 million ha in 2008.

In the fifth example, the adoption of no-tillage in semi-arid regions is explored. In these regions, wheat is often grown. In spite of wheat not being a GM crop, no-tillage in these areas has increased rapidly. This increase may be associated with wheat being grown in rotations that include GM crops (Anderson 2009). For example, in Argentina, common crops in the rotation are corn, soybean, and wheat (Salado-Navarro and Sinclair 2009). In these systems, many of the problem weeds in wheat are controlled when GM corn and GM soybean are planted.

10.2.3 Combined GM Crop and Tillage Impacts on Wealth Creation and Profitability

If conservation tillage and GM crops are adopted simultaneously, then the associated increased wealth and profitability may be associated with improved water use efficiency. No-tillage when compared to a moldboard plow increases snow catch and reduces runoff and evaporation from the soil surface (Triplett and Dick 2008). Hatfield et al. (2000) reported that evaporation following cultivation in Iowa was 10–12 mm over a 3-day period, while evaporative water losses in no-tillage was less than 2 mm. Reduced evaporation is attributed to crop residues that remain on the soil surface (Klocke et al. 2009). The resulting impact on plant-available water and yields can be significant. Baumhardt et al. (2010) reported that in Texas, no-tillage increased available water from 16.8 cm for stubble mulch tillage to 19.6 cm, whereas in China, no-tillage increased water storage 3.7 cm in the surface 2 m (Su et al. 2007) and in Argentina, Salado-Navarro and Sinclair (2009) reported that no-tillage increased plant available water. Klocke et al. (2009) reported that each cm ha^{-1} reduction in irrigation costs in Nebraska resulted in a reduced pumping cost of \$8.75 ha^{-1}. They also reported that each cm of water that was transferred from evaporation to transpiration increased corn yields and profit 296 kg ha^{-1} and \$58.61 kg ha^{-1} (\$0.198 kg^{-1}), respectively.

No-tillage can have different impacts on yields in humid and arid environments. In humid areas, higher soil moisture contents in no-tillage fields can increase yields in well drained soils and decrease yields in poorly drained soils (Triplett and Dick 2008). However, different results are observed in arid and semi-arid regions, where a much larger percentage of the field is water limited. Higher soil moisture percentages in no-tillage can reduce the need for fallow. In semi-arid regions, the impact of no-tillage on plant available water and ultimately yields can be significant. For example, a rule of thumb in the United States Northern Great Plains is that each 1 cm of precipitation greater than 10.2 cm produces an additional 136 kg of wheat per ha (Engel et al. 2001). Based on this value, a 5 cm increase in available water can increase wheat yields 680 kg ha^{-1} in Montana.

In a second example, double cropped wheat followed by Argentine soybean rotations increased from 8 % in 1996 to 17.5 % in 2009 (Brookes and Barfoot 2011). Double cropping creates wealth by producing more food, and GM soybeans (see Stojšin et al., Chap. 9) help producers adopt conservation tillage, reduce weeds, and save water.

In a third example, wealth is created by improved weed control. Yield losses due to weed pressure can be estimated using the hyperbolic model. The mathematical form of this model is

$$\text{yieldloss} = \frac{I \times D}{\left[1 + \left(\frac{I \times D}{A}\right)\right]} \tag{10.2}$$

where D is the weed density, I is the incremental yield loss for a given weed, and A is the maximum yield loss for a given weed (Cousens 1985). For common ragweed (*Ambrosia artemisiifolia*), I in corn has been reported to range from 5.22 to 5.80 (% loss)/(weeds m^{-2}) while A values can range from 20 to 100 % of maximum yield (Clay et al. 2010a). In a South Dakota 65 ha field, about 15 % of the field had common ragweed populations greater than 10 weeds m^{-2} in 1995. Based on an I value of 5.22 and a weed population of 10 weeds m^{-2}, corn yield would be reduced by 48.4 %. The average corn yield in the field was 8.96 Mg ha^{-1}, and a 50 % reduction in 15 % of the field would result in grain production loss of 48.7 Mg (Fig. 10.3). It should be noted that the use of glyphosate as a post-emergent application by this producer improved overall weed control by reducing populations of Canada thistle (*Cirsium arvense*) and several annual weeds, as well as reducing overall herbicide costs by about 50 %.

Others have reported fuel savings with conservation tillage. Dill (2005) reported that the conversion from conventional to no-tillage cotton saved 53 L of fuel ha^{-1}. Parvin and Martin (2005) had similar results and reported that the adoption of GM cotton reduced tractor hours per acre by 49 %, labor hours by 43 %, and diesel fuel use by 20–30 %. Stein and Rodriguez-Cerezo (2009) reported similar findings for Canadian-produced canola. Songstad (2010) further evaluated fuel consumption associated with corn production using RUSLE2. Their research showed that changing from conventional to no-tillage corn production reduced fuel consumption by 45 % and that when these savings were extrapolated over the 35.2 million hectares of corn produced in southern Missouri, Illinois, and Indiana the savings would approach 800 million US dollars. Brookes and Barfoot (2011) estimated that the global farm level income gain from GM crops in 2009 was 10.8 billion US dollars.

10.3 Environmental Impacts

10.3.1 Shift in Herbicide Usage

The adoption of GM crops has contributed to a decrease in the application of several soil-applied herbicides. From 1990 (prior to GM crops) to 2002, the total amount of alachlor used in US corn and soybean production was reduced by 96 % (from nearly

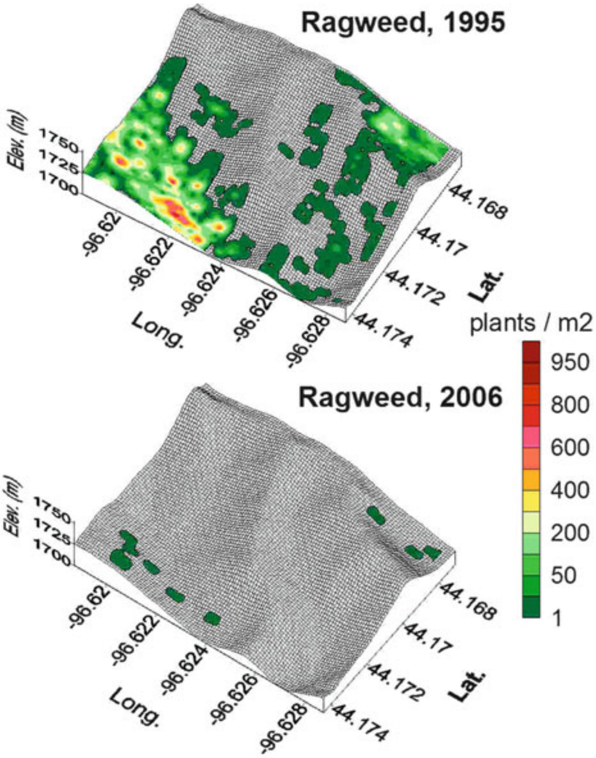

Fig. 10.3 Common ragweed (*Ambrosia artemisiifolia*) estimated densities in 65 ha field pre- (1995) and post (2006)-adoption of Roundup Ready® corn and soybean (authors unpublished data). Weeds were counted at 2,500 grid points in the eastern South Dakota field in the spring just prior to post-emergence weed control application. Conservation tillage was used in the field

22.7 million kg to 0.9 million kg) and metolachlor use was reduced by 86 % (from 20.9 million kg to 3.1 million kg) with a concomitant tenfold increase of glyphosate use in corn and cotton and a 20-fold increase in soybean (NASS 2008). Most other soil-applied herbicide chemistries, except for atrazine in corn, were either eliminated or reduced to levels that were much less or no longer significant enough to be reported in the NASS database.

The shift away from soil-applied to foliar herbicides positively impacted crop production and the environment. The efficacy of foliar applied herbicides can be very high but is dependent on the type of herbicide applied, plant species, surfactants present in the solution, and ambient temperature, among other factors (Pline et al. 1999; Satchivi et al. 2000; Steckel et al. 1997). For example, Satchivi et al. (2000) reported that 72 h after application, 35 and 60 % of the glyphosate was absorbed into the plant tissue of velvetleaf (*Abutilon theophrasti*) and giant foxtail (*Setaria faberi*), respectively, if 1 % ammonium sulfate was present in spray solution. Glufosinate sorption by leaves of giant foxtail ranged from 53 to 67 %, 24-h after application (Pline et al. 1999; Steckel et al. 1997) whereas sorption into velvetleaf was about 42 % (Steckel et al. 1997). Application rates of many newly developed foliar chemicals are lower than older soil applied chemicals. The lower rates reduce their potential concentration in runoff water. In addition, herbicides incorporated into plant tissues have less potential to move to surface and groundwater.

10.3.2 Herbicide Impact on Water Quality

The U.S. Environmental Protection Agency (EPA) guidelines for various chemicals, including herbicides, in drinking water were developed for the U.S. Safe Water Drinking Act that enacted maximum contaminant level (MCL) and health advisory (HA) standards for various water contaminants (USEPA 2009). EPA MCL guidelines define the legal threshold limit or the amount of a hazardous substance allowed in public drinking water, whereas an HA is a guidance value based on non-cancer health effects to a chemical for different exposure durations (days, lifetime). The MCL or HA value differs depending on the chemical in question. The MCL for atrazine, alachlor, and glyphosate are 3, 2, and 700 μg L^{-1}, respectively. Metolachlor and metribuzin have HA values of 700 and 70 μg L^{-1}, respectively (USEPA 2009), whereas glufosinate does not have defined values for either MCL or HA.

Herbicide concentrations in surface water are a function of the type or timing of application, amount applied, herbicide chemistry, and sampling date. In many areas of the world, nonpoint transport of pre-emergence herbicides has reduced surface and ground water quality (Battaglin et al. 2005; USGS 1999). Historically, the most frequently found herbicide in surface water has been atrazine, which was ranked number one in total kg of active ingredient applied from 1987 to 1997 (Aspelin and Grube 1999). Metolachlor (ranked number 2 in use from 1993 to 1997) and alachlor (ranked number 2 in use in 1987 and number 12 in 1997) are the other herbicides that have often been detected in surface waters (Larson et al. 1999). A more complete discussion of the transport of these chemicals to surface and ground waters is beyond the scope of this chapter and are available in Papiernik et al. (2006), Clay et al. (2002), and Clay (2003).

Most herbicides can be detected in surface water runoff after rain events and some have been detected in ground water after leaching events. Levels detected in water are usually <0.2 % of the application rate but even these low amounts can approach or be above MCL or HA values (Thurman et al. 1991, 1992). During the growing season, herbicide concentrations in stream water adjacent to agricultural fields often decrease with the highest concentration generally being measured in the spring and early summer (Ferrari et al. 1997; Wauchope et al. 1997). Battaglin et al. (2005) reported that glyphosate in water samples collected pre-emergence, post-emergence, and at harvest from nine Midwestern US states was not detected in any sample at concentration above the EPA MCL of 700 μg L^{-1}. However, atrazine was detected at concentrations greater than 0.1 μg L^{-1} in 94, 96, and 57 % of the samples collected in pre-emergence, post-emergence, and harvest samples, respectively.

Wauchope et al. (2002) predicted that because glyphosate and glufosinate were applied at lower rates, applied to foliage rather than to soil, and have greater soil sorptivity if in contact with soil than preemergent herbicides, their concentration in runoff would be one-fifth to one-tenth of the concentration of atrazine and alachlor in runoff water. This prediction was subsequently tested by Screpanti et al. (2005) and Shipitalo et al. (2008). Shipitalo et al. (2008) reported that herbicide losses in herbicide tolerant corn (glufosinate)/soybean (glyphosate) rotation were reduced in both the number of events when herbicide losses occurred and the amounts of herbicide found in runoff. Shipitalo et al. (2008) reported that glyphosate was detected in 29 out of 654 runoff events compared with 89 events when metribuzin was detected and 485 when alachlor was detected. In soybean, the maximum mean annual, flow weighted concentration of glyphosate was 9.2 μg L^{-1}, compared with 9.5 μg L^{-1} of metribuzin, and 44.5 μg $L^{-1}$of alachlor (higher than its MCL concentration of 2 μg L^{-1}). Glufosinate runoff from corn was similar to alachlor (0.1 % vs. 0.07 % of total applied, respectively) but 75 % less than atrazine (Shipitalo et al. 2008). Shipitalo et al. (2008) concluded that replacing soil residual herbicides with glyphosate or glufosinate reduced the overall occurrence of dissolved herbicide concentrations in field runoff.

An additional factor impacting the offsite movement of glyphosate and glufosinate is tillage. No-tillage and GM crop adoption can have a complex impact on water quality. In fact, adoption of no-tillage residue management, while reducing the total amount of water runoff from soil, actually increases herbicide concentration in runoff (Wauchope et al. 2002). This increase is a result of (1) no soil incorporation of the herbicide and (2) wash-off from surface crop residues that is usually greater than from soils (Martin et al. 1978; Mickelson et al. 2001). Application of glyphosate to tilled soil with rainfall 1 day after application resulted in a maximum glyphosate loss in runoff of 0.03 % of applied (Screpanti et al. 2005) with a maximum concentration of 16 μg L^{-1}, which is significantly lower than its 700 μg L^{-1} MCL value.

The change in types of herbicides used, from alachlor or atrazine that have low MCLs, to glyphosate or glufosinate has the potential to reduce the toxicity of agricultural chemicals and transport of chemicals from agricultural lands to non-target areas. Glyphosate and glufosinate are rarely detected in water due to their foliar application and, if in contact with soil, glyphosate's high sorption and glufosinate's rapid metabolism in soil. In addition, Wauchope et al. (2002) noted that both glyphosate and glufosinate have significantly lower chronic mammalian toxicity than some other herbicides, and both are vulnerable to breakdown in the drinking water treatment process. These properties reduce risks of exposure through drinking water and aid in the positive impacts GM crops have on drinking water quality.

10.3.3 Herbicide Fate in Soil

When herbicides are applied to soil they can be transported, decomposed, or sorbed onto the soil matrix. Herbicide transport to nontarget areas can be minimized by rapid decomposition and/or strong sorption to the soil matrix. Different chemicals have different mineralization rates and sorption characteristics that are dependent on site-specific interactions among the soil, climate, biology, and herbicide chemistry. The rate that herbicides are broken down can be described by the decomposition rate constant and the half-life. The half-life is the length of time required to degrade the chemical to 50 % of the applied amount. Herbicides with long half lives generally have a higher potential for movement. For example, alachlor half-life in soil is 21 day and residual weed control can be observed for up to 10 weeks after application whereas glufosinate has a half-life of 7 day (WSSA 2007). This short period of time limits the number of runoff or leaching events that the chemical may be exposed to during the season. Herbicides may have different half-lives in soil and water systems. For example, glyphosate may be more rapidly decomposed in water than soil (Deer 2004; Schuette 1998). A list of half-lives in soil of many commonly used herbicides is available in Deer (2004).

Many herbicides are tightly bound to the soil matrix. The strength of the binding is impacted by interactions between the herbicide chemistry and the soil (Koskinen and Harper 1990). Sorption is the removal of an ion or molecule by the soil through adsorption and/or the absorption process. The term sorption is used to describe this process when the removal mechanism is unknown. Sorption is controlled by many chemical and soil properties including the water solubility, pH, p*K*a, the octanol/water partition coefficient, soil organic matter, and the soil texture. Generally sorption increases as organic matter and clay contents increase.

Herbicide sorption affects how much herbicide plant roots take up, the amount that could potentially leach with drainage water, the rate of breakdown to metabolites, and concentration in runoff water. Most soils have a negative charge and act as filters to remove positively charged herbicides from percolating water. Sorption coefficients are experimentally derived and describe the amount of herbicides retained on soil vs. the amount of herbicides observed in solution. The higher the number, the more herbicides retained by soil. For example, soil sorption coefficients (K_d) of alachlor, atrazine, metolachlor, and metribuzin range from 2 to about 7 mL g^{-1}. A K_d of 2 implies that two molecules of herbicide would be found in soil for every molecule of the herbicide found in solution. A more detailed discussion of and sample calculations associated with herbicide sorption are available in Clay et al. (2010a).

Environmental benefits would be expected if herbicides that are easily transported are replaced with herbicides that are rapidly mineralized or strongly sorbed to soil. For example, the replacement of alachlor, atrazine, and metolachlor (herbicides frequently applied prior to GM crops) with glyphosate and glufosinate would be expected to reduce the impact of agriculture on the environment (Deer 2004; Wauchope et al. 1997).

Glyphosate interaction with soil greatly limits its potential impact on water supplies. Glyphosate is very water soluble when formulated as a salt, however, because the herbicide molecule is highly charged, it has a K_d that exceeds 300 mL g^{-1}in almost all soils. In addition, the amount of glyphosate that can be removed from the soil particle (desorbed) after initial sorption is negligible (<1 molecule for every 1 million sorbed). This desorption amount can be compared to other herbicides where desorption can range from 30 to near 90 % of the amount applied. Due to its rapid sorption (<1 min to total sorption) and its tight binding to most soils, glyphosate has a lower environmental impact than many chemicals (Cerdeira et al. 2005; Cerdeira and Duke 2006; Duke et al. 2003; Goldsborough and Brown 1993; Kolpin et al. 1998; Miller et al. 1995). Glufosinate has a lower sorption coefficient (about 23 mL g^{-1}) than glyphosate (Screpanti et al. 2005), but this sorption is still 3–10 times greater than the values for triazine or acetanilide herbicides.

10.3.4 Soil Resilience

A consequence of the combined adoption of conservation tillage and GM crops is decreased erosion and improved soil resilience. McCarthy et al. (1993) reported that by leaving 30 % of the soil covered with crop residues, soil erosion can be decreased by 50 %. Similar results were reported in Argentina where Penna and Lema (2003) observed that converting from tilled to no-tillage reduced soil losses by 75 % (from 10 to 2.5 Mg ha^{-1}). On a percentage basis, similar reductions (1.2–0.2 Mg ha^{-1}) were reported in Brazil (Service 2007). The adoption of no-tillage has also been correlated with increased arthropod and earthworm numbers (House and Parmelee 1985) and increased numbers of fungi mycelia (Beare et al. 1997).

Associated with reduced soil disturbance is reduced CO_2 generation in continental climates (Clay et al. 2010b; Hill 1990; Hooker et al. 2005; Rhoton 2000; Steinbach and Alvarez 2005; Triplett and Dick 2008; Tyler et al. 1983). Using meta-analysis of historical studies conducted in Mollisols located in Central United States, Clay et al. (2010b) reported that tillage intensity was positively correlated with the first order soil organic carbon (SOC) mineralization rate constant [$k_{\mathrm{SOC}} = 0.0115 + 0.00631(\text{tillage intensity})$, $r = 0.823$ ($p < 0.05$)]. Based on this equation, changing from a chisel-plow/disked system to a zero-till system would reduce the SOC mineralization rate by 757 kg C $(\text{ha year})^{-1}$ if the soil contained 60,000 kg SOC. When extrapolated over a 100 ha field, located in United States upper Great Plains, 75.6 Mg ha^{-1} would be sequestered annually. It has been estimated that no-tillage adoption has been increasing at approximately 6 million ha annually (Derpsch et al. 2010). Brookes and Barfoot (2011) had similar results and reported that from 1996 to 2009, the linked adoption of GM traits and no-tillage/reduced tillage systems may be responsible for 115 billion kg of CO_2 being sequestered in soil.

Slowing the rate that SOC is mineralized can also increase soil productivity, plant-available nutrients, and soil cation exchange capacity (Alvarez and Steinbach 2009; Ismail et al. 1994; Karathanasis and Wells 1989; Reeves 1997; Rhoton 2000). However, these gains will not be measured in all climates. A negative relationship between temperature and SOC storage reported by Clay et al. (2010b) suggests that carbon sequestration potential may be much lower in tropical and humid middle latitude climates. For example, Causarano et al. (2006) and Sisti et al. (2004) reported that adopting no-tillage had a minimal impact on SOC in Southeastern United States and Brazil. The lack of tillage differences in areas with warmer temperatures year round is due to rapid mineralization of non-harvested carbon (stalks, roots, and shoots) and SOC.

10.3.5 Environmental Impact Quotient

An alternative approach for evaluating GM crops on the environment is to calculate the field environmental impact quotient (EIQ). The environment impact quotient (EIQ) value summarizes a large number of potential impacts into a single number (Kovach et al. 1992). The field EIQ value is determined by multiplying the active ingredient times the EIQ value with smaller EIQ values having lower potential impacts. For example, the EIQ for glyphosate and atrazine were 15.3 and 22.9, respectively. Brookes and Barfoot (2011) reported that from 1996 to 2009 GM crops have reduced herbicide spraying by 393 million kg of active ingredient (8.7 % reduction) which contributed to a 17.1 % reduction in the EIQ in the cropping area devoted to GM crops.

10.3.6 Development of Herbicide Resistant Weeds

The development of herbicide resistant weeds is not unique to GM crops. Most pests, in response to a control practice, either modify their behavior or improve their ability to detoxify the pest management practice. The more often a given control practice is used, the higher the risk for the development of resistance. Herbicide resistance in a weed population is defined as the genetic capacity of a weed to survive a herbicide treatment that, under normal use conditions, would have been effectively controlled. The development of specific weed resistance to a specific herbicide was first reported in the late 1960s with triazine herbicides. In agriculture, currently there are over 346 weed biotypes around the world that have confirmed resistance to a wide array of herbicides with different mechanisms of action (Heap 2011). The risk of resistance development increases with repeated use of a single herbicide or herbicides with the same mode of action and not following best management practices (Duke and Powles 2008; Shaw et al. 2009).

Resistant weed problems can occur in as little as two seasons if the same herbicide or chemicals with the same mode of action are used repeatedly. To date, only 1–6 % of surveyed producers reported increased weed pressure when using GM glyphosate varieties, whereas the remaining 94–99 % of those surveyed indicated that weed pressure decreased or remained about the same (Kruger et al. 2009). The first report of a glyphosate resistant weed was rigid ryegrass (*Lolium rigidum*) in Australia in 1998 (Powles et al. 1998). Today in 2011, in the United States alone, there are currently 13 confirmed weed biotypes that previously had been controlled with glyphosate that are now resistant, and others have been confirmed worldwide (Heap 2011). Goosegrass (*Eleusine indica*) in Malaysia is the first reported case of weed resistance to glufosinate (Anonymous 2009).

To reduce both the development and spread of resistant species, best management practices (BMPs) that include the use of multiple control tactics within a cropping system and among cropping seasons should be followed (Moss 2007). These practices include using integrated weed management practices, using full recommended rates, cleaning equipment between fields to stop the spread of weed seeds or other propagules, rotating chemical families that have different modes of action, using crop rotations, scouting fields before herbicide application to determine weed species and pressure and after the application to determine efficacy and remaining problems, and not allowing resistant plants to reproduce.

10.4 Conclusion

Genetically modified crops and tillage system technology improvements have changed agriculture. The rapid adoption of GM crops has been attributed to two primary traits: insect and herbicide tolerance. This chapter reviewed the current literature on herbicide tolerant GM crops, conducted meta-analysis on near-isoline yield data present in the literature to determine the impact of GM crops on yield, and investigated the impact of GM crops and conservation tillage adoption on wealth creation and environmental impacts. A review of literature and meta-analysis indicated: (1) that even though current herbicide tolerant and non-GM crop iosolines have similar yields, profitability for farmers has increased and (2) agricultural management techniques changed with conservation tillage adoption and linked to the increase of GM crop adoption. The combined adoption of conservation tillage and GM technologies has reduced agricultural impact on the environment and increased soil and water quality. Soil quality improvements are associated with reduced tillage and increased carbon sequestration. Environmental improvements are seen with reduced applications of some herbicides that have high EIQ values with herbicides that have lower values and the replacement of some herbicides that had inherently long half-lives and weakly sorbed to soil with herbicides with those with short half-lives or strongly sorbed to soil. To minimize the impact of these weeds and restrict further development of unwanted resistant biotypes, additional herbicide families should be used in conjunction with GM crops with additional herbicide resistance genes. GM crops with resistance to single herbicides must be used judiciously and best management practices should be followed.

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Part V

International Sustainable Agriculture and Food Security

Chapter 11
The Role of Biotechnology in Sustainable Agriculture of the Twenty-First Century: The Commercial Introduction of Bollgard II in Burkina Faso

Jeff Vitale and John Greenplate

11.1 Introduction

This chapter was written in support of the authors' belief that Bt cotton can play a significant role in sustaining cotton production in West African countries where its viability over the long term is uncertain. We do this by telling the story of Burkina Faso's experience over the last decade, during which time Bt cotton was tested, approved, and produced commercially. To provide the reader with an understanding of the complexity of issues confronting the Burkina Faso cotton sector, the chapter begins with an historical overview, from the French Colonial period through the recent introduction of Bt cotton. We next present empirical evidence of how Bt cotton has impacted Burkina Faso cotton production based on household surveys that encompass the first 3 years of commercial introduction, 2009 through 2011. Household income, production costs, pesticide use, and associated health issues are addressed. A section is then devoted to the sustainability of agricultural biotechnology and includes projections of energy savings made possible by the introduction of Bt cotton in Burkina Faso. The chapter ends with a discussion of the long-term implications from a successful introduction of Bt cotton in Burkina Faso could have on SSA agriculture.

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11.1.1 Agriculture in Sub-Saharan Africa

Sub-Saharan Africa (SSA) remains largely underdeveloped compared to virtually every other continent and region in the world (UNDP 2011). Over the past three decades, SSA has consistently ranked at the bottom of the United Nations Human Development Index (HDI) (Fig. 11.1). While the United Nations HDI has increased globally since 1980, SSA has experienced the slowest rate of growth, with persistently low scores in poverty measures such as nutrition, education, and health. Over the past few years, there has been a renewed interest and sense of urgency to develop SSA (Ejeta 2010). The United Nations Millennium Declaration of 2000 established new goals for African development, challenging African governments and international donors to achieve milestones in economic, social, and political dimensions. Africa sits squarely in the sights of the Millennium Development goals of cutting world poverty and hunger by at least one-half by 2015 (UN 2000).

Agriculture will play a critical role in African development well into the twenty-first century (World Bank 2008). A strong agricultural sector is not only the means by which food security can be enhanced, but it's also a necessary condition for economic growth. Strong agriculture is critical for lifting rural households out of the throes of poverty in which they have been mired for generations. The link between agricultural development and economic growth has been well established. In China, for instance, agricultural growth was 3.5 times more effective in generating economic growth and reducing poverty than investments elsewhere in the economy; in Latin America, agriculture was 2.8 times more effective in spurring economic growth (Christiaensen and Demery 2006).

Agriculture will need to be transformed with substantially increased productivity and the development of agri-business for growth-led policies to be successful in SSA (World Bank 2009; UNIDO 2011). Although most of SSA relies on agriculture for a large proportion of its economic and social livelihoods, generating 60 % of GDP and employing 70 % of its population, the performance of agriculture has been disappointing over recent decades. Throughout most of SSA, agriculture has been stagnant as reflected in comparative global maize yields (Fig. 11.2). The figures show that, in Sub-Saharan Africa, cereal yields are largely below the yields in other regions of the world. Based on FAOSTAT (2011), the yield gain over the 48-year period from 1961 to 2009 was 135 % in SSA, 174 % in Australia, 344 % in China, and 164 % in USA for maize (Fig. 11.2). SSA has had the lowest yield increase rates compared to other regions in the world, primarily due to slow or non-adoption of modern agricultural technology advances. The traditional farming practices and sporadic use of modern (twentieth century) agricultural technologies has generated few noticeable increases in productivity. Despite agriculture's economic and social importance, agriculture is underinvested and often ignored by policy makers and governments. Many SSA countries have experienced long-term declines in agricultural output and productivity, relying on food imports to make up for production shortfalls. This drains foreign reserves, increases poverty, and sparks social unrest.

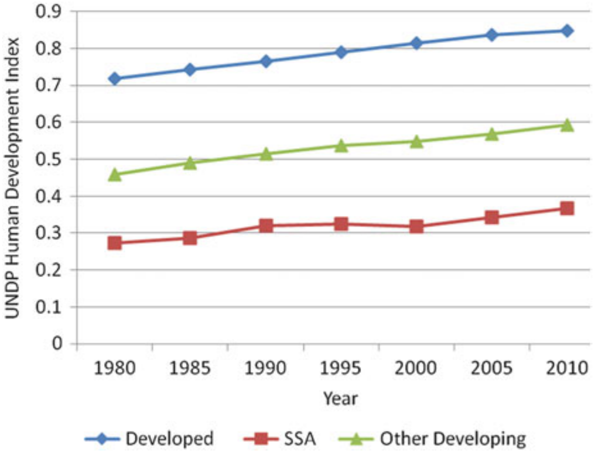

Fig. 11.1 UNDP Human Development Index for developing, SSA, and other developing countries from 1980 to 2010. *Source*: UNDP (2011)

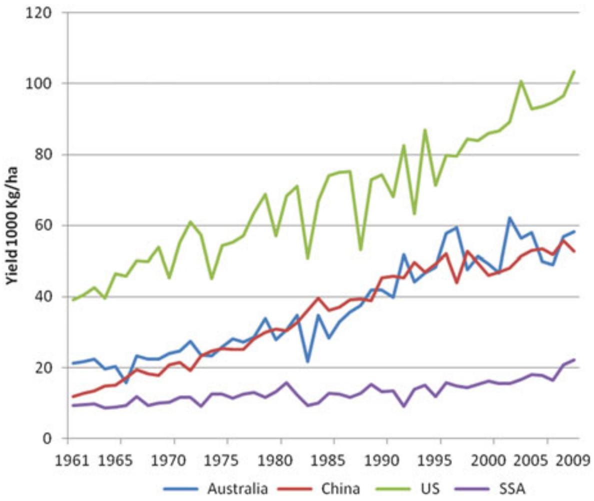

Fig. 11.2 Comparison of maize yields in SSA with other regions of the world illustrating the significant yield gap. *Source*: FAO (2011)

Recent food crises have highlighted the vulnerability of SSA countries to shocks in global markets.

Sustaining agricultural growth has been an ongoing struggle for most of SSA that will likely become more intense over the coming decades. Sub-Saharan Africa has a high population growth rate with a large youth population (under 35) for whom agriculture will be called upon to provide sustenance and livelihoods for decades to come (World Bank 2007). While wealthier parts of the world (Asia and Middle East) are able to address food deficits through imports, most of SSA is too poor to adopt this strategy without significant donor assistance.

Improving agricultural output will need to be achieved by expanding yield frontiers to increase land and labor productivity (Sanders et al. 1996). Expanding acreage under cultivation, a traditional means to increase food production, is becoming a less viable option as population pressure competes increasingly for the supply of arable land resources (Boserup 1965; McMillian et al. 1998). Many societies have improved total agricultural output by increasing yields on limited acres through the adoption of more intensive production methods that combine soil fertility amendments, improved germplasm, and crop protection technology (Paarlberg and Paarlberg 2000). Such use of science and technology was first pioneered in the USA and Europe in the first half of the twentieth century, later spreading to Latin America and Asia through the Green Revolution in the latter half of the twentieth century (Pingali 2012). Africa, however, was largely bypassed by the Green Revolution and found only limited success in modernizing agriculture along those paths (Ejeta 2010). The Asian and Latin American Green Revolutions, pioneered by Norman Borlaug, were focused primarily on the introduction of hybrid maize and rice varieties (see Borlaug et al., Chap. 12). While maize is a major staple food in East and South Africa, Green Revolution technology relied heavily on irrigation and inorganic fertilizers for productivity gains, neither of which could be cost effectively delivered to African smallholder producers.

Africa will need its own Green Revolution to generate the productivity gains required to feed and economically sustain rural and urban populations throughout the twenty-first century (Khush 1999; Ejeta 2010). Reducing Africa's hunger by one-half, as willed by the Millennium Challenge, would require cereal yields to increase by at least 50 % over the next two decades. Africa's agricultural community will need to rival the productivity gains achieved by their counterparts in developed countries. In the USA, for instance, the science-based transformation of agriculture following World War II has increased cereal yields by an average annual rate of 2.1 % over the past few decades (Paarlberg and Paarlberg 2000). Even if SSA were to match those productivity gains achieved in the USA over the next two decades, cereal yields would only increase by 42 %, falling several percentage points short of reaching the milestones set by the Millennium Challenge. Aware of the daunting challenge, Kofi Annan (as acting UN Secretary General) pronounced the need for a dramatic transformation of Africa's agriculture, sounding the call for an African Green Revolution in the twenty-first century. Since then, major donors such as the Bill & Melinda Gates Foundation and the Howard G. Buffett Foundation have stepped forward. In 2006, the Alliance for A Green Revolution in Africa (AGRA) was founded by the Gates and Rockefeller foundations with its primary mission to drive agricultural transformation, similar to the way that Winrock International has promoted improvements in Asia and Latin America over the past few decades (Toenniessen et al. 2008).

Since Africa was largely bypassed by the Green Revolution that transformed Asia and Latin America, the emerging challenge for Africa is to identify new and innovative solutions that will address its agricultural production needs in full consideration of its unique environmental conditions as well as its social, cultural, and economic institutions. An African Green Revolution would generate substantial benefits by unleashing Africa's full agricultural potential. Decades of constraints on productivity growth has created a large yield gap between yields obtained by SSA farmers on their farms versus the much higher yields reported in field crop research. An African Green Revolution would close that yield gap through the introduction of modern crop protection techniques, soil nutrient management, and improved germplasm (Ejeta 2010; Toenniessen et al. 2008).

11.1.2 Potential Role for Agricultural Biotechnology in Sub-Saharan Africa

An African Green Revolution in the twenty-first century would be able to capitalize on new disciplines such as biotechnology and bioengineering, which could provide farmers with new types of crop technology that weren't available during the Asian and Latin American Green Revolutions (Borlaug 2000; see Borlaug et al., Chap. 12). Developed over the last decades of the twentieth century, biotechnology is expected to continue to result in dramatic technical breakthroughs as crop scientists continue to utilize genetic markers to accelerate breeding improvements and develop new genetic insertions (transgenes) to enhance agronomic and yield characteristics (Perlak et al. 1990). Unlike the Green Revolution of the previous century, which, for various reasons, did not benefit Africa as it did Asia and Latin America, biotechnology may be expected to address an array of agronomic constraints of great importance to SSA, including drought tolerance (Paarlberg 2008; see Oikeh et al., Chap. 13). Existing biotechnology traits can provide immediate benefits and improved efficiency in two principal areas: weeds and insect pests (Purcell and Perlak 2004). Bt crops, for instance, produce proteins that are toxic to certain economic insect pests and thus protect the growing crop from damage from those pests, e.g., Bt cotton and Bt maize (Perlak et al. 1990). Herbicide tolerant crops (see Lee et al., Chap. 10) are genetically altered to withstand the application of certain broad spectrum herbicides, enabling growers to control weeds effectively by spraying directly over their growing crops, e.g., Roundup Ready crops (Liang and Skinner 2004). These technologies could provide positive impacts in several major crops of importance to SSA, including cotton, maize, and cowpeas. In the long run, with focused research and investments in human capital, biotechnology interventions are also expected to make substantial contributions through the development of drought tolerant and disease resistant crops (Paarlberg 2008).

For biotechnology to make a significant impact on SSA agriculture, adoption rates will need to be greatly accelerated (Paarlberg 2008). Africa's overall use of biotechnology still lags far behind adoption rates seen throughout many regions of the world (James 2011). Although GM crop advantages are generally scale-neutral, benefiting both the smallholder as well as the large commercial producer, the biotechnology debate in Africa has been divisive (Vitale et al. 2011). Concerns over the boundaries of science have been loudly voiced by special-interest groups, which have influenced African policy on biotechnology (Paarlberg 2001; Spielman 2007). Regulatory and institutional constraints imposed by many African governments have delayed the introduction of bioengineered crops, while the commercial release and adoption of biotech crops have proceeded on most other continents (Cohen and Paarlberg 2002). In cotton, for instance, the adoption of Bt cotton has taken place on a global scale, yet Africa accounts for a disproportionally small percentage of Bt cotton acres. Since its 1996 debut on American cotton farms, the global adoption of Bt cotton has increased to 10 million ha in nine countries (James 2009). Of the 10.3 million farmers growing biotech crops in 2006, close to 90 % were small resource-poor farmers from developing countries (James 2006). Africa accounted for less than 1 % of the world's area of Bt cotton even though it produces 20 % of the world's cotton (James 2006).

11.1.3 Burkina Faso Explores Biotech (Bt) Cotton

While opposition to biotechnology in Africa has largely kept biotech crops off the continent, Burkina Faso has emerged as one of the most biotech-progressive countries in Africa (Vitale et al. 2011). In 2003, in collaboration with the Monsanto Company, Burkina Faso began a 5-year program of field testing Bt cotton, initially on government experiment stations and later in open-farm tests (Vitale et al. 2008). As field testing was being conducted, biosafety legislation and protocols governing regulatory oversight and approval of biotechnology products were developed by the government. Also during this time a cooperative research agreement between Monsanto and the Burkina Faso government enabled the introgression of the Bt technology into Burkina Faso's locally adapted cotton varieties. The Government of Burkina Faso approved Bt cotton varieties for commercial release in 2008. The first year of commercial release, 2008, was primarily for commercial seed production. In the following year, however, Bt cotton was sold broadly to Burkina Faso cotton producers. By 2010, Burkina Faso planted 270,000 ha of Bt cotton (roughly 63 % of the country's cotton acreage), marking it as the largest ever introduction of a biotech product on the African continent.

The introduction of Bt cotton in Burkina Faso is a watershed event for biotechnology in Africa. If Bt cotton is successfully introduced in Burkina Faso, it is expected to spur the introduction of Bt cotton elsewhere in SSA. Burkina Faso's experience with Bt cotton is well representative of the conditions and hurdles that biotechnology will face elsewhere in Africa. The 2009 introduction marked the culmination of several years of work in developing the scientific, legal, and business infrastructure to enable the commercial release of Bt cotton. By doing so, Burkina Faso has shown that biotechnology can be introduced even in countries where capacity is initially lacking, but through coordination and linkages between stakeholders representing the interest of the seed industry, government, ginners, and producers, the necessary institutional frameworks can be developed. Subsequent introduction of Bt cotton could then take place in neighboring countries that share similar agro-ecological zones, farming systems, and cotton industry structures (e.g., Mali). Success with Bt cotton could also make it easier for other GM crops to be introduced, such as Roundup Ready Bt cotton and Bt maize. In the long term, biotechnology is expected to address additional constraints and crops. The WEMA (Water Efficient Maize for Africa) project (see Oikeh et al., Chap. 13), for instance, is a partnership of several African governments, AATF, CIMMYT, and Monsanto, with funding from the Bill & Melinda Gates and Howard G. Buffett foundations. As its name implies, its goal is to eventually provide small growers with maize varieties that utilize water more efficiently.

The African debate on biotechnology is expected to intensify and focus on Burkina Faso over the next few years, attaching regional and global importance to its ongoing experiment with Bt cotton. Even though Bt cotton has obtained commercial success in its first couple years of introduction and has been widely adopted by producers, there is a critical need to evaluate the performance of Bt cotton. Experience in other countries has found various constraints that can limit and even reverse the introduction of Bt crops. Unfavorable seed pricing and poor yield performance have been reported in India, while the lack of an adequate credit and marketing system has limited the adoption of Bt cotton in South Africa. In China, poor management of secondary pest problems and the erosion of pesticide input savings have been reported in some areas. Hence, identifying the initial trends in Bt cotton's performance over its initial 3 years of use in Burkina Faso is important so that its potential for sustainability over the long term can be assessed.

11.2 Development and Growth of Africa's Cotton Sector Since Independence

11.2.1 Cotton Is a Good Fit for West Africa

Cotton is one of the most important crops in West African agriculture. In the grassy savannas of West Africa that span from Western Mali to Chad, cotton is the economic catalyst in rural communities where it accounts for the majority of farm income and rural employment (Vognan et al. 2002). Cotton has been a particularly important source of economic growth in rural areas where economies are built around the crop (Bingen 1998). In Burkina Faso, over 2.2 million Burkinabé derive their income from producing, ginning, or transporting cotton (CARITAS 2004; Elbehri and MacDonald 2004). Rural households are highly dependent upon cotton for supplying their basic needs, as cotton typically accounts for 60 % of household income (Vognan et al. 2002). Public services such as schools, roads, public heath, and a variety of agricultural extension services have traditionally been provided by cotton revenues. The cumulative effects of these investments have been responsible for alleviating rural poverty in many of the areas where cotton has been successfully introduced (Bassett 2001).

Cotton is well adapted to local environments, and when integrated into a mixed farming system with cattle and cereal crops, it is one of only a handful of cropping systems in SSA identified by the InterAcademy Council (2004) as being capable of

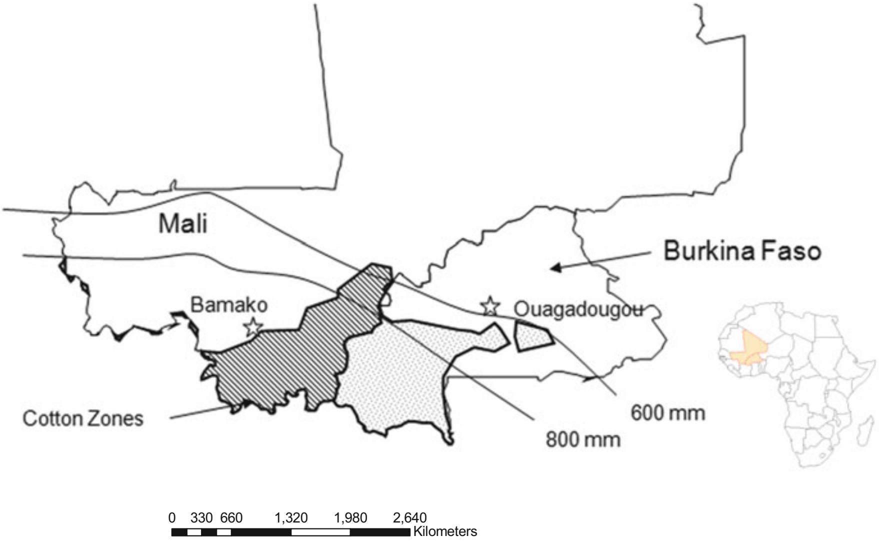

Fig. 11.3 Cotton production zones in Mali and Burkina Faso are found primarily above the 600 mm isohyet line where rainfall averages 600 mm year^{-1}

significant productivity increases over the long term. Cotton production in Mali and Burkina Faso occur primarily in the Sudanian (600–800 mm) and Sudano-Guinean (800–1,100 mm) agro-ecological zones (Fig. 11.3). Cotton is produced in Burkina Faso, and throughout West Africa, by smallholder producers. On average, a Burkina Faso cotton farm will plant about 3.8 ha of cotton in a 3-year rotation with maize, or perhaps another cereal crop such as sorghum or millet (Vitale et al. 2010). Cotton lint yields average about 450 kg ha^{-1}, which is quite good for rainfed conditions in the above-mentioned agro-ecological zones. Burkina Faso's yields compare favorably with many other parts of the world, although significantly lower than those typically seen in the USA, around 900 kg ha^{-1} (Willams 2010). Burkina Faso is able to make up for some of the yield gap since it often has a slightly higher quality than machine picked cotton. Compared to US cotton producers, Burkina Faso cotton producers spend about 73 % less per ha on their variable production costs, which includes items such as seeds, fertilizers, insecticides, and labor (Vitale et al. 2011). US cotton farmers spend considerably more on fixed costs, about $119 per ha, than Burkina Faso cotton farmers (Vitale et al. 2011). The higher returns obtained by US producers result only from the higher cotton prices that US cotton farmers receive, since the Burkina Faso producer holds a competitive advantage in production costs. Average cotton production costs in Burkina Faso are $0.30 per kg compared to $0.46 per kg in the USA (Vitale et al. 2011).

11.2.2 Cotton in Regional and Global Economies

Cotton is also a major source of economic growth and development at the macro level. Since the early 1960s when the independence movement swept through the region, cotton has become the region's "white gold," one of the leading sources of export earnings and hard currency for governments. Following independence, most West African countries nationalized key industries, particularly export driven ones like cotton. The socialization of cotton production enabled governments to generate revenue by maintaining direct control over the distribution and marketing of cotton's input and output channels. This implicit "taxing" of cotton exports has provided substantial earnings since cotton's share of GDP reaches up to 10 % in countries such as Burkina Faso and Mali. In Burkina Faso, for instance, cotton generates revenue in excess of $320 million, over 51 % of Burkina Faso's export earnings, and in Mali cotton exports account for 25 % of total export earnings (Vitale et al. 2010).

While West Africa accounts for only a small portion of world cotton production, typically about 5 %, it is an increasingly important player in the world market. West Africa is now the second leading exporter of cotton in the world, trailing only the USA in world market share. Led by the big four countries of Burkina, Mali, Benin, and Cote D'Ivoire, West Africa's share of world cotton exports rose from 2.4 to 9.4 % over the past 20 years (Goreux 2003). Exporting nearly all of its' cotton production,[1] West Africa produces cotton fiber of relatively high quality[2] and retains low production costs through its reliance on manual production techniques and the low opportunity cost of household labor. Higher transportation costs in reaching ports, however, erode some of West Africa's cost advantage in the land locked countries of Burkina Faso, Mali, and Chad.

11.3 Sustaining Cotton Production in SSA

11.3.1 History of Cotton in West Africa

Cotton yields throughout SSA have followed the same general pattern as maize yields over the past few decades, with performance that has lagged behind most other parts of the world (Fig. 11.4). While cotton yields doubled between 1961 and 2009 in SSA, yields in other key cotton producing countries, such as Australia and

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[1] In most years West Africa exports 97 % of its cotton production to the world market (ICAC 2006).

[2] Most of West Africa's cotton lint is of medium to medium-high grade. Quality issues would be further enhanced if contamination was reduced and segregation improved. Moreover most West African cotton has been bred to provide seed cotton with a high lint percentage by weight (gin turnout). The 42 % gin turnout seen in Mali is much higher than most US varieties (ICAC 2006).

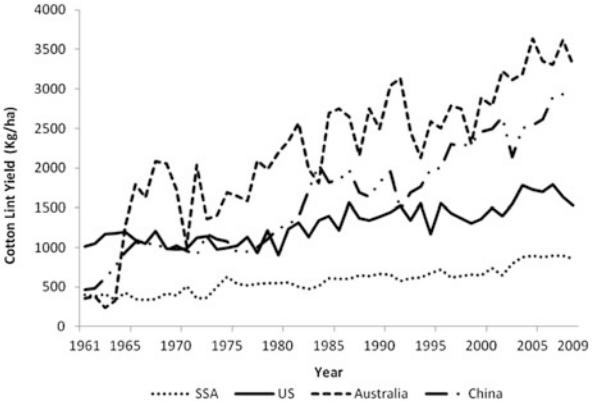

Fig. 11.4 Cotton yield comparisons between SSA and other countries. *Source*: FAO (2011)

China, more than tripled during that same time period (Fig. 11.4). Although cotton yields remain lower than world benchmark levels, the development of the West Africa cotton sector has, however, been one of the major agricultural success stories in the region, particularly when compared to the underperformance of cereal crops (Bingen 1998; Sanders et al. 1996; Lele and Adu-Nyaka 1992; Bassett 2001). Prior to independence in the early 1960s, cotton was produced under French colonial control, an era structured primarily on "command and control" dictates from colonial authorities, often ignoring the economic and social welfare of rural households (Roberts 1996; Bassett 2001). Cotton was labor-intensive, produced using traditional, low input practices including hand-to-hoe plowing, and extremely low cotton yields.

Following the French colonial period, however, cotton "took off" in West Africa during the early years of independence beginning around 1960 (Sanders et al. 1996). Between 1961 and 1978, cotton yields more than quadrupled in Burkina Faso, and more impressive gains were achieved in Mali where seed cotton yields increased from 138 to 1,089 kg ha^{-1} between 1961 and 1978 (Vitale et al. 2011). The higher cotton yields achieved by West African countries are evident in Fig. 11.4, but their effect is reduced due to underperformance in other cotton producing countries throughout SSA where the impact of independence had a negative effect on cotton production. The cotton development efforts of CIRAD (Centre de coopération internationale en recherche agronomique pour le développement) during the 1960s and 1970s extended the use of modern inputs such as chemical fertilizers, insecticides, herbicides, and improved cotton seeds to producers in Burkina Faso, Mali, and other Francophone countries in SSA that enabled significant advances in productivity (Sanders et al. 1996). Extension services were established to work with and assist farmers in successfully adopting new cotton technologies. With these advances, the West African cotton sector quickly gained a competitive stance in world markets.

Cotton production was also increased through an expansion in the cotton land base in SSA (Fig. 11.5). Burkina Faso's cotton acreage, for example, increased from 42,000 ha in 1961 to 119,000 ha in 1978, corresponding to a 283 % increase in cotton area (Vitale et al. 2011). Two decades later, in 1998, cotton acreage had

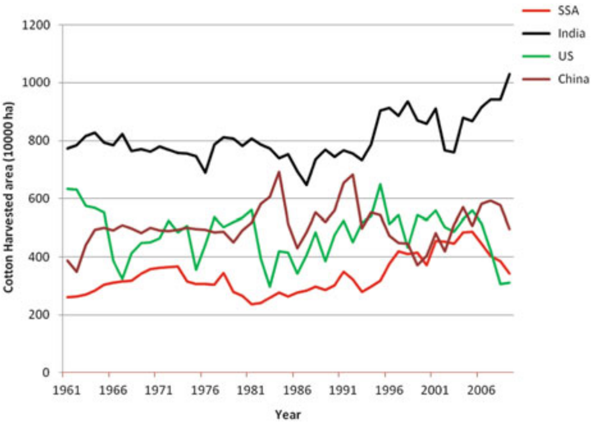

Fig. 11.5 Cotton area comparisons between SSA and other countries. *Source*: FAO (2011)

reached 504,000 ha in Burkina Faso, a tenfold increase in area planted since independence in the early 1960s. The substantial increase in cotton area was initially achieved through the introduction of animal traction in the traditional cotton growing areas, and since the early 1980s through the agricultural expansion into the sub-humid frontier (McMillian et al. 1998). Animal traction greatly increases labor efficiency in plowing, planting, and weeding operations, easing seasonal bottlenecks in labor that occur during the critical early months of the growing calendar. Postindependence development efforts were successful in increasing the adoption of animal traction. By 1990, Burkina Faso had 100,000 working draft animals and currently about 90 % of cotton producers in Burkina Faso farm with animal traction.

Despite the advances just described, the sustainability of cotton has recently been threatened in Burkina Faso and throughout most of SSA. Cotton yields continue to lag the new yield frontiers achieved in other regions such as China and Australia. Perhaps even more worrisome, however, is the significant decline in cotton area that has occurred over the past several years in SSA (Fig. 11.5). Pest problems, volatility in world cotton prices, poor institutional structure, and environmental degradation have tarnished cotton's "white gold" allure throughout much of SSA. Recurrent price collapses in world cotton markets beginning in 1999, coupled with increased production costs, have created a crisis in many parts of the West African cotton sector. Three of the larger producers in the region, Mali, Benin, and Cote D'Ivoire, became temporarily insolvent in 2000 when cotton prices went into a temporary free fall. Since then prices have recovered somewhat, but credible concerns are growing among all major stakeholders (producers, policy makers, and donors) that West Africa could lose part, or all, of its cotton sector. The tenuous nature of cotton production is a reality experienced elsewhere, as well. In many parts of the world cotton has been a difficult crop to sustain over the long term, facing similar agronomic, institutional, and environmental challenges which include water shortages. The history of the US Southern Plains, where cotton production went from boom to bust in a mere 20 years (1920–1940), is a reminder of the potential fragility of cotton. Already in Mali, for instance, producers have begun to shift cotton acres into maize and other cereal crops in order to better generate higher and more stable farm income (Baquedano et al. 2010).

11.3.2 Pests Threaten Cotton Sustainability in West Africa

There is growing evidence that cotton yields have begun to decline in Burkina Faso and Mali, posing a clear threat to sustainability if the trend continues (Baquedano et al. 2010; Vitale et al. 2011). Over the past two decades, damage caused by insect pests has become a major issue confronting the West Africa cotton sector, which has been a contributing factor to the recent cotton yield declines (Banwo and Adamu 2003; Oerke 2002). In Sub-Saharan Africa, pests are a large problem since favorable climactic conditions allow multiple pest generations per year, fostering heavier pest densities (Abate et al. 2000). The larva of *Helicoverpa armigera* (Order: Lepidoptera; Family: Noctuidae), or the cotton bollworm, is the main cotton pest in Burkina Faso and throughout West Africa (Vaissayre and Cauquil 2000). On unprotected fields, Burkina Faso researchers claim that insect pests can damage up to 90 % of the cotton crop (Traoré et al. 1998). In severe infestations, pests leave so little behind that the most cost-effective alternative is often for farmers to abandon their fields (Traoré et al. 1998). Pests compete directly with the farmer for yields, reducing profits. The economic losses from pest infestations are more problematic in smallholder production where food security can be jeopardized, particularly since rural households value food at a premium to cover high marketing costs (De Janvry et al. 1991). Insect problems are expected to worsen over the coming decades throughout the West Africa region. All of the major global climate change models forecast higher temperatures that will potentially promote higher pest populations within the region (Hulme 2005; Pimentel 1993).

Over the past 10 years, *H. armigera* control measures have not been successful in controlling pest populations (Programme Coton 1999). Conventional pest control measures have been losing their effectiveness as pest populations have developed resistance to pyrethroid insecticides, the primary agents used in Burkina Faso from 1985 through 2000 to control *H. armigera* (Programme Coton 1999; Goldberger et al. 2005; Martin et al. 2002). As chemical agents have grown increasingly ineffective, Burkina Faso farmers have intensified the use of insecticides, especially where cotton production has expanded into more marginal agricultural lands along the frontier where pest populations are often greatest (McMillian et al. 1998). In addition to becoming increasingly ineffective and costly, conventional pest control has also become more hazardous to human and animal health due to increased use of more broadly toxic endosulfans (Vognan et al. 2002). The commonly used pesticides in West Africa contain chemical compounds that are toxic not only to pests but also to humans when safety precautions are not followed. The spraying methods currently used by farmers (typically back-pack sprayers) often present significant health hazards (Ajayi and Waibel 2003; Drafor 2003; Maumbe and Swinton 2003). Poisoning incidents among cotton producers in West Africa are common with many occurring due to endosulfan (Glin et al. 2006). In Benin, numerous cases have been reported in recent years, including 105 poisoning cases in the 2007/08 cotton growing season (Badarou and Coppieters 2009). Kodjo (2007) reported that endosulfan poisoning cases typically reach 500 per annum. Later in this chapter, we report that 77.4 % of pesticide poisoning cases over a 3-year period (2008–2010) were endosulfan based.

In a typical year, Burkinabé farmers spend roughly $60 million on insecticides to control Lepidoptera and other pests (Vognan et al. 2002; Toe 2003). Conventional pest control methods, utilizing six sprays throughout the growing season, protect only about 11 % of the cotton yield from pest damage; about 23 % of the cotton yield will still be lost and as many as ten sprayings may be required (Oerke 2002). West African cotton farmers incur yield losses ranging between 20 and 65 % from pest and insect damage (Tefft 2004; Oerke et al. 1999). In Burkina Faso, cotton yield losses often surpass 30 % on fields treated with recommended insecticide applications (Vaissayre and Cauquil 2000; Goze et al. 2003; Traoré et al. 2006). By comparison, about 15 % of the yield gains were achieved through significant advances in cotton technology that increased productivity. Global cotton production is lost to insects every year (Oerke 2005).

Secondary pest problems from piercing and sucking insects are also growing in importance. The most common sucking pests are the jassids (*Empoasca facialis*) and aphids (*Aphis* spp.). Cotton producers typically spray twice a year for the piercing and sucking insects and wait until boll formation has occurred to control them. Cotton yields have also been negatively influenced by soil nutrient depletion and other stresses caused by environmental degradation (Vognan et al. 2002). Studies indicate a declining nutrient balance (NPK) through southern Mali and failure of producers to provide their fields with adequate levels of organic fertilizers (Tefft 2004).

11.4 The Introduction of Bt Cotton in Burkina Faso

11.4.1 What Is Bt Cotton?

Opportunities to increase cotton yields through conventional approaches, e.g., increased fertilization and improved germplasm, have largely been exhausted in West Africa, but Bt cotton may offer producers an alternative approach to raising cotton yields through improved pest management that reduces production costs while exhibiting benign effects on the environment (Huesing and English 2004). Bt cotton was developed using genetic engineering techniques that inserted genes into cotton to encode and promote the production, within the plant, of proteins toxic to certain caterpillar pests of cotton (Perlak et al. 1990). In Bollgard II, these proteins, Cry1Ac and Cry2Ab, are encoded by genes originating from the common soil bacterium *Bacillus thuringiensis* (Bt). These Cry proteins are both highly effective in killing certain lepidopteran larvae (caterpillars) (Greenplate et al. 2003). Once ingested, the Cry proteins bind to specific molecular receptors on the lining of the caterpillar's gut where they create holes and quickly cause death (Hofte and Whiteley 1989). Individual Cry proteins are highly specific to certain caterpillars but do not target other insects (Hofte and Whiteley 1989; MacIntosh et al. 1990; Sims 1997), unlike conventional pesticides, many of which kill across a wide spectrum of both targeted and non-targeted (sometimes beneficial) insects. Formulations of microbial Bt fermentation products, containing Cry proteins, have been used for more than 60 years as natural insecticides in spraying programs in agriculture and forestry pest control (Aronson et al. 1986). While these Bt formulations can be quite effective under certain conditions, the products have never been widely adopted in crops such as cotton for various reasons. Cry proteins have short half-lives when placed under field conditions due to UV light degradation and other environmental factors. Many types of insect larvae may escape control by these products if spray coverage is not optimal, including wash-off when applied. Fermented Bt products are relatively expensive compared to conventional control methods due to the high costs of fermentation. Interestingly, these Bt fermentation formulations are regularly used as "natural" insecticides in the smaller market of organic cotton and other high valued niche crops (Coleman 2012).

11.4.2 Burkina Faso Becomes Interested in Bt Cotton

Discontent and frustration with conventional pest control methods prompted Burkina Faso's initial interest in Bt cotton. Stakeholders in the Burkina Faso cotton sector began to explore new pest control options to increase productivity, improve the competitiveness of Burkina Faso cotton growers in international markets, and reduce the environmental and health consequences of chemical sprays. International donors (USAID) and regional organizations (ECOWAS) were successful in making Burkina Faso cotton stakeholders (cotton companies and producers) and national research institutes (INERA) aware of the benefits of Bt cotton at conferences and workshops, fueling interest in the technology. In May of 2000, the first biotechnology meeting took place in Ouagadougou, Burkina Faso, where the cotton growers union (UNPCB) and Cotton Companies of Burkina (APROCOB) were briefed on experiences from other parts of the world describing the benefits of Bt cotton. The May 2000 meeting was the first step taken towards establishing regulated Bt cotton field trials with seed industry leaders Monsanto and Syngenta.

11.4.3 Burkina Faso Builds the Framework to Evaluate and Approve Bt Cotton

Conducting the field trials required the development of legal and technical frameworks, including biosafety legislation to formalize regulatory oversight for the research and commercialization of agricultural biotech products. The government Ministries of Agriculture, Environment, and Research and Higher Education became heavily involved in research and oversight. Burkina Faso's national agricultural research center, Institut de l'Environnement et de Recherches Agricoles (INERA), claimed the responsibility for conducting the primary research needed to test Bt cotton, including the implementation of compliance measures with biosafety protocols. The Professional Association of Cotton Companies of Burkina (APROCOB) and the national cotton producer cooperative association, or growers' union (UNPCB), played key roles in the commercialization process, providing technical and managerial assistance as needed.

The Ministry of Environment (MOE) was tasked as the primary legal authority in the commercialization process and was given charge of developing a regulatory infrastructure, consistent with the new Biosafety laws, to govern testing, development, and subsequent environmental release. The National Biosafety Agency, within the MOE, was established by 2006 and became the competent authority establishing standards for submitted regulatory dossiers and granting approval for field testing and the eventual commercialization of Bt cotton. A portion of the resources required for the testing and commercialization process along with collaborative input on research protocols was provided by Monsanto, drawing on past experiences commercializing Bt cotton in other world geographies. Monsanto's role included assistance in transferring the Bt genes to two of the regional commercial cotton varieties grown in Burkina Faso.

Burkina Faso's national agricultural research center, INERA, conducted the 3 years of field trials from 2003 to 2005. The field tests were conducted as part of research agreement between INERA and Monsanto. The initial tests were conducted under confined conditions and designed to evaluate efficacy and environmental effects, including pollen-mediated gene flow, and effects on nontarget arthropods, including bees. Tests were conducted on two INERA research stations in opposite ends of the country (Farako-Bâ located close to Bobo-Dioulasso in the west and Kouaré located close to Fada N'Gourma in the east). The field research evaluated the effectiveness of Monsanto's Bollgard® II and Syngenta's VIPCot® within the climate and insect conditions specific to Burkina Faso (Vitale et al. 2008; Hema et al. 2009). In 2006, the National Biosafety Agency approved an additional confined field trial outside of the INERA research farm environment; this Bollgard II (BG II) field trial was located on a seed-treatment farm in Boni located about 120 km from Bobo-Dioulasso. The Boni trial represented the first test of Bollgard II technology in the two local germplasm varieties.

11.4.4 Promising Preliminary Results

Results of Burkina Faso's first 4 years of research on Bt cotton were encouraging. On average, Bt cotton increased yields by 35 %, reaching as high as 48 % in one of the years. The study also found that the number of pesticide treatments required each year could be reduced from six to two, eliminating the need for the initial four sprays targeting caterpillar pests. The retention of two late-season sprays to control secondary pests, those not targeted by the Bt proteins (aphids and jassids), was recommended by INERA scientists based upon their studies with BG II. A reduction in both pesticide use and number of treatments made it possible to save $27.83 per ha, a 62 % cost reduction, based on the trial results (Vitale et al. 2011).

In July 2007, Bt cotton achieved another important milestone when the National Biosafety Agency gave its approval to conduct more numerous larger trials much closer to the real operating conditions of cotton growers. That year also marked the first year of large-scale testing of BG II in the local germplasm varieties. In collaboration with the cotton companies and the cotton growers union, INERA conducted field trials of these two local varietal versions of Bollgard II on 20 testing sites within the cotton growing zones under the control of the three major cotton companies SOFITEX, SOCOMA, and Faso Coton. All trials were carried out applying appropriate established biosafety protocols. The 2007 test results were also encouraging, with average cotton yield increases of 20 % when comparing Bollgard II to conventional cotton sprayed with insecticides.

11.4.5 Commercial Introduction and Marketing of Bt Cotton in Burkina Faso

In June of 2008, the National Biosafety Agency authorized the commercial planting of BG II in Burkina Faso. This was a significant accomplishment for Burkina Faso, marking the first commercial use of Bt cotton in the country and only the third commercial release of a bioengineered crop in Africa. In the 2008 cotton growing season, SOFITEX, together with its contract seed producers, planted 15,000 ha of the above-mentioned two local varieties containing Bollgard II. The modest area of 15,000 ha was due to the limited supply of BG II seed available at that time and represented a seed multiplication year for the anticipated broad commercial deployment that occurred in 2009.

In addition to the trials demonstrating the safety and potential value of this technology, the commercial introduction of Bollgard II in Burkina Faso also required the development of a business model linking public and private sectors (public-private partnership; see Oikeh et al., Chap. 13). A business model was developed over time as a result of meetings and negotiations among the key cotton stakeholders: UNPCB, APROCOB, GoBF, and Monsanto. The business model required an innovative approach to enable Bt cotton seed to be distributed in

Burkina Faso's marketing channels that remain vertically controlled by APROCOB. Under this cotton industry structure, an equitable scheme of benefit sharing had to be arranged among APROCOB, UNPCB, and Monsanto while also accounting for risk and uncertainty in returns on investment.

Although cotton reform and the breakdown of vertically controlled cotton sectors has been recommended by many donor agencies over the past decades as part of structural adjustment, the parastatal structure made it easier to handle the potentially overwhelming problem of having to sell and contract Bt cotton seed to a large population of smallholder producers that number about 300,000. Under a more typical marketing channel, it would be costly for seed companies to adopt their usual approach of dealing directly with producers in signing contracts and enforcing legal compliance to prevent reselling and reusing Bt cotton seed. However, under the vertically controlled cotton industry in Burkina Faso, Bt technology was able to be inserted further upstream in the supply chain and marketed directly to APROCOB. This greatly reduced the number of contracts and agreements from a number as large as 300,000 down to a few representing the members of APROCOB. This marketing arrangement does, however, transfer much of the legal burden from the producers to APROCOB. The resulting business model formed what might be considered a hybrid public–private partnership between Monsanto and the three national cotton companies, all of which were shared in ownership by the GoBF, private entities, and UNPCB. A pricing structure was negotiated under which most of the value added by Bollgard II (as determined by INERA's in-country testing) was to be retained at the farm gate with the grower. As reported later in this chapter, over the first 3 years of commercial use producers earned an average of $64.57 per ha, which equates to 53.8 % of the total value added from Bollgard II in Burkina Faso.

11.5 Measuring the Impact of Biotechnology in Burkina Faso

11.5.1 Introduction

This section presents findings from 3 years of field surveys documenting the socioeconomic and health impacts of the adoption of Bt cotton (BGII) among smallholder cotton farmers in Burkina Faso. The Burkina Faso field surveys are of particular interest since the empirical evidence of Bt cotton performance in SSA is limited to only a handful of studies in the Makhatini Flats of South Africa, where Bt cotton has been grown since 2001 (Ismael et al. 2001; Gouse et al. 2004; Hofs et al. 2006; Ismael et al. 2001). While results varied across the studies, each one found that Bt cotton was successful on both commercial and smallholder farms. Cotton yield increases of approximately 25 % were achieved with Bt cotton in the Makhatini Flats, accompanied by reduced spraying costs of 66 % and an average increase in farm income of \$137 ha^{-1}. Much less evidence is available regarding the impact of Bt cotton on improving human health through reduced pesticide use. Although none of the Makhatini Flats studies included health impacts, significant levels of poisoning incidents caused by pesticides have been documented in Zimbabwe, Ghana, and Benin. Hence, the Burkina Faso field surveys presented in this chapter contribute greatly to the available literature on the impact of Bt on both socioeconomic and human health indicators in SSA. As presented later in this chapter, the surveys project that across the 3 years of surveys Bollgard II reduced the number of pesticide poisonings by an estimated 30,380 cases and a corresponding benefit to producers of \$3.27 million from non-incurred medical expenses and lost wages.

11.5.2 Burkina Faso Producer Surveys

Household surveys were conducted by INERA over a 3-year period (2009 through 2011) to assess the impact of Bollgard II on various social, economic, and health impact indicators. The INERA surveys were conducted with a representative sample from the three main cotton growing zones, each controlled or administered by a separate cotton company: SOFITEX in the west, SOCOMA in the center, and Faso Coton in the east. The survey villages were randomly selected and represent typical conditions in each of the cotton zones. A total of ten villages were included in the survey, and within each village households were randomly selected. The number of surveys increased for the third year. The survey instrument was developed by INERA researchers at the Programme Coton research center in Bobo Dioulasso, Burkina Faso, and was administered by local extension workers.

The household surveys had three parts. The first part included demographic and other background information to characterize households on land and livestock holdings, age, and gender of occupants, household farm labor, and income. The second part of the survey collected information on production practices and other variables required for estimating the economic impacts of BG II. This included the number and type of insecticides applied on cotton fields, fertilizer applications, seeding density, labor demands, and herbicide applications. Cotton yields were measured by INERA agronomists at harvest time for each of the household's fields. In the third part of the survey, households were queried on their history of pesticide use to document self-reported cases of poisonings over the past 7 years.[3] For each poisoning case, households were also asked to provide additional information on the severity of illness, days of lost labor, and medical expenses incurred.

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[3] This chapter only reports on the occurrences of pesticide poisonings. Additional questions elicited information on the handling, application, disposal, and other safety issues related to pesticide use.

11.5.3 Yield Impact

One of the most important and widely reported measures of agronomic performance is the generation of higher cotton yields. Since cotton yields are influenced by effects other than the presence of the Bt genes, e.g., rainfall, farm management practices, and pest pressure, an analysis of variance (ANOVA) model was constructed to explain cotton yields. Using ANOVA, the significance of the Bt genes on cotton yield can be rigorously tested from the observed data, reducing the bias that would occur if statistical inferences were based on *t*-test comparisons of population means. An ANOVA model of cotton yield was estimated that explained yields using gene type (GENE), location (ZONE), farm size (TYPE), and the number of late season sprays (SPRAYS) using the following equation:

$$\text{Yield} = \text{GENE} + \text{ZONE} + \text{TYPE} + \text{SPRAYS} + \text{YEAR} \qquad (11.1)$$

Gene type (GENE) had two effects levels, one for Bt cotton (BG II) and the other for conventional cotton. The farm size (TYPE) effect had three levels for large, small, and manual (hand-hoe) farms. The location (ZONE) effect included three survey sites, one in each of the cotton company zones of operation: SOFITEX, SOCOMA, and Faso Cotton. The number of late season pest sprays (SPRAYS) was included as a treatment effect with three levels, since many BG II producers did not follow the recommended regimen of two late season sprays (2) and instead either did not spray (0) or sprayed only once (1). The ANOVA yield model also included three interaction terms, one for the interaction of gene type with each of the other three effects. The interaction terms were included to test whether the Bt effect varied significantly across the remaining three effects, i.e., whether the Bt technology had a biased effect across farm size, location, or late-season spray. The ANOVA yield model was solved using the PROC GLM statement in the SAS statistical software package.

11.5.4 Economic Impact

The economic impact of Bollgard II was assessed by measuring the change in cotton profit from producing Bollgard II relative to conventional cotton using partial budget analysis (Kay et al. 2006). This is a farm accounting statement that reports only the revenues and costs that vary as a result of changes in farm management practices, production outcomes, and market conditions. The farm budgeting approach has been used in previous impact studies on Bt cotton (Ismael et al. 2001; Pemsl et al. 2004; Gouse et al. 2003). In this study, the partial budget analysis includes the observed changes that occur from introducing Bt cotton, namely cotton yield and changes in production costs for insecticide treatment, labor, and seed.

Using partial budgeting, the economic impact from growing Bollgard II for a producer is obtained from the following equation:

$$\begin{aligned}\Delta\text{Income} = {} & P \times \text{AREA} \times \Delta\text{YIELD} \\ & - (\Delta\text{INSECT} + \Delta\text{LABOR} + \Delta\text{SEED} + \Delta\text{OTHER})\end{aligned} \tag{11.2}$$

where ΔIncome is the economic impact for a typical producer, P is the price for harvested cotton paid to producers, AREA is the area of Bollgard II cotton planted, ΔYIELD is the yield difference between BG II and conventional cotton, ΔINSECT is the difference in insecticide treatment costs, ΔLABOR is the difference in labor costs, ΔSEED is the difference in seed costs, and ΔOTHER is the difference in other costs such as fertilizer that could vary between BG II and conventional cotton. Equation (11.2) states that the economic impact is given by the change in revenue, the first term on the right hand side of the equation, less the incremental changes in production costs from growing Bollgard II.

The change in yield, $\Delta\text{YIELD}_\text{i}$, is calculated as the difference between BG II and conventional cotton yields, $Y_{\text{BG II}}$ and Y_{CONV}, as follows:

$$\Delta\text{YIELD} = Y_{\text{BG II}} - Y_{\text{CONV}} \tag{11.3}$$

The changes in revenue and production costs were structured using standard farm management accounting relationships (Kay et al. 2006). The change in insecticide costs is given by the difference between the number of insecticide treatments applied on BG II cotton plots, $N_{\text{BG II}}$, and the number of treatments applied on conventional cotton, N_{CONV}, multiplied by the price of each insecticide treatment, P_{INS}. This equation is given by the following:

$$\Delta\text{INSECT} = (N_{\text{BG II}} - N_{\text{CONV}})P_{\text{INS}} \tag{11.4}$$

The change in labor costs was calculated using two components. The first was the time savings from applying insecticide, including the travel time to the field, calculated as speed of travel, SPEED, multiplied by distance traveled, DIST. The rural wage rate, WAGE, of $1.50 per day was used to value the producers time, and the travel time to the field was 5 km h^{-1} (Vitale et al. 2010). The second component was from the increased labor required to harvest cotton on the BG II plots. This was the difference between BG II and conventional cotton production, harvest efficiency, HARV_{EFF}, and was calculated as 18.9 kg of cotton per day based on field survey data. Based on those two components, the change in labor costs is given by the following:

$$\begin{aligned}\Delta\text{LABOR} = {} & -\text{WAGE} \times \text{DIST} \times \text{SPEED} + \text{AREA} \times \Delta\text{YIELD} \\ & \times \text{HARV}_{\text{EFF}}\end{aligned} \tag{11.5}$$

The change in seed costs is calculated as the difference between BG II and conventional seed costs. Since seeding density, DENSITY, could vary between BG II and conventional cotton, the change in seed costs is calculated as follows:

$$\Delta\mathrm{SEED_i} = \mathrm{AREA} \times (\mathrm{P_{BG\ II}} \times \mathrm{DENSITY_{BG\ II}} - P_{\mathrm{CONV}} \times \mathrm{DENSITY_{CONV}}) \quad (11.6)$$

Equations (11.2) through (11.6) were calculated using data from the household surveys and also data obtained from the cotton companies and UNPCB, which provided input prices and the cotton price paid to producers. For instance, the price paid to producers in 2009 for harvested cotton was \$0.366 kg^{-1} of raw seed cotton (harvested lint plus seed). The price of BG II seed for planting was \$5 kg^{-1} in 2009, which corresponded to a cost of \$50 ha^{-1} for a typical seeding density of 10 kg ha^{-1}. Conventional cotton seed for planting, sold to producers from the national cotton company, was \$0.89 kg^{-1} in 2009 and corresponded to a cost of \$8.88 ha^{-1} based on a typical seeding density of 10 kg ha^{-1}. Prices were updated for 2010 and 2011 growing seasons.

The economic impacts are estimated using an analysis of variance (ANOVA) model to avoid biasing the effect of the Bt genes on economic profits analogous to the potential bias when explaining cotton yield. An ANOVA model was constructed that explains the economic impacts from Eq. (11.2) using gene type (GENE), location (ZONE), farm type (TYPE), and the number of late season sprays (SPRAYS):

$$\mathrm{IMPACT} = \mathrm{GENE} + \mathrm{ZONE} + \mathrm{TYPE} + \mathrm{SPRAYS} \quad (11.7)$$

The ANOVA economic impact model in Eq. (11.7) was solved using the PROC GLM statement in the SAS statistical software package, including interaction terms as discussed above.

11.5.5 Health Impacts

Human health concerns increase as agricultural systems are intensified with the greater use of chemicals and other toxic agents. Africa's overall use of agrochemicals is substantially lower compared to use by commercial producers in the USA and other parts of the world. Cotton, however, is a noticeable exception in Africa; fertilizers and pesticides are applied at levels close to those used by cotton producers in the USA, Australia, and Asia. The intensive use of agrochemicals, often multiplied due to the buildup of resistance among pest populations, creates the potential for health and environmental hazards for producers and surrounding communities.

Cotton is one of the most intensively managed crops wherever it is grown, and its negative impact on human health has been the focus of studies in the USA. Farmer health issues have begun to emerge as a significant problem in African agriculture. While studies have documented the hazards to human health from the use of pesticides on cotton fields, many cases remain undocumented due to the poor public health infrastructure in rural areas. Producers have limited access to medical facilities and few African countries monitor poisoning incidents.

Pesticide use is generally more hazardous in Africa than elsewhere. Information on how to safely apply, store, and dispose of chemical pesticides is often not available to producers due to weak extension services and producer illiteracy. Government regulations regarding safe pesticide use may not exist or are not adequately enforced. Even when properly informed, African cotton producers often lack the means to purchase adequate safety equipment. When pesticide incidents do occur, even mild cases can turn severe. Missing medical insurance markets and low household incomes restrict producer's ability to access medical treatment, often leading to self-diagnosis and self-treatment of poisoning symptoms. Poisoning incidents inflict damage not only on the health and physical well-being of the cotton producer but also on economic livelihoods. Antle and Pingali (1994) report a significant relationship between producer health and agricultural productivity, including how pesticide use among Philippine farmers led to a decline in agricultural productivity.

Despite the growing importance of farmer health issues in Africa, there is limited empirical evidence on the prevalence and severity of poisoning incidents in Africa. The practices employed by producers when pesticides are applied have been identified as a significant factor leading to illness when adequate safety measures are not followed (Maumbe and Swinton 2003). A priori, it was thus hypothesized that the use of safety measures such as protective clothing (gloves, shirt, pants), respirator, washing clothes, showering, and rinsing equipment immediately after application and the proper storage/disposal of left-over/empty pesticide containers were factors influencing the likelihood of poisoning incidents. Based on those expectations, the human health surveys asked producers to list the type of clothing used when applying pesticides, storage and disposal methods, and whether they showered and washed their clothes following pesticide application.

The household surveys also documented cases of poisoning incidents, including symptoms and corresponding costs of illness from lost labor and medical bills (Maumbe and Swinton 2003). Because access to healthcare facilities is limited in the rural areas, it is expected that most of the poisoning incidents go unreported and/or undocumented. Hence, the survey measures the number of incidents that are self-reported by households and were not necessarily verified by health professionals. Producers were asked to go back as far as 5 years when self-reporting pesticide poisoning incidents, beginning with the 2005 growing season. Beyond this time period, memory and recollection difficulties would likely compromise accuracy of responses. Attempts were made to corroborate the cases of self-reported poisoning incidences at local health centers, but the large number of cases that went unreported through self-diagnosis and self-treatment made it difficult. Health center records did, however, contain significant numbers of pesticide poisoning reports from nearby villages, adding some credence to the self-reported cases documented in our surveys.

An econometric model was developed to explain the number of pesticide poisoning incidents reported by each household and, in the process, identify variables that can be significantly linked to pesticide poisoning incidents (Maumbe and Swinton 2003). Included in the model were background characteristics of the victim (age, gender, and education level), farm management variables (field size, number of sprays, and type of sprays), and safety practices (clothing, washing). The regression equation was fit to the observed data using the Poisson distribution.

Corresponding to each poisoning incident, the cost-of-illness was measured using farmer's self-reported medical treatment expenses, which included hospital visits, doctor fees, and medicine. Also included in the cost of illness was the opportunity cost of lost wages, which was estimated at \$2 day^{-1}, the prevailing wage rate in rural areas. The actual cost-of-illness borne by afflicted farmers is higher than the costs obtained in this study. Our calculations did not factor in pain and suffering or other non-monetary costs, including time and resources spent preparing local remedies. Previous research has shown that pain and suffering can be a significant component of cost-of-illness, often surpassing the costs associated with lost wages and medical expenses. Although pain and suffering can be measured empirically, doing so requires advanced surveying techniques, such as contingent valuation, which was beyond the scope of the study. Hence, the cost-of-illness presented in this study is conservative.

11.5.6 Energy Impacts

An energy analysis was conducted to determine the impacts of Bt cotton on reducing energy usage. An energy model was developed based on the observed farming practices from the Burkina Faso field surveys. A crop enterprise budget was constructed for cotton production, which provides a detailed accounting of the farm practices and inputs used in producing cotton (Kay et al. 2006). Energy use was calculated for each farm practice using the energy required to operate machinery, including human labor, as well as the energy required to manufacture, transport, and apply inputs. The manufacturing requirements were taken from published reports that document the energy requirements for insecticides, fertilizer, and herbicides on a per unit basis (Pimentel 1999).

11.6 Empirical Findings

11.6.1 Demographics

Summary statistics of the 3 years of household surveys (2009–2011) are listed in Table 11.1. The area planted in BG II varied between 1.3 ha for the smallest manually worked farms (hand labor only; no animal traction) in the Faso Coton zone to 5.1 ha in SOFITEX on large farms (2 or more bullock-pairs of animal

Table 11.1 Statistical summary of household and producer characteristics of the surveyed Burkina Faso cotton producers averaged across the 3 years of surveys (2009–2011)

	SOFITEX[a]				SOCOMA				Faso Cotton				All zones
Item	Large[b]	Small	Man.	Ave./total	Large	Small	Man.	Ave./total	Large	Small	Man.	Ave./total	Ave./total
GM cotton households surveyed[c]													
2009	48	29	3	80	15	25	–[d]	40	11	27	2	40	160
2010	88	56	7	151	14	24	–	38	3	22	4	29	218
2011	66	31	12	109	23	42	8	73	14	61	0	75	257
Total	202	116	22	340	52	91	8	151	28	110	6	144	635
Household size (persons)	16.7[e]	11.0	11	13.9	24.1	10.0	–	18.7	11.5	9.5	11	10.1	14.1
Household farm labor (persons)	10.1	6.4	3.8	8.3	21.6	6.1	–	14.3	5.5	4.4	3.5	4.6	8.6
Area in GM cotton (ha)	5.1	2.9	2.0	4.1	4.1	2.1	1.5	2.8	2.5	1.7	1.3	1.8	3.3
Area in conventional cotton (ha)	4.1	2.6	1.9	3.3	2.8	1.5	1.7	2.0	1.5	0.7	–	0.7	2.6
Distance to GM cotton field (km)	3.7	3.7	8	3.6	2.9	2.8	–	2.8	5.8	5.0	8	5.4	3.8
Experience growing cotton (years)	31.9	25.5	13	28.0	9.1	11.1	–	9.8	8.5	10.8	13.0	10.2	20.4
Household income ($ per year)[f]	924	513	–	780	575	280	–	455	691	471	–	520	655

[a] Cotton production zone refers to the areas of operation of the three national cotton companies: SOFITEX, SOCOMA, and Faso Cotton

[b] Farm types are defined as follows: Large are farms with 2 or more animals for assistance in field operations, small are farms with 1 animal for assistance in field operations, and man. are farms where everything is done manually without any assistance of animals

[c] Sample size reports the total number of GM cotton producers surveyed. Observations with missing data resulted in different sample sizes for each of the variables

[d] Missing data is represented by "–" and required adjusting the weights used in calculating averages (see footnote e)

[e] Weighted averages are used when calculating averages across farm type and zone. Weights were determined based on the number of usable observations, i.e., adjusted for missing data. The variables household size, experience growing cotton, distance to GM cotton field, and household income were collected only in 2009, the first year of the survey

[f] Household income included farm income from crop and live stock sales, nonfarm income, and remittances

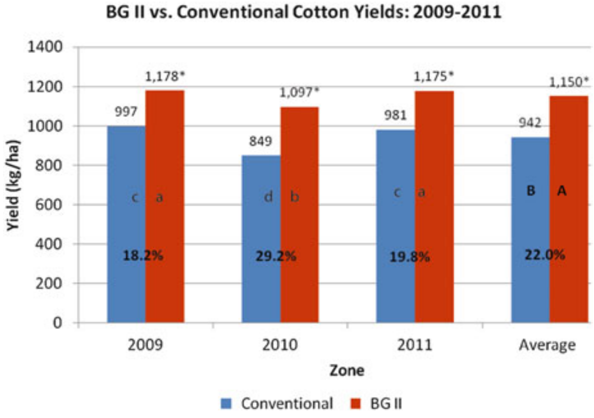

Fig. 11.6 Bollgard II versus conventional cotton yield comparisons: 2009–2011. Bollgard II cotton yields were significantly higher than conventional yields in each year and on average across all 3 years as indicated by the *asterisk*. *Lowercase letters* represent significant differences (95 % ($P < 0.05$) confidence level) in the annual mean yields and the *uppercase letters* show the annual mean yield comparison (95 % ($P < 0.05$) confidence level) averaged over the three production zones. *Source*: Authors' calculations based on INERA field surveys

traction). Across all three zones, households contained an average of 14.1 persons, with 8.6 of them actively engaged in the family's farming operations which included, but were not limited to, cotton production. The most experienced cotton producers in the survey were from the SOFITEX production zone, with an average tenure of 20.4 years (Table 11.1). SOFITEX is the traditional cotton producing zone where cotton has been produced since the colonial era, whereas the SOCOMA and Faso Coton zones have only recently been introduced to cotton production beginning in the 1980s (Bassett 2001). The longer experience with this cash crop likely explains why household incomes—including both farm and nonfarm income—were found to be significantly higher in the SOFITEX zone, with an average household income of $780 per year. In the Faso Coton zone household incomes were found to be $520 per year and in the SOCOMA zone household incomes averaged $455 per year.

11.6.2 Agronomic Benefits

Bollgard II generated significantly higher ($P < 0.01$) yields than conventional cotton in its' first 3 years of commercial introduction, with an average yield that was 22.0 % higher than conventional cotton among surveyed producers (Fig. 11.6; Table 11.2). The 3-year average of raw (unginned) cotton yield was 1,150 kg ha^{-1} for Bollgard II, corresponding to a 22.0 % increase over conventional cotton's average yield of 942 kg ha^{-1} (Table 11.2). There was no significant difference in

Table 11.2 Bollgard II yield advantage relative to conventional cotton for years 2009–2011

	Cotton production zone[a]												
	SOFITEX				SOCOMA				Faso Coton				
Yield item (kg ha^{-1})	Large[b]	Small	Man.	Ave.	Large	Small	Man.	Ave.	Large	Small	Man.	Ave.	All Zones
Gene type	2009												
BG II	1,300	1,059	997	1,201 b	1,234	1,420	–	1,350 a	988	939	1,065	959 c	1,178 A
Conventional	1,118	1,088	888	1,031 c	1,088	1,215	–	1,222 b	903	724	480	702 d	997 B
BG II yield advantage (%)	16.3	−2.7	12.3	16.5	13.4	16.9	–	10.5	9.4	29.7	121.9	36.6	18.2
	2010												
BG II	1,113	947	772	1,026 d	1,939	1,301		1,414 a	1,785	1,216	903	1,231 b	1,097 A
Conventional	711	852	816	767 e	–	1,120		1,121 c	858	1,013	–	987 d	849 B
Advantage (%)	56.5	11.2	−5.4	33.8	–	16.2	–	26.1	108.0	20.0	–	24.7	29.2
	2011												
BG II	1,293	1,169	1,297	1,258 a	1,192	1,286	1,088	1,235 b	1,173	954	–	995 c	1,175 A
Conventional	1,105	1,084	870	1,053 b	948	964	1,060	972 c	866	825	–	834 d	981 B
Advantage (%)	17.0	7.9	49.1	19.5	25.7	33.4	2.6	27.0	35.4	15.6	–	19.3	19.7
	2009–2011 Average												
BG II	1,235	1,058	1,022	1,162 a	1,455	1,336	1,088	1,333 b	1,315	1,036	984	1,062 c	1,150 A
Conventional	978	1,008	858	950 b	1,018	1,100	1,060	1,105 c	876	854	480	841 d	942 B
Average increase	26.3	5.0	19.1	22.2	42.9	21.5	2.6	20.6	50.2	21.4	105.0	26.2	22.0

Lowercase letters represent significant differences (95 % ($P < 0.05$) confidence level) in the annual mean yields, and the uppercase letters show the annual mean yield comparison (95 % ($P < 0.05$) confidence level) averaged over the three production zones. At the bottom of the table is shown the significance levels based on the 3-year average yields. Entries with "–" indicate missing data

[a] Cotton production zone refers to the areas of operation of the three national cotton companies: SOFITEX, SOCOMA, and Faso Cotton

[b] Farm types are defined as follows: Large are farms with 2 or more animals for assistance in field operations, small are farms with 1 animal for assistance in field operations, and man. are farms where everything is done manually (no assistance of animals)

Bollgard II yield advantage across the 3 years, with yield increases that ranged from a low of 18.2 % in 2009 to a high of 29.2 % in 2010 (Table 11.2). Bollgard II yields were always significantly higher than conventional cotton, including comparisons made between years when conventional yields were above their 3-year average and Bollgard II yields were below their 3 year average (Fig. 11.6). Conventional cotton yields were highest in 2009, reaching 997 kg ha^{-1}, yet the 2009 conventional cotton yields were still significantly lower than Bollgard II yields in each of the 3 years, including when Bollgard II yields were at their lowest, i.e., in 2010 when Bollgard II yields averaged 1,097 kg ha^{-1} (Fig. 11.6).

The ANOVA model was used to investigate whether the yield enhancing performance of BGII varied by location, farm type, or by the intensity of pesticide spray application. The analysis-of-variance (ANOVA) model identified five variables as having a significant effect in explaining cotton yield. Some of the variables, however, were significant only when included in the model through interaction with year, which indicated the effect was significant within one (or more) of the years.

The variable representing location, zone, had a significant effect ($P < 0.0001$) on cotton yield and corresponding yield advantage. The highest yields for Bollgard II were obtained by producers in SOCOMA, where yields reached as high as 1,414 kg ha^{-1} in 2010 and averaged 1,333 kg ha^{-1} over the 3 years (Table 11.2). This is likely related to the fact that the SOCOMA region has the least exploited soils, e.g., higher remaining soil fertility, as compared to the other zones. Bollgard II yields were significantly lower in the SOFITEX zone, with 3-year average yields of 1,162 kg ha^{-1}, which were significantly higher than SOCOMA only in one out of the 3 years, 2011 (Table 11.2). Faso Coton had the lowest Bollgard II yields, which averaged 1,062 kg ha^{-1} over the 3 years. Bollgard II yields in all 3 years were significantly lower in Faso Coton than SOCOMA, and except for 2010 Bollgard II yields were significantly lower in Faso Coton than in SOFITEX (Table 11.2). Conventional yields were also significantly different across zones, and followed the same trend as Bollgard II, with yields that were significantly highest in SOCOMA, with an average yield of 1,105 kg ha^{-1} over the 3 years, and lowest in Faso Coton, with an average yield of 841 kg ha^{-1} (Table 11.2). Conventional yields in SOFITEX averaged 950 kg ha^{-1} over the 3 years, significantly lower than SOCOMA but significantly greater than in Faso Coton (Table 11.2).

Although Bollgard II yields were highest in SOCOMA, Bollgard II producers in all three zones obtained significantly higher yields compared to conventionally grown cotton (Table 11.2). Producers in the Faso Coton zone generated the highest average yield advantage, 26.2 %, followed by SOFITEX with an average yield advantage of 22.2 % and SOCOMA with a 20.6 % yield advantage (Table 11.2). The finding that across the 3 years some zones perform better than others may be explained by the influences of some combination of factors including environmental characteristics, pest pressure, and secondary pest spray differences. However, any of the Bollgard II nontarget pest stress factors causing the yield differences, e.g., weather, water availability, soil fertility and secondary (non-Bollgard II targeted) pest pressure, affect both Bollgard II and conventional equally. Hence, even in zones where yields have been found to be lower than elsewhere, Bollgard II

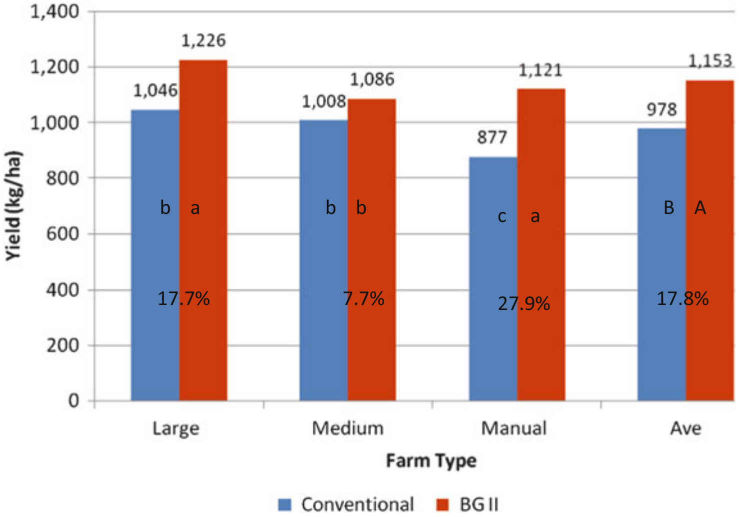

Fig. 11.7 Comparison of Bollgard II versus conventional cotton yields across the three farm types: large, medium, and manual. Yields are averaged over the first 3 years of large-scale commercial introduction, 2009–2011. *Lowercase letters* represent significant differences (95 % ($P < 0.05$) confidence level) in mean yields across the 3 years, and *uppercase letters* represent weighted average yield comparisons (95 % ($P < 0.05$) confidence level) over the 3 years. *Source*: Authors' calculations based on INERA field surveys

has still performed significantly better than conventional cotton (Table 11.2). Bollgard II, when managed following recommended practices, e.g., application of two sprays targeting secondary pests, outperforms the control of the Lepidopteran target pests when compared to conventional cotton, even when other stress factors are present.

Farm type was also found to have a significant effect ($P < 0.0001$) on cotton yields and yield advantage according to the ANOVA model, with the highest yields over the first 3 years obtained by the large and manual producers growing Bollgard II cotton (Fig. 11.7). Large producers had an average Bollgard II yield of 1,226 kg ha^{-1} over the 3 years that was 9.4 % higher than the corresponding yield of manual producers, 1,121 kg ha^{-1}, but the difference was not significant ($P > 0.05$). Manual producers achieved the greatest yield advantage from Bollgard II, 27.9 %, compared to 17.7 % for the large producers and 7.7 % for the medium size producers (Fig. 11.7). The better relative performance of the manual producers compared to the large and medium producers is an important finding since critics of Bt cotton typically argue that the technology is biased against small, resource constrained producers. The 3 years of household surveys provides empirical evidence to suggest quite the opposite: Bollgard II has enabled manual producers, by adopting Bt cotton, to compete with the larger, better equipped, and often more skilled conventional cotton growers. Although manual producers are the least productive when growing conventional cotton, e.g., 17.5 % lower yields than the large producers and 15.5 % lower yields than the medium producers, with the adoption of Bollgard II manual producers obtained significantly higher yields than the large and medium producers growing conventional cotton (Fig. 11.7). A plausible scenario is that when Bollgard II is adopted, manual producers are likely to enjoy a greater relative yield impact because, in general, cotton fields of manual farmers are believed to be poorly managed compared to the larger farm types. Bollgard II may be considered farm scale-neutral: the pest control impact is there from the moment the seed is planted and is not as dependent upon farmer pest control practices. Farm type had its largest effect on Bollgard II yield advantage in Faso Coton, where manually equipped farmers had much lower conventional cotton yields than the large and small farms (Table 11.2). The manually equipped farmers in Faso Coton had conventional yields of 480 kg ha^{-1}, only about one-half (53.1 %) of the conventional yields obtained by large producers, 984 kg ha^{-1} (Table 11.2). It may be important to consider that these manual farms represented a small sample ($N=2$) out of the surveys completed in the Faso Coton zone ($N=40$) due to the small proportion of manual producers in the faming population (5 %).

There also appears to be an emerging trend that growing Bollgard II results in producers expanding their cotton acreage. Across all 3 years, for example, Bollgard II was planted with an average size of 3.3 ha per farm, compared to 2.6 ha per farm for conventionally grown cotton, corresponding to a 26.9 % increase in cotton acreage (Table 11.1). This observation on cotton acreage can be made consistently across zones and for the different farm types (Table 11.1). It can be assumed that this trend in cotton area expansion is a result of the perceived benefits from growing Bollgard II, e.g., yield advantage, higher income benefits, and reduced insecticide spraying. Further field research will need to be conducted, however, to validate this point.

The broader lack of significance of farm size as a source of variation, i.e., farm type was significant but yields on large farms were not significantly higher than manual producers, is an expected finding due to the scale neutrality of Bt cotton and is consistent with results from other studies. In South Africa, studies found that large-scale (mechanized) farms benefitted in the same proportion as smallholder farmers, although they benefitted in different ways (Ismael et al. 2001; Gouse et al. 2003). Large-scale producers benefitted primarily from labor and operating cost savings (fuel), whereas smallholder producers in South Africa benefitted more from yield advantage. In Burkina Faso, both large and manual producers benefitted equivalently in terms of yield advantage, although large producers, due to more generally more productive conditions, achieved greater absolute yield increases.

Results of the 2009 through 2011 field surveys indicate that Burkina Faso producers have obtained yield advantages that compare favorably with the performance of Bt cotton in other parts of the world (Elbehri and MacDonald 2004). Two previous studies found similar Bt cotton yield increases among smallholders; these include Ismael et al. (2001) who report an average yield increase of 18 % from a survey of South African smallholder farmers and a Chinese study by Huang et al. (2002) who report a 15 % increase in cotton yields. Several studies have reported significantly lower yield advantages from Bt than the ones reported in this

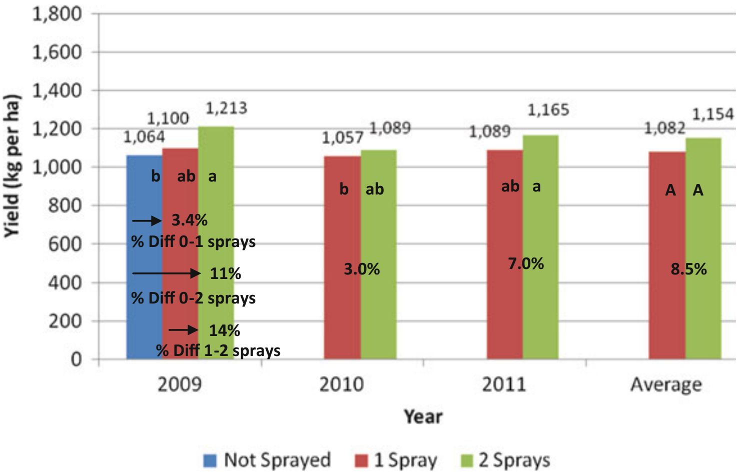

Fig. 11.8 Effects of late-season insecticide sprays on Bollgard II yields across the first 3 years of commercial introduction, 2009–2011. The zero spray categories for the 2010 and 2011 surveys are not included since the small sample size precluded their use in the ANOVA model. Average yields shown in the figure for 1 and 2 spray(s) were calculated using weighted averages over the 3 years based on the number of observations in each year. *Source*: Authors' calculations based on INERA field surveys

chapter. In the USA, Marra (2001) found only a 3–5 % increase in US cotton yields, and elsewhere no significant yield increases have been reported including in South Africa (Gouse et al. 2003) and India (Orphal 2005). Higher yield increases have also been reported. In India, where results have been mixed, Qaim (2003) reports yield increases of 58 %. Qaim and De Janvry (2005) cite yield increases of up to 42 % among smallholder farmers in Argentina. Yield advantages for individual years and zones in this study (Table 11.2) fall within these previously reported yield increases from developing nations. The 22 % mean yield advantage across the 3 years of this study is consistent with the findings of the broad Burkina Faso field trials conducted in 2007, where yield advantages from BG II averaged around 20 %.

11.6.3 Role of Insecticide Sprays

The number of pesticide spray applications had a significant effect ($P < 0.05$) on Bollgard II yields, with its greatest effect occurring in the first year of the study, 2009 (Fig. 11.8). This was the first year of commercial introduction, and a majority of producers did not follow the recommended practices for protecting against secondary pests, leaving fields unprotected from these piercing–sucking pests which are not controlled by Bt. While conventionally treated cotton requires a regimen of six sprays, four early season sprays targeting primary pests (Lepidoptera) and two late-season sprays targeting secondary pests (piercing and sucking),

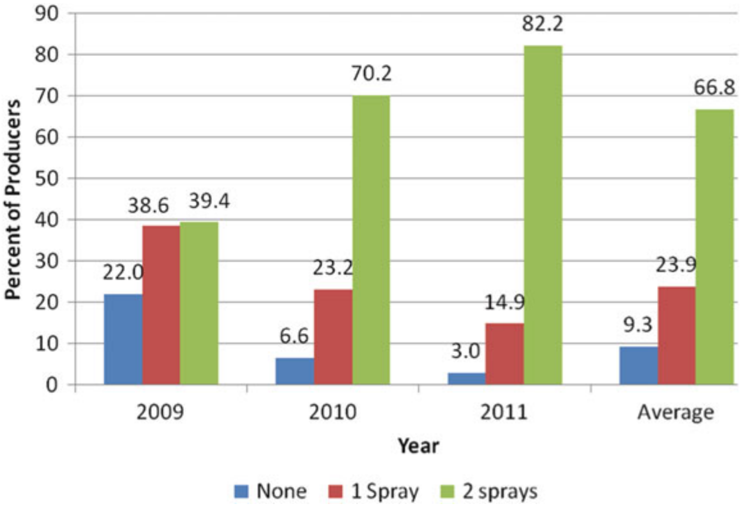

Fig. 11.9 Number of late season sprays applied by producers over the 3-year period, 2009–2011. Graph illustrates the proportion of producers within each spray category ranging from zero to two sprays. Average percent of producers shown in the figure was calculated using weighted averages over the 3 years based on the number of observations in each year. *Source*: Authors' calculations based on INERA field surveys

Bollgard II cotton reduces the need for the four early-season sprays since it is effective in controlling Lepidoptera. Two late season sprays are still beneficial with Bollgard II cotton since secondary pests are outside its control spectrum. According to the 2009 field surveys, a majority of Bollgard II producers, 60.6 %, did not apply the recommended pair of insecticide sprays late in the season to control secondary pests, e.g., Aphids and jassids (Fig. 11.9). This may have been the result of producers not being properly informed and/or believing that they didn't need to spray for secondary pests when growing Bollgard II.

Analysis of the 2009 household surveys found that late season insecticide sprays had a significant effect on Bollgard II performance, lowering yields for producers who did not spray by an average of 14 % compared to producers who followed extension recommendations and sprayed twice (Fig. 11.8). The effect in SOFITEX was greater, where producers who sprayed twice obtained yields (1,179 kg ha^{-1}) that were 37 % higher than those who didn't spray at all (Table 11.3). Since 2009, extension and other outreach activities have made producers aware of the need to continue late season sprayings, and the INERA household surveys have continued to monitor the effect of insecticide sprays on cotton yield. In 2010, the number of producers following the recommended number of late season sprays increased significantly from 18 to 78 %, and in 2011 there was even greater compliance with 82 % of the producers following the recommended practices (Fig. 11.9). The adherence to recommended spraying practices was particularly strong in SOFITEX where 92 % of the producers in 2011 sprayed twice (Vitale *2011 Final Report*). In

Table 11.3 ANOVA model results for 2009 Bollgard II yields and corresponding cotton income across the main factor of the number of late season insecticide treatments applied by cotton producers

	Cotton production zone[a]									
	SOFITEX ($N = 91$)			SOCOMA ($N = 13$)			Faso Coton ($N = 40$)			
Insecticide treatments	Large[b] $n = 56$	Small $n = 35$	Ave. $n = 91$	Large $n = 4$	Small $n = 9$	Ave. $n = 13$	Large $n = 11$	Small $n = 27$	Ave. $n = 38$	All zones $n = 142$
Bollgard II yields (kg ha^{-1})										
0	1,036c	759c	929	1,485	1,995	1,838	–	–	–	764
1	1,263b	1,095b	1,198	1,275	1,395	1,358	779b	886b	855	1,121
2	1,569a	1,303a	1,467		1,127	780	1,108a	972a	1,011	1,282
Ave.	1,287	1,006	1,179	1,433	1,476	1,463	988	939	953	1,145
Conventional cotton yields (kg ha^{-1})										
6	1,118	1,088	1,031	919	879	909	903	724	702	931
Bollgard II income ($ ha^{-1})										
0	−10.36c	−75.64b	−35.47	97.24	315.36	248.25	–	–	–	0.03
1	57.10b	21.80a	43.52	12.61	93.99	68.95	−64.43b	−42.40b	−48.78	21.15
2	156.46a	94.74a	132.72	–	−9.63	−6.67	47.32a	−17.17a	1.50	84.84
Ave.	62.36	−8.94	34.94	76.03	121.61	107.59	6.52	15.24	12.72	35.64
Conventional cotton profit ($ ha^{-1})										
6	4.00	7.33	−17.84	−76.23	−47.38	−69.02	−44.36	−103.1	−108.4	−42.79

[a] Cotton production zone refers to the areas of operation of the three national cotton companies: SOFITEX, SOCOMA, and Faso Cotton

[b] Farm types are defined as follows: Large are farms with 2 or more animals for assistance in field operations, small are farms with 1 animal for assistance in field operations, and man. are farms where everything is performed by hand

general, SOFITEX is expected to benefit the most from pest protection since it has the longest history of continuous cotton cultivation and the annually consistent pest pressure.

The improved pest management practice in 2010 is a reasonable explanation for why BGII yield advantages were greater in 2010 and 2011 compared to 2009[4] (Fig. 11.6). Cotton yields were 3 % higher in 2010 for producers who sprayed twice late in the season compared to those who sprayed only once (Fig. 11.8), and while the difference was not significant, income for producers who sprayed twice was $17.78 per ha higher than those who sprayed once (Vitale *2010 Final Report*). With nearly a 3:1 returns-to-investment ratio in 2010, i.e., a $17.78 economic return for an additional $6 investment in the second insecticide spray, producers likely would justify the continued promotion of the two late sprays for Bollgard II. In 2011, the substantially larger survey provided additional evidence that yield performance and economic returns were enhanced by the two late sprays. While insecticide sprays did not have a significant effect on cotton yields as shown in Fig. 11.8, made difficult by the small sample size, average yields in 2011 were 7.0 % higher for producers who sprayed twice compared to those who sprayed only once (Fig. 11.8). Vitale (2013) find the corresponding economic returns as being 11.1 % higher for producers who applied the second spray compared to producers who sprayed once, providing an even stronger economic rationale for the two late season sprays than in 2010. In 2011, the $6 investment in the second spray generated an additional $27.71 per ha in cotton income, nearly a 5:1 returns to investment ratio, up from the 3:1 ratio found in 2010 (Vitale *2011 Final Report*). Hence, the 3 years of survey findings support the initial recommendations made in 2009 that two late season insecticide sprays against Bollgard II non-targeted secondary pests are prudent.

The varying effect of late-season sprays on cotton yield is due to differences in pest density from one year to the next and other factors that were not included in the ANOVA model. It is also possible that with a vast majority of the producers following the late-season spray recommendations, pest pressure at the village level was reduced due to the increased use of pesticides by farmers throughout the village. While in some years the sprays will have less effect than others, the 2009 findings provide empirical evidence that the cost of not spraying when pest pressure is high can have a significant negative effect on cotton yield and income. Producers are likely better off spraying for secondary pests every year since losses from even 1 year of heavy pest pressure outweigh the costs of applying insecticide for several low-pressure years.

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[4] However, the successful efforts to encourage producers to follow recommended practices precluded the opportunity to statistically test the effect of late season sprays in 2010 or 2011 since the number of producers who did not spray was too small for ANOVA models. The low numbers of producers who sprayed once were also small, and while the number of producers who sprayed once were large enough to be included in ANOVA models, the small sample sizes created wide statistical confidence intervals for comparing means in the second and third years and were not well suited for appropriate balanced statistical analyses using weighted averages.

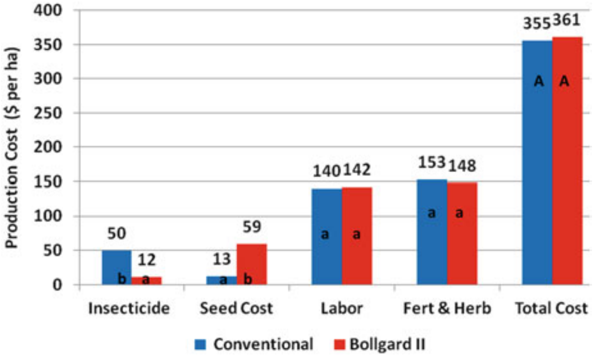

Fig. 11.10 Comparison of production costs for Bollgard II versus conventional cotton averaged across the first 3 years of large-scale commercial introduction, 2009–2011. Averages shown in the figure are weighted according to the number of observations in each year. *Lowercase letters* represent significant differences (95 % ($P < 0.05$) confidence level) in production within each cost category, and the *uppercase letters* represent significant differences (95 % ($P < 0.05$) confidence level) for total costs. *Source*: Authors' calculations based on INERA field surveys

11.6.4 Economic Benefits

Producers were able to retain nearly all of the increased revenue earned by Bollgard II cotton since production costs were nearly identical for Bollgard II and conventional cotton[5] (Fig. 11.10; Table 11.4). Bollgard II cotton had an average production cost of \$361.37 ha^{-1}, which was \$6.12 ha^{-1} higher than the production cost of conventional cotton, \$355.26 ha^{-1}, but the difference was not significant (Fig. 11.10; Table 11.4). When the additional yield realized in Bollgard II is considered, Bollgard II is a better investment than conventional cotton. Hence, although Bollgard II cotton seed costs are often cited as a major constraint to adoption, there is no evidence of unfair seed pricing in Burkina Faso (Qaim and De Janvry 2003).

Bollgard II increased cotton income by an average of \$64.57 per ha over conventional cotton across the 3 years, a 51.1 % increase in household income for an average cotton producing household with 3.32 ha of cotton (Table 11.5). The impact of Bollgard II on cotton income was stable across time, generating significantly higher income in each of the 3 years compared to conventional cotton (Fig. 11.11). The greatest impact of Bollgard II was in 2011, when cotton income averaged \$95 per ha more than conventional cotton (Fig. 11.11). Although the difference in cotton income was greatest in 2011, this was also the year when both Bollgard II and conventional cotton producers obtained their highest income, benefitting from the substantially higher prices paid by the cotton companies.

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[5] Production costs were nearly constant across the three years, varying only modestly between 2009 and 2011. Because of the low inter-year variability, only 3-year average values for production costs are presented in Table 11.4 and Fig. 11.10.

Table 11.4 Production cost comparison between Bollgard II and conventional cotton based on purchased inputs: insecticide use, labor effort, and seed cost: average production costs from 2009 to 2011

	Cotton production zone[a]												
	SOFITEX ($N = 94$)				SOCOMA ($N = 13$)				Faso Coton ($N = 40$)				
Item (\$ ha^{-1})	Large[b]	Small	Man.	Ave.	Large	Small	Man.	Ave.	Large	Small	Man.	Ave.	All zones
Bollgard II													
Insecticide	11.56	13.67	13.73	12.48	8.99	8.49	10.00	8.58	11.48	12.55	20.21	12.09	11.54
Seed Cost	61.25	60.44	60.56	60.90	65.42	65.54	60.00	65.20	51.93	56.98	53.69	53.86	59.44
Labor	147.56	136.84	140.39	143.20	152.80	153.47	143.60	152.19	143.09	134.41	131.97	135.97	142.47
Fert & Herb	147.14	148.47	130.92	146.74	152.82	157.91	155.66	160.87	162.83	142.54	102.14	145.22	147.92
Total cost	367.51	359.41	345.60	363.33	380.03	385.40	369.26	385.71	369.35	346.47	308.01	347.16	361.37
Conventional cotton													
Insecticide	43.66	48.38	54.41	46.64	66.81	48.10	41.85	54.16	50.96	50.52	58.00	50.75	49.79
Seed cost	12.32	12.77	14.65	12.80	11.67	12.09	13.55	12.07	12.29	12.41	8.88	12.33	12.52
Labor	146.36	146.02	135.06	143.44	138.81	138.82	145.44	139.69	135.84	131.81	114.49	131.36	139.83
Fert & Herb	162.82	163.01	146.87	160.78	150.89	141.09	127.97	149.47	142.31	148.91	134.73	147.70	153.12
Total cost	365.16	370.18	350.99	363.71	368.18	340.10	328.81	355.39	341.45	343.65	316.10	342.15	355.26
Cost comparison: Bollgard II—conventional cotton													
BG II—Conv.	2.35	−10.77	−5.40	−0.38	11.85	45.31	40.45	30.31	27.90	2.82	−8.09	5.01	6.12

[a] Cotton production zone refers to the areas of operation of the three national cotton companies: SOFITEX, SOCOMA, and Faso Cotton

[b] Farm types are defined as follows: Large are farms with 2 or more animals for assistance in field operations, small are farms with 1 animal for assistance in field operations, and man. are farms where everything is done manually (no assistance of animals)

Table 11.5 Cotton income comparison between Bollgard II and conventional cotton: average income 2009–2011

	Cotton production zone[a]												
	SOFITEX				SOCOMA				Faso Coton				
Item ($ha^{-1})	Large[b]	Small	Man.	Ave.	Large	Small	Man.	Ave.	Large	Small	Man.	Ave.	All zones
Bollgard II													
Revenue	561.62	468.29	542.65	527.01	587.55	618.80	592.12	607.33	542.24	478.05	393.78	486.99	534.86
Prod. cost	367.51	359.42	345.60	363.33	380.03	385.40	369.26	385.70	369.35	346.47	308.01	347.16	361.38
Cott. income	194.11	108.87	197.05	163.68	207.52	233.40	222.85	221.62	172.89	131.58	85.77	139.82	173.49
Conventional cotton													
Revenue	506.38	504.36	448.89	489.79	229.49	484.70	577.27	492.39	406.84	390.43	170.67	383.28	464.18
Prod. cost	365.16	370.19	350.99	363.71	368.18	340.10	328.81	355.39	341.45	343.66	316.10	342.15	355.26
Cott. income	141.22	134.18	97.90	126.08	−138.6	144.60	248.46	137.00	65.39	46.78	−145.43	41.14	108.92
Cotton income comparison: Bollgard II—conventional cotton													
Δ Income	52.89	−25.31	99.15	37.60	346.21	88.80	−25.61	84.63	107.50	84.80	231.20	98.69	64.57

[a] Cotton production zone refers to the areas of operation of the three national cotton companies: SOFITEX, SOCOMA, and Faso Cotton

[b] Farm types are defined as follows: Large are farms with 2 or more animals for assistance in field operations, small are farms with 1 animal for assistance in field operations, and man. are farms where everything is done manually (no assistance of animals)

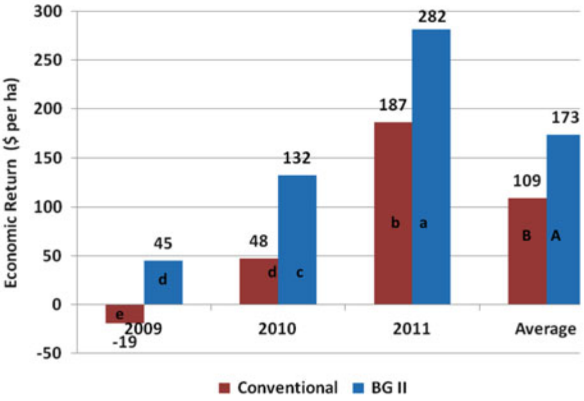

Fig. 11.11 Comparison of Bollgard II versus conventional cotton economic returns ($ per ha) over the first 3 years of large-scale commercial introduction, 2009–2011. *Lowercase letters* represent significant differences (95 % ($P < 0.05$) confidence level) in mean economic return across the 3 years, and the *uppercase letters* show the mean economic return comparison (95 % ($P < 0.05$) confidence level) using weighted averages over the 3 years. *Source*: Authors' calculations based on INERA field surveys

Between 2010 and 2011, cotton prices increased 24 % from a price of \$0.50 lb.$^{-1}$ of cotton lint in 2010 to a price of \$0.62 lb.$^{-1}$ of cotton lint in 2011. Similar price increases occurred between 2009 and 2010, when cotton prices increased 25 % from \$0.40 to \$0.50 lb.$^{-1}$ of cotton lint. The substantial price increase in 2011 explains why conventional cotton earned significantly higher cotton income in 2011 than it did the previous 2 years. The cotton price increase was large enough in 2011 to elevate conventional cotton income higher than even Bollgard II income in the previous 2 years (Fig. 11.11). The low price paid to cotton producers in 2009 is particularly evident for conventional cotton producers, whose incomes were negative even though cotton yields were highest in that year (Figs. 11.6 and 11.11). The negative returns in 2009 do not indicate that producers lost money that year; rather, it results from valuing family labor at the prevailing wage rate of ca. \$1.50 day^{-1}. When valued as such, returns to labor in 2009 were below the prevailing wage rate explaining the negative returns. Since family wages are typically paid through in-kind exchanges among the head of the household and household members, the negative income reflect lower levels of intra-household exchanges rather than financial austerity.

The economic analysis from the 2009 and 2010 growing seasons provide a potential interpretation of how smallholder producers could develop a simple partial budget heuristic to decide whether BG II would be profitable, i.e., how producers should be able to make a straightforward calculation of associated costs and benefits. For instance, it would be readily apparent to producers that insecticide and seed costs would more or less cancel one another out, as increased labor from harvest would more or less cancel out labor savings from fewer insecticide sprays. Consistent with the motivation to maximize profit, smallholder producers could then realize that with no net change in production costs the bulk of the increased revenue from Bollgard II's yield advantage would stay on-farm, accruing directly to them. Moreover, the adoption of BG II would not increase risk. Since production costs do not increase significantly, producers do not have to worry about "paying back" investments in poor production years as is often the case when adopting improved technology.

An ANOVA of production costs did not find any treatment effects, e.g., zone, year, farm type, as having a significant effect on production costs (Table 11.5). The production costs in SOCOMA were calculated as the highest among the three zones, \$385.71 ha^{-1} for BG II and \$355.39 ha^{-1} for conventional cotton, but the difference in production costs among the zones was not significant (Table 11.4). Likewise, although the large farms had the highest production costs on average within each production zone, there was no significant difference among farm types ($P < 0.05$). The household surveys also found no significant differences ($P < 0.05$) in fertilizer or herbicide costs (Table 11.4). Those production costs are similar since producers generally adhere to the recommended fertilizer and crop management practices established by the Burkina Faso cotton companies.

The positive returns found in this study are consistent with results from other studies. Ismael et al. (2001) report returns of 11 and 77 % on gross margins among smallholder producers in South Africa in two successive growing seasons, 1998/99 and 1999/2000. They also explain the higher returns from Bt cotton as a combination of higher cotton yields and lower pesticide costs that offset increased seed costs as found in this study. In a more recent study in South Africa, Bennett et al. (2006) also report positive economic returns from growing Bt cotton among smallholder producers. In China, the study by Huang et al. (2002) found, based on the first year of Bt cotton use (1999), that adopters earned a positive net income, whereas non-adopters had negative net incomes. Likewise, the findings of Huang et al. (2003) are similar to the results reported in this chapter, showing that Bt cotton enabled producers to earn a positive net income. In India, results have been mixed, but higher returns from Bt cotton have been reported. Perhaps the most substantial studies were those by Bennett et al. (2004) and Morse et al. (2005) based on a large survey of 9,000 India cotton producers. While both studies found higher returns on Bt cotton plots, results varied significantly from 1 year to the other and among subregions.

Bollgard II had a positive impact on labor costs through reducing the number of hours required to apply pesticides by an average of approximately two-thirds. While this translated into a labor cost savings of \$7.96 ha^{-1}, the higher yields obtained by growing BG II resulted in higher harvest costs. While higher labor costs are associated with Bollgard II in Table 11.4, there was no significant difference in labor costs between Bollgard II and conventional cotton. Moreover, when the added revenue from the higher yields obtained by Bollgard II is considered, the increased labor from harvest is remunerative, indicating that Bollgard II does provide an overall positive economic impact on household labor. The findings for Burkina Faso are consistent with studies in South Africa. Both Kirsten and Gouse (2003) and Shankar and Thirtle (2005) report similar findings, i.e., no significant labor cost

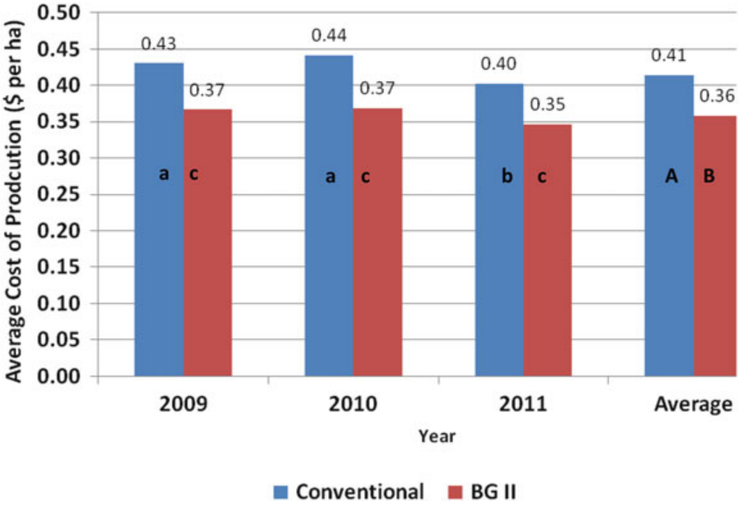

Fig. 11.12 Comparison of Bollgard II versus conventional cotton average cost of production over the first 3 years of large-scale commercial introduction, 2009–2011. *Lowercase letters* represent significant differences (95 % ($P < 0.05$) confidence level) in the average cost of production across the 3 years, and the *uppercase letters* show the weighted average (95 % ($P < 0.05$) confidence level) average cost of production over the 3 years. *Source*: Authors' calculations based on INERA field surveys

savings from Bt cotton due to higher harvest costs negating the benefits from lower labor costs associated with reduced pesticide applications. More substantial labor cost savings have been reported for the application of Bt cotton in developed countries, where the opportunity cost of operator time and machinery running costs are greater than in smallholder settings such as Burkina Faso.

The economic benefits of Bollgard II can be viewed in other ways as well. The average cost of producing a pound of cotton lint was significantly lower for Bollgard II than conventional cotton, averaging 13.5 % lower across the 3 years (Fig. 11.12).[6] According to the survey, when averaged over the 3 years, the average production cost of Bollgard II was $0.358 per lb. of cotton lint, which was $0.056 per lb. less than conventional cotton's production cost of $0.414 per lb. of cotton lint (Fig. 11.12). Hence, Bollgard II producers earned $0.056 more than conventional cotton producers for each pound of cotton sold. This average trend did not vary among years; Bollgard II had significantly lower average production costs in each of the 3 years (Fig. 11.12). The close proximity of the average production costs shown in Fig. 11.10 (insecticide savings are neutralized by increased BGII seed prices) indicates that the primary source of the increase in cotton profit from

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[6] Average production costs are calculated as production costs divided by yield. Average production costs provide a useful measure of profitability since they indicate how much profit is made per unit produced, i.e., profit is given by the difference between selling price and average production cost. Hence, to break even average production costs must be less than selling price.

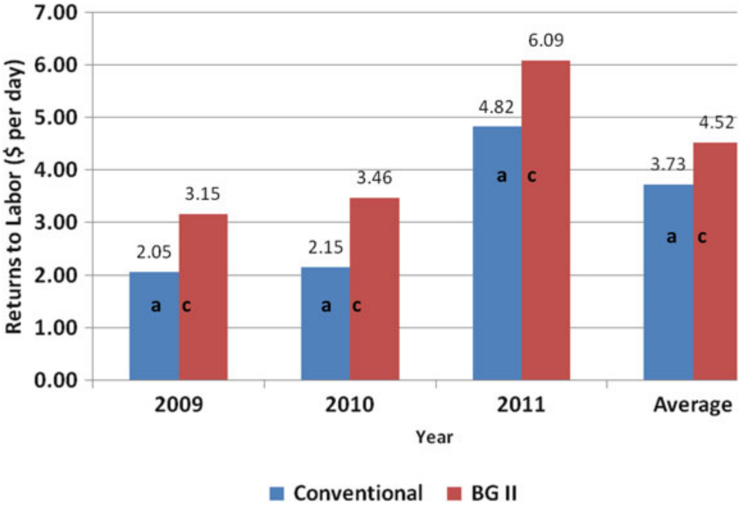

Fig. 11.13 Comparison of returns to labor for Bollgard II and conventional cotton across the first 3 years of large-scale commercial introduction, 2009–2011. *Lowercase letters* represent significant differences (95 % ($P < 0.05$) confidence level) in mean returns to labor across the 3 years, and the *uppercase letters* show the mean returns to labor comparison using weighted averages (95 % ($P < 0.05$) confidence level) over the 3 years. *Source*: Authors' calculations based on INERA field surveys

growing Bollgard II was generated by the yield increase. The higher cotton price in 2011 was an additional component that placed a greater value on output compared to the previous 2 years.

Bollgard II producers earned significantly higher returns to labor than producers of conventional cotton over the 3 years of this study (Fig. 11.13). In Burkina Faso, where cotton production is labor intensive, households allocate approximately 76 days of labor to each hectare of cotton produced.[7] Households planting Bollgard II were found to have a 3-year average returns to labor of $4.52 per day, an increase of 21.2 % compared to conventional cotton producers whose labor returned an average of $3.73 per day (Fig. 11.13). Returns to labor was consistent across the 3 years, with Bollgard II generating significantly higher values than conventional cotton in each year. The difference in returns to labor between Bollgard II and conventional cotton varied modestly across years, from a low of $1.10 per day in 2009 to $1.32 in 2010 (Fig. 11.13). The largest returns to labor were obtained in 2011 for both Bollgard II and conventional cotton, which were nearly twice as large as they were in the previous 2 years due to the substantial increase in the cotton price paid to producers (Fig. 11.13). In all 3 years, returns to labor for both Bollgard

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[7] In the 2010 report, returns to labor were calculated using 76 days of labor per ha to maintain consistency with the INERA report. This value of labor was not obtained from the survey data, but appears to have been obtained from previous research. Returns to labor calculated as profit divided by the days of labor per ha.

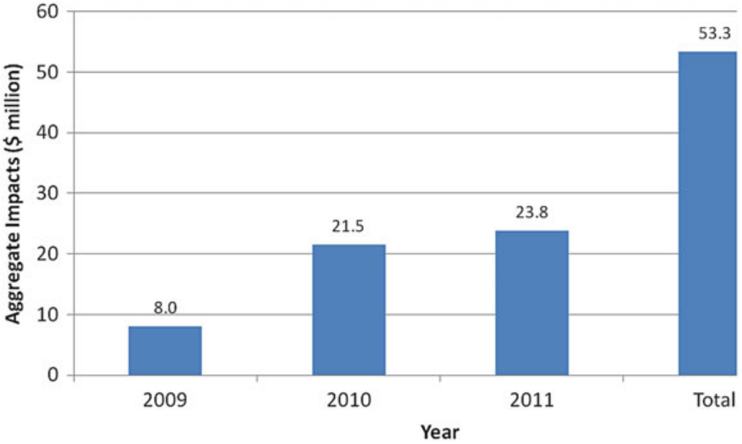

Fig. 11.14 National level impacts of Bollgard II in Burkina Faso over the first 3 years of commercial introduction. *Source*: Authors' calculations based on INERA field surveys

II were significantly higher than the prevailing institutional wage rate of $2.33 per day. Producers growing conventional cotton, however, had only one out of the 3 years when returns to labor were above the prevailing wage rate, 2011 (Fig. 11.13).

11.6.5 How Benefits Were Distributed

National level impact of the commercial use of Bollgard II totaled $53.3 million over the first 3 years of introduction based an extrapolation of the survey findings to other locations in Burkina Faso[8] (Fig. 11.14). Aggregate impacts varied across the 3 years based on changes in prices, yields, and planted acreage. The large area and high cotton price in 2011 resulted in the greatest annual impact of $23.8 million (Figs. 11.14 and 11.15). Aggregate impacts were nearly as large in 2010, $21.5 million, when planted Bollgard II acreage was the largest, and Bollgard II obtained its greatest yield advantage (Figs. 11.6 and 11.15). The higher cotton price paid to producers in 2011 outweighed the area and yield effects, resulting in the slightly larger aggregate impacts in 2011. The first year of Bollgard II introduction, 2009, had the lowest aggregate impact. This was largely caused by the modest planted

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[8] The extrapolation calculated the aggregate impact using per ha economic returns reported in the figures. The national impacts reported in Fig. 11.14 are based on the cotton price paid to producers. Additional benefits could accrue to the cotton companies from the increased quantity of cotton sold on world markets. Since the cotton companies marketing margins were not available, those benefits could not be assessed.

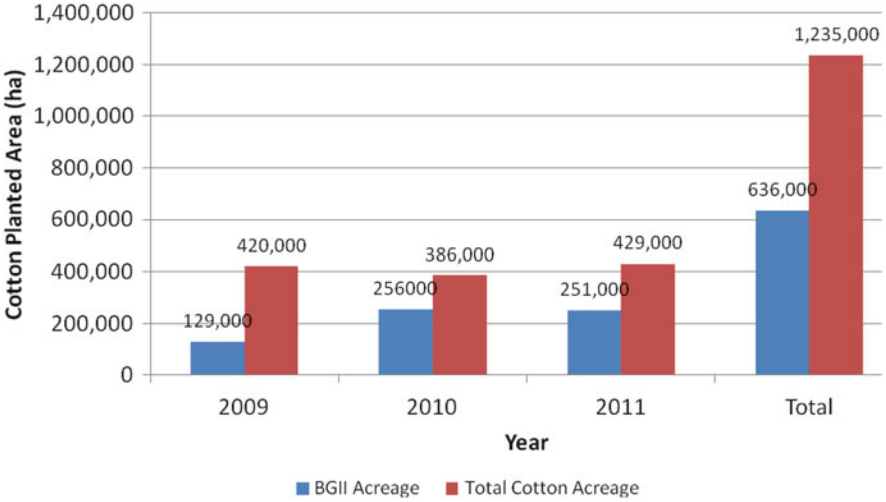

Fig. 11.15 Bollgard II cotton areas produced over the first 3 years of cotton production. *Source*: Authors' calculations based on INERA field surveys

acreage of Bollgard II in 2009, ca. 129,000 ha, due to constraints on seed availability that improved significantly by 2010.

Producers would capture a majority of the benefits, 53.8 %, with the remaining 46.2 % going to the Burkina Faso cotton companies and technology provider. This level of benefit sharing is consistent with studies in the USA and South Africa that find producers typically capturing between one-half and two-thirds of the benefits, with the remaining portion shared among seed companies, cotton industry and the technology providers. Since national level impacts are directly proportional to planted acreage, the aggregate impacts are expected to increase further over the next few years once seed production is able to satisfy demand. For example, if the benefits obtained by producers in 2011 were able to be adopted over 80 % of the total cotton acreage (ca 500,000 ha), aggregate benefits would total $114 million over a 3-year period. It is also important to note that the results shown in Fig. 11.14 are based on cotton areas that have been recently updated and hence they differ from the annual reports. Because the updated areas have been revised downward, the impacts illustrated in Fig. 11.14 are less than those previously reported.

11.6.6 Health Impacts and Implications

The introduction of Bollgard II cotton provides safer working conditions by reducing pesticide applications and limiting producers' exposure to potentially toxic agents that are often contained in pesticides. Pesticide poisonings occurred frequently according to the INERA household surveys, which found 49.8 % of the

Table 11.6 Impacts of pesticide use on human health

Variable	Production zone			
	SOFITEX	SOCOMA	Faso Coton	All zones
Frequency of poisoning incidents				
Households self-reporting one or more poisoning incident	44	25	27	96
Total self-reported poisoning incidents	118	41	40	199
Mild incidents (symptoms lasting less than 3 days)	100	34	26	160
Severe incident (symptoms lasting 3 or more days)	18	7	14	39
Households surveyed	118	40	41	199
Poisoning victim profile				
Age (years)	33.9	29.8	30.5	32.3
Gender (percent male)	100	95.1	100	98.9
Agent applied during poisoning incident				
Endosulfan (number of cases)	103	25	26	154
Pyrethroid (number of cases)	15	16	14	45
Economic loss resulting from poisoning incident				
Lost wages ($ per poisoning incident)	24.77	12.30	4.10	16.83
Medical expenses ($ per poisoning incident)	11.98	30.37	8.70	15.10
Total economic loss ($ per poisoning incident)	36.75	42.67	12.8	31.93

households self-reporting at least one poisoning incident over the past 7 years, from 2004 through 2010[9,10] (Table 11.6).

The annual occurrence of pesticide poisoning incidents among surveyed households is illustrated in Fig. 11.16. Poisonings occurred most frequently in 2008, when 18.1 % of the households experienced a poisoning incident, whereas the lowest frequency of occurrence was in the following year, 2009, when 5.5 % of the surveyed households self-reported a poisoning incident (Fig. 11.16). Nearly all of the poisoning victims were male, 98.9 %, with an average age of 32.3 years (Table 11.6). The high incidence of male poisoning does not indicate gender bias; however, rather it is consistent with the equally high proportion of males, 97.3 %, who perform the spray operations. Social norms discourage women from performing farm practices such as pesticide applications.

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[9] There is a 1-year lag in the reporting of pesticide poisonings since the households ask about incidents that occurred in the previous year. For example, in the first year of the surveys, 2009, producers were asked for poisoning incidents that occurred in 2008. This is necessary since surveys occur during the production period, before all of the insecticides have been applied. The 2009 surveys also asked producers to self-report pesticide poisoning incidents that had occurred over the previous 5 years, 2004–2008.

[10] The producer surveys collected the number of self-reported poisoning incidents that occurred within the household. For each incident reported, respondents listed the type of insecticide used, symptoms incurred, extent of illness, medical expenses, lost wages, and background information on the poisoned individual.

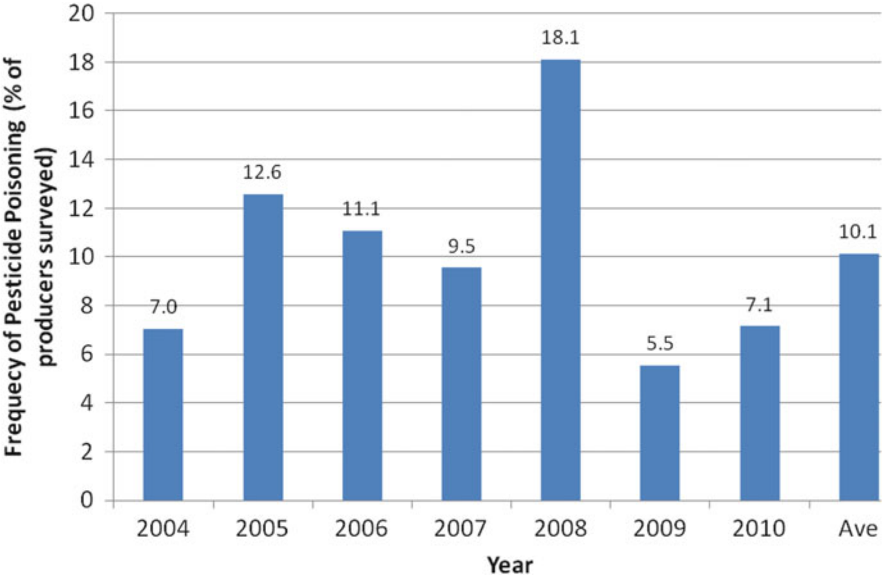

Fig. 11.16 Annual frequency of self-reported pesticide poisonings among surveyed households. *Source*: Authors' calculations based on INERA field surveys

The survey results over the past 2 years provide evidence suggesting that the adoption of Bollgard II has helped reduce the frequency of poisonings. Based on all 3 years' surveys, a majority of the reported poisoning cases (81.3 %) occurred during the application of pesticides targeting Lepidoptera (i.e., bollworms), which are not sprayed by Bollgard II producers. This could explain why in the first 2 years of commercial use, 2009 and 2010, reported pesticide poisonings have noticeably declined, falling to two of the lowest years observed, with frequencies of 5.5 and 7.1 % (Fig. 11.16). Only 2004 had a lower poisoning frequency than either 2009 or 2010, with a frequency of 7.0 %, that was 0.1 % lower than the poisoning frequency in 2010 (Fig. 11.16). Pesticide poisoning events have averaged 6.3 % since Bollgard II was introduced in 2009, corresponding to a 37.6 % reduction in poisoning episodes compared to the mean of 10.1 % that was observed in the 5-year period (2004–2008) prior to its commercial introduction (Fig. 11.16). This substantial decline in pesticide poisonings could be explained by the reduction in pesticide applications by Bollgard II producers since 2009.

Planting Bollgard II cotton, reduced pesticide sprays by 66 % or more, greatly reducing potential pesticide exposure and the resulting negative health and economic costs from medical expenses and lost wages. Based on the standard pesticide spraying practices employed by conventional cotton producers, which targets primary pests with four early season sprays and secondary pests with two late season sprays, the probability of a poisoning incident occurring during a single spray application over the 7 years of the household surveys was estimated at 1.04 %. Based on the 2011 producer surveys, which found a 75 % reduction in pesticide sprays used by Bollgard II, the number of pesticide poisoning incidents, aggregated to the national level, would be reduced by a projected 30,380 cases. Projecting the survey findings across the broader population of Burkinabé cotton producers and using the average findings from all 3 years of the surveys, Bollgard II is estimated to have reduced the number of pesticide poisoning incidents in 2011 by 11,800 cases, from 30,100 to 18,300 incidents.

The human health impact findings are considered important since there are undocumented reports and speculation regarding pesticide poisonings in the West Africa region, but limited empirical evidence to support claims. Moreover, the surveys indicate that pesticides are a danger not only to producers but also to the surrounding community. Improper storage and handling led to several poisonings from drinking and eating out of emptied pesticide containers, including reported cases of death and suicide. By commercializing Bollgard II, Burkinabé villages may be exposed to fewer health and environmental risks by removing an estimated 0.62 million pesticide containers associated with conventional cotton production.

Households reported a range of symptoms and illnesses resulting from the poisoning incidents, including headaches, vomiting, dizziness, and flu-like symptoms, including coughs and difficulty breathing. The cost of each pesticide incident was assessed based on medical expenses (medicine and doctor bills) and lost wages. This is a conservative approach since any pain and suffering associated with an illness was not included in the survey. The average cost of an individual poisoning incident, as reported by producers in the INERA surveys, was US$39.22, including US$16.83 in labor costs and US$22.39 in medical expenses. Aggregating the findings from the household surveys to the national level, the use of Bollgard II cotton could generate a positive economic impact of US$1.09 million per year in recouped wages and medical expenses from reduced pesticide poisoning incidents. These findings on health benefits are considered important since pesticide poisonings go largely undocumented, leaving only speculation regarding the frequency and extent of pesticide poisonings in the region. The human health surveys also asked respondents to specify the costs associated with each poisoning incident, including lost wages, medical bills, and prescriptions. On average, total health costs assigned to poisoning and aggregated for the entire farming population of 300,000 producers reached $1.11 million per year according to the survey results (Fig. 11.17).

Concern over health issues associated with pesticide spraying was also found to be a major reason why cotton producers chose to adopt Bollgard II cotton rather than continue growing conventional cotton. In the most recent survey year, 2011, about one out of every six producers (16.0 %) responded that the potential to minimize health risks, by reducing the number of pesticide sprayings, was the single most important reason for adopting GM cotton. A majority of the producers, 63.5 %, cited a combination of pesticide reduction, including lower cost, along with higher yields, as the most important reasons for adopting Bollgard II. Although combined with higher yields and lower pesticide costs in this response, it is a strong indication that the incremental health benefit from fewer pesticide applications was a motivating factor among this group of respondents. The INERA surveys collected

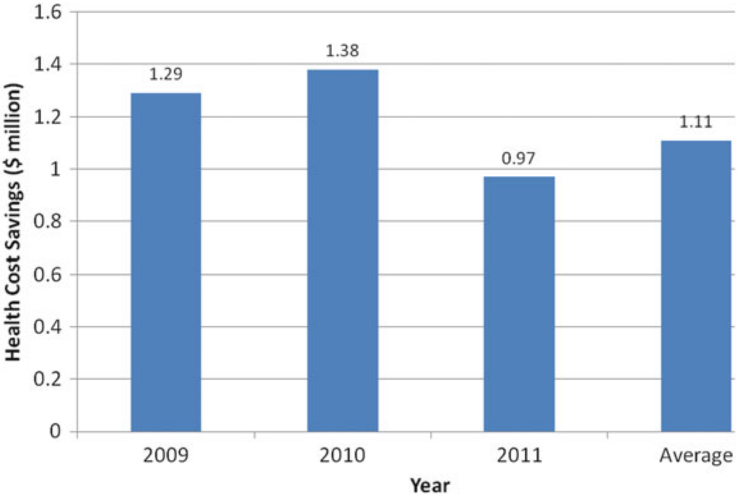

Fig. 11.17 Health cost savings over the past 3 years from the introduction of Bollgard II and based upon self-reporting evidence from the household surveys. *Source*: Authors' calculations based on INERA field surveys

data on the safety and handling practices of producers in 2009, the first year of the surveys (Table 11.7). The surveys collected information on education level, pesticide training, and safety precautions used by individuals responsible for applying pesticides. Wearing protective clothing during the application of pesticides was found to have the greatest effect on reducing pesticide poisonings (Table 11.7). Producers who wore protective clothing had significantly fewer pesticide poisoning incidents. Nineteen percent (of the total sample) of producers who wore protective clothing self-reported a pesticide poisoning incident; in comparison, producers who did not wear protective clothing were more than twice as likely to have incurred a poisoning incident, with a 50 % occurrence in pesticide poisonings (Table 11.7). The importance of wearing protective clothing and its beneficial effect on reducing poisonings has been found in other studies and should continue to be emphasized in training programs.

Extension services from the cotton companies provide workshops on safety precautions and best management practices when handling, storing, and disposing pesticides. Attending extension training did not reduce the number of cases of poisoning among the surveyed producers (Table 11.7). Of the producers who self-reported a poisoning incidence, a greater proportion, 39 % (of total sample), had attended a safety training workshop compared to 30 % (of total sample) producers who did not attend (Table 11.7). This unexpected finding is not easily explained and may indicate natural variability combined with safety training which is ineffective for various reasons.

Bathing and washing clothes following pesticide spray operations are some of the techniques that are taught in extension training programs and are part of the recommended safety practices provided to producers. However, contrary to

Table 11.7 Producer characteristics and pesticide application practices among surveyed producers from the 2009 human health surveys

			Poisoning cases[a]			
	Sample population		No poisoning		Yes	
Item	%	*N*	%	*N*	%	*N*
Education (years of schooling)	7.4	191	7.3	59	7.7	132
Attended pesticide safety training workshop						
No training	41 %	79	11 %	21	30 %	58
Training	59 %	112	20 %	38	39 %	74
Washed clothes following pesticide application						
Dot not wash clothes	36 %	69	12 %	23	24 %	46
Clean cloth	64 %	122	19 %	36	45 %	86
Wear protective clothing during application						
No	72 %	138	22 %	42	50 %	96
Yes	28 %	53	9 %	17	19 %	36
Washed body (bathed/showered) following application						
No	19 %	37	9 %	18	10 %	19
Yes	81 %	154	21 %	41	59 %	113
Farm size (ha)	3.89	191	3.62	59	4.01	132

[a] The "Yes" category refers to households who self-reported the occurrence of at least one pesticide incident during the period 2004–2008

expectations, neither of those variables had a positive influence on reducing the likelihood of pesticide poisoning incidents (Table 11.7). Among the producers who self-reported a pesticide poisoning incident, 45 % had washed their clothes after application, whereas those who did not wash their clothes after application had a lower frequency of pesticide poisoning, 24 % (Table 11.7). Likewise, 59 % of producers who bathed following pesticide application self-reported poisonings, compared to the much lower incidents self-reported by producers who did not shower following pesticide application, 10 % (Table 11.7). As with extension training, the seemingly paradoxical findings suggest the negative effect implied by the surveys may be coincidental and not causally linked.

Cotton growers with the larger farm area may have greater exposure to pesticides since they generally spend a longer time spraying their farms. The survey results are consistent with this expectation: of the 69.1 % of the producers who self-reported at least one poisoning incident, farm sizes averaged 4.01 ha, compared to the 3.62 ha average farm size of producers who did not self-report any poisoning incident (Table 11.7).

11.6.7 Energy Impacts

Table 11.8 attempts to show the energy use associated with cotton production in Burkina Faso. Introducing Bollgard II would arguably have measurable impacts on reducing the energy required to produce cotton (Table 11.8). Among the inputs used

Table 11.8 Energy use in Burkina Faso cotton production cotton

Crop management activity	Inputs used	Application rate	Energy use (Btu ha^{-1})	Energy use (Btu kg^{-1} of raw cotton)
Plow	Animal power	2 bullocks	5,158,400	4,689
	Human labor	100 h ha^{-1}	555,520	505
Fertilize	N (fossil fuel)	150 kg ha^{-1}	8,099,700	7,363
	P (fossil fuel)	50 kg ha^{-1}	440,800	401
Plant	Cotton seed	20 kg ha^{-1}	698,102	635
Pesticide	Fossil fuel	3 kg ha^{-1}	1,111,040	1,010
Herbicide	Fossil fuel	0.3 kg ha^{-1}	111,104	101
Weed	Human labor	50 h ha^{-1}	277,760	253
Harvest	Human labor	300 h ha^{-1}	1,666,560	1,515
Total			17,420,884	15,837

in cotton production, only animal traction and inorganic fertilizer account for more energy than pesticides. For an average producer, Bollgard II would reduce energy use by roughly 700 Btu kg^{-1} of cotton produced (roughly 2/3 of the total of 1,010 Btu kg^{-1} assigned to pesticide use), corresponding to a 4.4 % decrease in total energy use (Table 11.8). Pesticides are ranked 3rd in energy consumption among all the required inputs for cotton production (Table 11.8). Because Bt cotton considerably reduces the use of pesticides, it substantially saves energy when compared to conventional cotton. Fertilizers represent the largest amount of energy among the inputs used in cotton production. Nitrogen fertilizers require more energy compared to potassium and phosphorus fertilizers. Transportation of fertilizers from manufacturing plants to the farm also requires energy. However, some studies have assumed that transportation energy requirement is very low compared to the energy requirement in the fertilizers production system. We estimated the energy requirement for transportation for cotton production in Burkina Faso at less than 1 % of the energy requirement at the manufacturing level. In this estimation we assumed that most of the fertilizers are imported from Lagos (Nigeria.) The transportation is done by road via Benin and Togo.

Animal traction is another input that actually uses a large quantity of energy. Animal traction uses 4,689 Btu kg^{-1}, followed by inorganic fertilizers that use 7,363 Btu kg^{-1} in cotton production. Because cotton production requires more energy than other crops such as millet, sorghum, and maize, it is important to adopt technologies that are more energy efficient in the cotton production industries (Vitale et al. 2011). In this study the authors report that the adoption of Bt cotton will reduce the energy consumption for cotton production from 15,837 to 14,371 Btu kg^{-1}. The largest part of the economy comes from energy savings from reducing the use of pesticides and the labor associated with spraying.

11.7 Discussion and Conclusion

Genetically modified cotton may serve as a working example of how African countries can address enhanced sustainability using modern, science-driven technology to increase production levels while reducing input use and improving the health of farm workers. An attractive feature of GM cotton is its potential to increase productivity in the near to short term, unlike varietal and pest eradication programs that require long-term investment horizons. The Burkina Faso story is emerging as a working model of how biotechnology can be successfully introduced in Africa, and how developing countries can overcome legal and regulatory challenges and build business models that link the private sector to small- and medium-sized producers.

One of the distinguishing features of the Burkina Faso cotton industry is the vertical integration in the input and output supply chains. While international donors have pushed for liberalization and the shift from parastatal to private ownership to improve efficiency, the vertical control of the Burkina Faso cotton industry by the cotton companies appears to make it better suited to introduce Bt cotton than a privately owned sector. This reasoning is consistent with Gouse et al. (2003) who propose that, in South Africa, the adoption of Bt cotton was stronger and more sustainable in situations where a single cotton company provided inputs to producers and also acted as the sole buyer of cotton. In contrast, the adoption of Bt cotton broke down when producers defaulted on loans to the Vunisa Cotton Company and sold their cotton to a rival gin. Smale et al. (2006) discuss that the strong government control over the cotton sector in China may also be a contributing factor to the success that China has had in commercializing Bt cotton.

Burkina Faso is taking shape as a working example of how a business model can be successfully implemented in an industry heavily influenced by the public sector wherein credit is provided for seed and in return producers are obligated to buy their seed and inputs from and sell their cotton to a single entity. A stabilizing factor in Burkina Faso is the political and financial influence of the cotton growers union (UNPCB) in cotton company policy due to its partial ownership status. Cotton prices are now negotiated prior to planting, and producers have had success in obtaining a greater share of the world price. Moreover, the legal framework has been greatly streamlined in the Burkina Faso cotton industry since contracting, and legal responsibility has been achieved through the national cotton companies and Monsanto. This bypasses the need to develop individual contracts with smallholder producers, which would be a daunting task in Burkina Faso given the large number of cotton producers (over 300,000).

If GM cotton continues on its current trajectory in Burkina Faso, its success may create a gateway for the future introduction and development of other biotech crops in Africa. In Burkina Faso, the demand for Bt cotton is driven by the high lepidopteran pest densities and the growing cost of conventional pest-control methods and cotton export markets that strengthen producers' willingness to pay for Bt products. Other cotton producing countries in the region, such as Mali and

Benin, would likely benefit as much as Burkina Faso and could be next in line to introduce Bt cotton once, or if, legal frameworks are established. While capacity may have been lacking initially, through proper planning, management, and partnership with the private sector, Burkina Faso has demonstrated that African countries can successfully introduce GM crops and, in so doing, move toward regaining a competitive stance in world markets.

The commercialization of GM cotton in African countries such as Burkina Faso and South Africa can also serve as a gateway to facilitate other crops. The recent hesitance of certain African countries to accept food aid containing GM maize speaks to the tangible concerns that some African societies currently have over GM crops, particularly when they are intended for human consumption. The increased public awareness of the benefits from a crop such as Bollgard II could, however, enhance public perception and acceptance of GM crops in general. In the long term, biotechnology is expected to address additional constraints and crops that could benefit larger segments of African societies, including consumers and agribusinesses.

There are some unique features of the Burkina Faso experience with Bt cotton that may make it more difficult to replicate with other crops and in other cotton producing countries. Compared to a food crop, introducing Bt cotton has several features that make it potentially more viable. The biggest factor would be human health concerns. The recent refusal of certain African countries to accept food aid containing Bt maize, mentioned above, could take years to overcome. There are technical barriers as well. Introducing BG II in Burkina Faso required the development of only two local BGII cotton varieties. Open pollinated food crops such as maize and cowpea would likely require an introgression into a larger number of lines and varieties since there are many local genetic lines and varieties that farmers have developed and maintained over the years. Information from Kenya suggests that smallholder producers would be unwilling to adopt foreign hybrid maize varieties preferring the taste and characteristics of local varieties. The cotton producers are also well organized in the UNPCB, and the highly centralized parastatal cotton industry is able to provide the legal and logistical infrastructure. Food crops are less well organized and contracting would require a different model than that used with Bt cotton in Burkina Faso.

Biotechnology is expected to enhance the sustainability of African agriculture by enabling the more productive use of resources (Vitale et al. 2011). Greater productivity would ease pressure on Africa's natural resource base, currently strained by population pressure and extensive means of production. Agriculture in the twenty-first century is expected to play new roles, including that of an energy provider (i.e., biofuels), but must do so in the face of growing environmental challenges (Conway 1997). Africa will need to set new standards for agricultural productivity through sustainable pathways that minimize agriculture's environmental footprint to accommodate the twenty-first century paradigm of dwindling resources associated with regional effects of global climate change and water scarcity (Jones and Thornton 2003). For Africa, it won't be as simple as borrowing ideas and technology from the twentieth century Green Revolutions in Asia and Latin America, which achieve a large portion of their productivity gains through the increased use of energy and water, e.g., inorganic fertilizers and irrigation (Ejeta 2010). In parts of Asia, for example, Green Revolution technology has led to environmental problems and the rethinking of its long-term sustainability in the region (Raul 2001). For an African Green Revolution to be successful in the twenty-first century, new methods of production will need to be developed that are not driven solely by economic and technical efficiency, but which also consider the long-term environmental sustainability.

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Chapter 12
The Borlaug Institute and Its Contributions to Worldwide Food and Economic Security

Julie Borlaug, Joseph N. King, Linda Cleboski, Johanna Roman, Ma'ad Mohammed, Michael McWorter, and Virginia M. Peschke

12.1 Introduction

> The first essential component of social justice is adequate food for all mankind.
> – N.E. Borlaug

As a Nobel Peace Prize laureate, Dr. Norman Borlaug was recognized for his profound impact on humanity through his fight against hunger and poverty (Fig. 12.1). His tool was agricultural science. His modes of operation were collaboration and mentorship. He was tenacious in his focus, bold in his ambition, and tireless in his pursuit. He worked and fought for his ideal vision of a world without hunger and poverty up until his death at age 95.

The vision of Dr. Borlaug is continued by dozens of organizations and countless scientists around the world, the vast majority of whom will be nameless in history. They work to increase food production, increase nutrition, and conserve the natural resources that are so vital to agricultural systems. The legacy of Dr. Borlaug will be defined by the new generations trained in agricultural science and their ability to collaborate across borders and across disciplines to continue to provide meaningful solutions to the persistent issues of hunger and poverty. Dr. Borlaug was a firm believer that the processes of scientific inquiry are essential to addressing economic and social inequality throughout the world.

While serving as Distinguished Professor of International Agriculture at Texas A&M, Dr. Borlaug envisioned an institute "to prepare and support students, faculty, agribusiness, farmers, and agricultural communities through three primary functions: innovative science and research, entrepreneurial extension and outreach activities, and collaborative service-oriented education." The strength and quality

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Fig. 12.1 Dr. Norman Borlaug in Africa

of the institute's programs would come from partnering with faculty in Texas AgriLife Research, the Texas AgriLife Extension Service, and the Texas A&M University College of Agriculture and Life Sciences.

Thus, the Texas A&M University System honored Dr. Borlaug by creating an institute that would continue his life's work. The Borlaug Institute serves as an integrative unit that leads and expands the international agriculture capabilities and interests across the Texas A&M University System through teaching, research, and extension activities. The mission of the Borlaug Institute is to prepare and support faculty members, international and domestic firms and communities, and students at Texas A&M and other universities for engagement and leadership in international agriculture in ways that promote service, entrepreneurship, environmental stewardship, and mutual respect among peoples in an increasingly interdependent world.

Building on Dr. Borlaug's work, the Borlaug Institute employs agricultural science to feed the world's hungry and to support equity, economic growth, quality of life, and mutual respect among people. As global interdependence grows, cooperation in international agriculture is increasingly vital. Our role is to encourage and enable students, faculty, citizens, and institutions to be global cooperators and to respond to opportunities in international agricultural development.

12.1.1 Borlaug Institute Core Principles

The Borlaug Institute strives to operate by a set of core principles in all its programs and activities. These principles were developed from Dr. Borlaug's life and teachings:

1. Train and support advocates and practitioners for sound science in agricultural development.
2. Apply integrated and collaborative approaches that consider all available tools.
3. Focus on small-holder farmers who do not currently have access to technology.
4. Reduce poverty through entrepreneurship and rural-to-urban value chains.
5. Train future leaders in agriculture—youth are an essential part of solutions.
6. Engage in development even during conflict. As Dr. Borlaug noted, "World peace will not—and cannot—be built on empty stomachs."
7. Value field and farmer experience. No job is complete until technology is transferred to end users.
8. Persist and persevere in all efforts. Do not settle for mediocrity.
9. Develop solutions through multidisciplinary teamwork.
10. Do not fear change and have courage in the face of obstacles. Be bold, take risks, and be willing to act.

The science of international agricultural development is a powerful tool and has done much to alleviate human suffering. Despite the progress made by Dr. Borlaug and countless others, much work remains to build a world free of hunger, full of opportunity, and respectful of natural resources. As illustrated by the examples that follow, the Borlaug Institute takes this challenge seriously and works to make this dream a reality.

12.2 Borlaug Institute Partnerships

12.2.1 General Structure of Partnerships

Building on the legacy of Norman Borlaug, the Borlaug Institute is engaged in activities critical to international agricultural development. Its areas of focus include contribution to global food security, human and institutional resources development, and promotion of institutional cooperation. These objectives are addressed through agricultural development projects and partnerships, which are the main focus of the Institute.

Funding for development programs typically comes from external donors and organizations such as the U.S. Agency for International Development (USAID) and the U.S. Department of Agriculture (USDA). The technical skills and training are provided by faculty and researchers of the Borlaug Institute and the Texas A&M University System, working in close collaboration with institutions in the host country. The Texas A&M University System employs more agricultural scientists than the centers of the Consultative Group on International Agricultural Research (CGIAR) combined.

The Borlaug Institute works to ensure that training is a key component of any development project, allowing the programs to become sustainable once formal involvement of the Borlaug Institute and other external partners has ended. Specific efforts devoted to training are discussed in more detail in Sect. 12.3.

12.2.2 Examples of Successful Projects

The Borlaug Institute maintains critical research partnerships with other agricultural colleges, international research centers, and development organizations. Such partnerships can be found in Africa, Latin America, the Middle East, Europe, and Asia. In this chapter, programs in four world areas are highlighted as examples.

12.2.2.1 Ukulima Farm Research Center: Limpopo, South Africa

The Howard G. Buffett Foundation has entered into a strategic partnership with the Borlaug Institute to promote African agricultural research, extension, and education at the Ukulima Farm Research Station in the Limpopo Province of South Africa. Its mission is to support science to increase African agricultural production, enhance rural livelihoods, and conserve natural resources. The primary focus of localized research will be the agro-climatic regimes of the Limpopo Basin (South Africa, Botswana, Zimbabwe, and Mozambique), but the intended impact and partnership potential reaches across Africa.

Ukulima Farm was created as a platform for organizations and researchers to develop technology and practices to advance African agriculture. The Ukulima concept is grounded in the principle that technology must be developed and tested in Africa in order for researchers to adequately address the many issues facing African agriculture. This unique platform provides an alternative to current systems of international agricultural research and provides for collaboration between scientists and a synergy of ideas. It promotes an integrated model of research, teaching, and extension for African agriculture.

The Borlaug Institute will implement a comprehensive long-term strategy that will focus research activities and also serve as an interactive tool with local development plans, national objectives in South Africa, and regional priorities for Africa. This strategy will broadly address the themes of African agricultural systems, biodiversity and ecosystem conservation, and conservation agriculture technology including dryland systems. This strategy builds on the strengths of agricultural research in Texas, experience with agricultural issues in Africa, and linkages with partner institutions in South Africa and southern Africa.

All research programs are expected to work towards the objectives of improving African food security and increasing livelihoods of agricultural communities. Programs are encouraged to have collaboration with African partner institutions and scientists and to include training of African students and scientists as part of the research program. In addition, when appropriate, programs are encouraged to have an extension component to demonstrate the direct impact on agricultural development in Africa.

12.2.2.2 Rwanda

The accomplishments of the Borlaug Institute and its many partners in Rwanda exemplify the philosophy of Dr. Borlaug that if the agricultural sector of a country can be established and strengthened, progress in areas such as health and infrastructure will follow.

The Rwanda SPREAD (Sustaining Partnerships to Enhance Rural Enterprise and Agribusiness Development) project is a USAID-funded project representing a partnership between the National University of Rwanda (NUR), the government of Rwanda, the Borlaug Institute, which administers the program, and numerous other institutions. Established in 2006, SPREAD continued the work started in 2001 by the PEARL (Partnership for Enhancing Agriculture in Rwanda through Linkages) and PEARL II projects, which were initially led by Michigan State University and later joined by Texas A&M University. As of this writing, a continuation project (SPREAD II) has been proposed, which would begin in 2012 and extend through 2017. Through the PEARL and SPREAD projects, the entire value chain for Rwandan coffee has been strengthened, from the knowledge and infrastructure to grow and process high-quality coffee to the markets to purchase such coffee and the mechanisms for quality verification. Through SPREAD, improved technology and organization have also been brought to growers of pyrethrum and chili peppers.

All of these programs have been designed to benefit farmers and rural communities by stabilizing and enhancing farm incomes, and they have been successful in helping thousands of farmers improve their livelihoods. In particular, the PEARL and SPREAD programs have demonstrated the effectiveness of strengthening multiple points within a value chain as a means of promoting sustainable economic growth. SPREAD has also had a significant health and wellness component (described in section "Health and Community Benefits") that has provided farmers and their families with increased access to health services and information.

Coffee Quality Improvements

In the coffee industry, the quality of the final product (referred to as cup quality) is the driver for profit at every point in the value chain. Cup quality is affected by many factors, one of the most important being the length of time from harvest to initial processing. The coffee "bean" familiar to most consumers is actually a seed at the center of a fruit, the cherry, that grows on a small tree. The coffee cherries are processed at coffee washing stations, which remove the outer fleshy parts of the cherry and produce green coffee beans for export and subsequent roasting. Research sponsored by SPREAD supported earlier findings showing that delivery of coffee cherries to the washing station within 3–4 h after picking significantly improves the final product when compared to delivery after 7 h or more. Coffee prices are tied to quality ratings; hence, even a few hours make a difference in the prices received by growers. SPREAD has also supported research in other areas, such as the fermentation methods used by coffee washing stations, to provide recommendations on maintaining or increasing quality at comparable or lower cost. The quality of coffee coming from the washing stations is monitored by support centers. During the off-season, these centers are used for training of farmers and coffee washing station personnel.

Coffee processing at the washing stations produces large amounts of pulp as a waste product. In other coffee-producing areas such as Latin America, the pulp is converted into organic fertilizer to be reapplied to the coffee crop, and such methods have recently been adopted in Kenya. SPREAD researchers are testing composting methods such as use of earthworms (vermiculture) or microorganisms to more rapidly break down the pulp. Such practices have the potential to reduce the environmental impact of coffee production in Rwanda as well as to increase coffee cherry yields.

Farmer Organization and Empowerment

Most of the farmers with ties to SPREAD are organized in farmer-owned cooperatives. This type of structure helps to strengthen the production and marketing capacity of farmers by providing a link between individual farmers and the market. The coffee cooperatives own washing stations, and their members and leaders receive training and support in applying for credit, managing loans, and other business skills. By providing these skills to cooperative leaders and farmers, a base is formed for economic growth that can be sustained beyond the involvement of a development project such as SPREAD. Leadership of these cooperatives is determined by election. The Rwanda Small Holder Specialty Coffee Company (RWASHOSCCO) is an exporting company owned by several of the cooperatives supported by SPREAD. RWASHOSCCO supports the member cooperatives in ways such as applying for Fair Trade Certification and assisting the cooperatives to obtain loans. Similar cooperatives have been formed for growers of chrysanthemum as part of the PYRAMID program, supported in part by SC Johnson.

One of the SPREAD programs, Brew Your Own, developed a method to allow farmers to roast and brew coffee from their own trees for use in their own homes. Two US coffee companies, Intelligentsia and Counter Culture, were partners in this effort. Rwandan farmers have traditionally viewed coffee as a product for rich people, requiring expensive processing equipment. In contrast, the Brew Your Own method uses no more than a clay pot, a screen, a rubber inner tube, and a wooden mortar and pestle, which can be supplied at a cost of about US$5 per family. In this way, farmers are able to enjoy and experience firsthand the fruits of their labor and to understand the effects of their production practices on coffee quality and therefore on family income.

Creating Markets for Coffee

The worldwide demand for high-quality coffee produces a “pull” on the market, and farmers in Rwanda have benefitted from increases in both price and demand for their coffee. From 2003 to 2007, the price per pound of fully washed Rwandan coffee doubled and continues to increase; over that same period, the number of coffee washing stations throughout Rwanda increased ninefold.

In 2008, Rwanda hosted its first “Cup of Excellence” competition, the first time that an African nation has hosted this internationally sanctioned program. A second competition was sponsored in 2010 and a third in 2011. Rwanda’s efforts in organizing these competitions have significantly increased its visibility as a source of origin of specialty coffee. The 2010 and 2011 competitions attracted internationally renowned judges (some of whom were coffee buyers) from Asia, Europe, North America, Australia, and Africa. In 2010, growers were informed of the competition at the beginning of the year by radio (described in section “Health and Community Benefits”); these radio programs featured interviews with cuppers (tasters) from the 2008 competition, who provided advice to the farmers. These messages were successful in encouraging farmers to deliver more high-quality coffee to the coffee washing stations involved in the competition, and similar broadcasts were done in 2011. The winning lots in 2010 and 2011 sold for over $20 a pound, with total lot purchase prices exceeding US$40,000 (http://www.cupofexcellence.org/).

To help maintain the demand for high-quality Rwandan coffee, testing has been conducted since 2007 to support appellation, which is geographically based labeling similar to that used for wine. Characteristics such as location, rainfall, soil type, altitude, slope direction, and others can have measurable effects on the quality of coffee produced in a particular area. Testing has been conducted since 2007 to identify the regions (terroirs) that produce high-quality coffee with sufficiently unique and reproducible characteristics to warrant such a designation. This research has also served to identify the types of soil and climate areas associated with different characteristics of the final product (see Hatfield, Chap. 4).

As Rwandan farmers have seen that their participation in the quality coffee value chain will increase their income, they are further motivated and sufficiently confident to invest in coffee production, e.g., by buying more land and ensuring that the cherries are quickly delivered to the washing stations. Although coffee is not consumed for food in the same way as wheat or other staples, the improvement of coffee culture and markets increases household spending power and thus directly affects the quality of life for thousands of growers.

Other Economic Developments

The success of the coffee quality program has spurred the emergence of other value chains, creating additional income for growers of other products. A current focus of the SPREAD project itself is pyrethrum, a type of chrysanthemum used to produce a natural insecticide (pyrethrins). Like coffee, pyrethrum was grown in Rwanda long before SPREAD, but production and pyrethrin yields had declined over time. SPREAD has worked with SC Johnson and SOPYRWA, a Rwandan processing company, to help farmers organize new cooperatives, provide business training to support sound financial management, and improve production practices such as flower drying.

Another example is cassava, which is widely used as a source of starch in the diet of Rwandans. Cassava is normally processed by women at home into a sticky dough called foufou, but the procedure is time consuming and labor intensive. Rwandans and other Africans living in Europe and North America wanted a way to prepare this traditional food without the need to process the cassava roots themselves. The growing markets for ground, prepackaged cassava flour have created an opportunity in Rwanda for investment in the infrastructure needed to process cassava. Initial work on the value chain for cassava flour was initiated during the PEARL I and PEARL II projects when a new product, "Bon Foufou," was developed to target the ethnic food market in Europe, especially in France. Contracts were established to sell Bon Foufou through the Auchan supermarket chain. The program continued under SPREAD in its first year by assisting ITUZE, a Rwandan cassava producers' cooperative, to develop a business plan to support this market, which included construction of a factory for cassava flour processing and packaging. The development of this industry adds value within Rwanda while potentially decreasing the overall cost of the product.

Other nonfarm economic development in Rwanda has also been associated with the coffee quality projects. For example, in cooperation with Project Rwanda, a USAID-funded program founded by bicyclist Tom Ritchey, a specialized "coffee bike" was designed and tested as a means of providing rapid delivery of coffee cherries to the washing stations. Furthermore, the use of bicycles for coffee transport has spurred additional economic activity such as the presence of bicycle repair shops at some coffee washing stations.

Health and Community Benefits

Through special funding from USAID-RWANDA, SPREAD has had the opportunity to provide health information and services through its Integrated Health Program. In SPREAD, agricultural development and health services have been deliberately linked because of their close connection in real life: growers and their families cannot fully participate in or enjoy the benefits of improvements on their farms and communities if they are sick or do not know how to avoid illness or injury. HIV testing and counseling, maternal and child health, information, and other services are provided to growers and their families at health centers, many of which are located in areas near coffee cherry purchase and processing centers. Where required to meet the needs of a community, mobile health centers are used.

Health education is provided to farmers and their families in various ways. One popular means is through radio programs developed by Coffee Lifeline Radio, a program developed in 2007 and currently sponsored by Green Mountain Coffee Roasters. The radios themselves are a unique durable, battery-free model supplied through Radio Lifeline, Inc., and the programs are broadcast on the NUR radio station, Radio Salus. Because of the success of the Coffee Lifeline Radio programs, a "Py Lifeline" radio program is being established in areas of pyrethrum production, providing similar radio programs on markets and health. Another very popular method of communication has been the use of community theater presentations, developed in partnership with the NUR Center for Arts and Drama. This program identified people in cooperatives as peer educators and taught them to develop skits that model healthy behaviors in areas such as family planning, reproductive health, HIV/AIDS, sanitation and hygiene, and nutrition. These peer educators train others in the community to do the same. The skits are immensely popular in Rwanda, and members of the community will come out to see these presentations. The farmers view these as sources of both entertainment and education, and the theater groups themselves participate in local competitions.

Coffee Quality Beyond Rwanda

In May 2010, World Coffee Research (WCR; formerly the Global Coffee Quality Research Institute) was established with start-up funds from over 20 specialty coffee companies. Several of these companies have committed to ongoing support for WCR, which is administered by the Borlaug Institute. The mission of WCR is "to grow the Arabica coffee supply chain in a sustainable way through collaborative agricultural research and development" (http://agrilife.org/worldcoffee/). The research supported by WCR will encompass both the production of specialty green coffee and the processing and other factors important to cup quality, and results will be shared industry-wide. In April 2011, Dr. Tim Schilling, director of WCR and a member of the Borlaug Institute, was awarded the Leadership Medal of Merit by the nonprofit Coffee Quality Institute for his work since 2001 with the coffee industry in Rwanda.

12.2.2.3 Guatemala/Latin America

Continuing Dr. Norman Borlaug's legacy to help farmers in developing nations fight hunger and increase food security is the force behind the Borlaug Institute's Latin American Programs. Such programs are focused on benefitting farmers in several Central and South American countries through the implementation of training and technical assistance programs that provide them with practical, hands-on instruction in improved methods of agricultural production.

Agricultural development programs conducted by the Borlaug Institute in Latin America are aimed at being sustainable. By building local capacity and by partnering with local and foreign institutions that work with Latin American farmers, the Borlaug Institute has been successful in promoting programs that will sustain the economic viability of rural farm operations. Project partners play a key role in helping promote an integrated approach aimed at improving the quality of life of project beneficiaries, while making the most efficient use of resources.

Through Borlaug Institute programs, Texas A&M experts have conducted dozens of agricultural development activities in Latin America, focusing on topics ranging from improving crop production to value chain and market development and expansion. The Borlaug Institute works with small farmers and cooperatives on increasing yields, enhancing rural enterprises, developing new products, promoting agribusiness, and implementing Sanitary and Phytosanitary Standards (SPS) and other safe and clean food processing standards and procedures in the livestock, meat, grain, and horticultural sectors of Latin America.

Examples of recent and current activities in Latin America include Food for Progress projects in Guatemala in which the Borlaug Institute works with indigenous farmers to expand food processing, promote improved agricultural techniques, provide farmer education and strengthen cooperatives, and promote the development of agriculture-related businesses. The Borlaug Institute and Texas A&M experts are also completing a technical assistance program for cattle producers in Ecuador and a Capacity Building program at Universidad Nacional Agraria La Molina in Perú. In addition, the Borlaug Institute and Texas A&M experts in SPS have recently provided technical assistance in SPS Systems in Panama and have delivered food safety programs for Central Americans in the USA. Texas A&M experts have also provided agribusiness training in Nicaragua and Guatemala and have completed two projects to expand the food processing sector and new product development in El Salvador. The Borlaug Institute has conducted youth development programs in Honduras and Guatemala through the Junior Master Gardener Program and has provided Texas A&M students with internship opportunities in Guatemala.

Food for Progress Programs in Guatemala

Food and nutritional insecurity is endemic in Guatemala, a country with a persistent state of chronic malnutrition, especially in rural areas. According to the National Survey on Maternal and Child Health (ENSMI) (2009), Guatemala's levels of food and nutritional insecurity are among the highest in the world. Ethnic inequalities highly contribute to food insecurity.

Building food security in Guatemala through Borlaug Institute programs can help curtail the onset of the current hunger crisis that the country is suffering. By focusing on poverty reduction through economic development, the Borlaug Institute staff has been successful in promoting market-led agricultural development programs in selected rural areas that have significant potential for agricultural trade.

In Guatemala, two USDA-funded Guatemalan Food for Progress projects led by the Borlaug Institute have been promoting sustainable agriculture and food security programs for farmers since 2005. The Borlaug Institute has been active in Food for Progress efforts to benefit the farmers and people of Guatemala through assistance with the production and marketing of nontraditional crops, establishing facilities for food processing and biodiesel production, producing and marketing organically grown products, and providing agricultural education and training. The Borlaug Institute also has been instrumental in helping develop human capital to ensure Guatemala's agricultural future.

The Agriculture in Guatemala: Technology Transfer, Education and Commercialization project, known as AGTEC, is the current Food for Progress project in which the Borlaug Institute is helping Guatemalan farmers from the area of Chimaltenango improve their lives by using new agricultural technology and practices taught through hands-on demonstrations and technical assistance programs. The program also helps indigenous farmers expand their ability to sell their products locally and through export. In Chimaltenango, there is a concentration of extreme rural poverty due to a large indigenous population. Poverty levels are as high 70–80 % in most departments in the Highlands. Borlaug Institute programs are helping farmers move from subsistence grain crops to high-value horticultural crops by offering technical assistance through the project's crop diversification and marketing programs. Sustainable environmental practices and organic farming are emphasized.

For example, cold-storage units and food processing facilities have been established by the project in rural agricultural communities, in response to food production, processing, and safety needs. The Borlaug Institute has been working to help increase farmer knowledge and to help provide farmers with access to new markets and technology. The program aims to help farmers improve every link in the agricultural value chain, including production processing, storage, packaging, shipping, and marketing.

Both Guatemalan Food for Progress efforts led by the Borlaug Institute have included the establishment of food processing centers, crop trial plots, greenhouses, irrigation systems, plant nurseries, post-harvest centers, and biodiesel production facilities. Project efforts also have included extensive education and training for thousands of Guatemalan farmers, as well as community leaders and agribusiness and agriculture ministry representatives. Topics have ranged from best agricultural practices, crop rotation, irrigation, production, harvesting, and sound environmental techniques to fair trade, microcredit, product marketing, food processing and safety, organic farming, agroforestry, and horticulture. Instruction is typically provided in Spanish by AgriLife Extension, Texas AgriLife Research, and other Texas A&M System experts, as well as experts from local institutions and organizations.

12.2.2.4 Iraq

The Borlaug Institute has been involved in several programs to rebuild the agricultural infrastructure in Iraq; to ensure that farmers and extension agents have access to timely, accurate information; and to provide agricultural education to Iraqi scholars.

Reconstruction and Business Development

Provincial Reconstruction teams (PRTs), established in Iraq in 2005, were primarily composed of military personnel but had civilian experts as key members. Beginning in 2006, the civilian members included extension agents from the USDA who were recruited to travel with the US military for periods of 3–6 months. This partnership between agricultural extension and the military came about in part because US Secretary of Defense, Dr. Robert Gates, who had previously served as president of Texas A&M, learned that soldiers were being asked questions about agricultural production, such as the proper setup of irrigation. In 2007, a team from the Borlaug Institute, including director Dr. Ed Price and five other Texas A&M faculty and staff members, traveled to Iraq at the invitation of the US Department of Defense (DOD) to provide advice on improving Iraqi agricultural employment. The following year, members of the Borlaug Institute, dubbed "Team Borlaug," visited provinces throughout Iraq to serve as advisors to regional military commanders, providing agricultural expertise, educational tools, and youth-oriented programs.

To address the needs of the extension agents and others in PRTs, the USDA PRT Portal program was set up as a means by which PRT members could obtain extension advice from agricultural experts in the USA through a website. The website contained links to informational documents as well as a link for sending questions to an extension agent, with a target response time of 24–48 h. The program was led by the University of Hawaii at Manoa, working in partnership with the Borlaug Institute and Texas A&M, and ended in 2010.

Some of the support for agricultural facility reconstruction was provided by ARDI (Agricultural Reconstruction and Development for Iraq), a USAID-funded project run from 2003 to 2006 and managed by DAI. ARDI worked along with the US military in the reconstruction effort. As a subcontractor, the Borlaug Institute provided a variety of services such as agricultural demonstrations, repairs to damaged facilities, and building of new facilities. Examples of specific areas include infrastructure for improved water use efficiency (see Oikeh et al., Chap. 13), livestock production and animal health, and seed production technology.

Support for the emerging Iraqi agribusiness sector has been provided by the USAID *Inma* Agribusiness Project, managed by the Louis Berger Group. *Inma* is an Arabic word meaning "growth," and the program is intended to help transition of agribusiness from government to the private sector through development of agribusiness and markets for agricultural products. As a subcontractor for this program, the Borlaug Institute has provided teams of experts in agricultural economics, agronomy, and fisheries.

Support for Extension

The Borlaug Institute has been heavily involved in the USDA-sponsored Iraq Agricultural Extension Revitalization (IAER) Project, led by Texas A&M in cooperation with the Iraqi Ministry of Agriculture. The purpose of this effort is to ensure that extension agents within Iraq have the necessary training and educational tools to provide advice to farmers and support agricultural production in the region. In 2009, 62 Iraqi extension agents received advanced training at five US universities as part of this program (USDA-FAS 2010b). US extension agents and other specialists also conduct training in Iraq. For example, in June 2011, three teams of extension agents from Texas AgriLife Extension (the extension program of Texas A&M University System), Washington State University, and the University of California–Davis traveled to Erbil, Iraq, providing training and assisting in the development of educational programs and materials. Training programs have included topics such as greenhouse/hoophouse vegetable production and irrigation system management.

Iraqi Scholars Program

US-based training of Iraqi scientists is being provided through the Iraqi Scholars Program. Under this program, 37 scholars from Iraq came to the USA in 2009 and 2010 to obtain Master of Science (MS) degrees in US universities. Many of these scholars were from the Iraqi Ministry of Agriculture; others were from various Iraqi universities or the private sector. For the first part of their training, the candidates studied English at Texas A&M. Once the students demonstrated proficiency in English, they applied to MS degree programs in other US universities. Because of the difficulties in adjusting to a new language and culture, many students returned home before completing the program, but others stayed. As of September 2011, all 12 students remaining in the program had transitioned from the English-language training to an MS degree program (Partida 2011).

12.3 Training Program Experiences Supported by the Borlaug Institute

From his years of teaching Mexican children to play baseball till his death, Norman Borlaug's life passion was to train and encourage young people to gain life skills that would provide them with opportunities to contribute to society. His focus on mentoring and training is one of the major inspirations for the Borlaug Institute.

12.3.1 Opportunities for Students at Texas A&M

As highlighted on the Borlaug Institute website, "A critical component of the Borlaug Institute mission is to empower students across the Texas A&M University System to gain a broader understanding of the world and to become global citizens." At home, the Borlaug Institute accomplishes this through programs such as seminars and assisting student groups in service projects.

The Borlaug Institute also offers students at Texas A&M a variety of international for-credit academic opportunities. Cooperating with the College of Agriculture and Life Sciences, students can participate in Study Abroad and Student Exchange Programs. Currently, all 14 departments in the College of Agriculture and Life Sciences offer a variety of faculty-led Study Abroad and Exchange Programs. These international travel programs provide opportunities to experience unique cultures and conduct research in a wide variety of ecological setting throughout the world. Study Abroad experiences can be focused on farming systems, economics and policy, ecology, nutrition and food science, molecular sciences, tourism, and recreational systems. In addition, the Institute is an active participant in several external programs designed to provide training opportunities in international development.

Texas A&M students also have the opportunity to participate in international service projects lasting 7–10 days or internships of 4–10 weeks. Internship opportunities are often associated with large multi-year international development projects administered by the Borlaug Institute. In some cases, students are able to conduct short research projects and obtain class credit. These international opportunities are often life-changing experiences for the students involved, while providing much-needed assistance to the development programs of the Borlaug Institute.

12.3.2 Short-Term Nonacademic Training Programs

12.3.2.1 Borlaug Fellowship Program

In the fall of 2003, Texas A&M University Dean of Agriculture Dr. Edward Hiler began to interact with then USDA Secretary Ann Veneman to establish a Borlaug Fellowship Program. The goal of the program was to foster the adoption and adaption of agricultural science and technology to support the agricultural and rural development needs of emerging countries. The vision was to embrace a wide variety of agricultural technologies, including those related to production, processing, and marketing, and would address ineffectual policies and regulations as well as weak extension and research capabilities. To achieve the goals, scientists, faculty members, and government officials would be provided a variety of practical laboratory and field experiences. The 6- to 8-week training program was to be accomplished using venues provided by U.S. land-grant universities, USDA or other government agencies, private companies, not-for-profit institutions, and international research centers. Each Fellow would be mentored by a host at the training location, to encourage networking and establish durable collegial relationships. The Fellows Program would promote food security and economic growth in developing and middle-income countries through newly acquired scientific knowledge gained by scientists, policymakers, and regulators from around the world.

After extensive discussions and planning, USDA Secretary Veneman formally inaugurated the Norman E. Borlaug International Science and Technology Fellows Program on March 29, 2004, in honor of Dr. Borlaug's 90th birthday.

Today, the Norman E. Borlaug International Science and Technology Fellows Program is administered by the USDA/FAS and is funded by US Departments of Agriculture and State and by USAID. Since 2004, hundreds of mid-career international leaders from Africa, Latin America, Central and Southeast Asia, the Middle East, and Eastern Europe have been Fellowship recipients.

The Borlaug Institute participates in the USDA Borlaug Fellowship Program by facilitating all training activities of visiting Fellows including the identification of host mentors in the academic departments of the College of Agriculture and Life Sciences at Texas A&M University.

When possible, the Fellows attend the annual World Food Prize activities each fall in Ames, Iowa. During Dr. Borlaug's lifetime, these activities included a meeting between Dr. Borlaug and the Fellows, a highlight of the event for both Dr. Borlaug and the Fellows alike. Today, the legacy continues with the Fellows attending breakout sessions featuring prominent speakers in science, government, and industry.

After a Fellow returns home, the host mentor will normally plan a follow-up visit to the Fellow's home country to give seminars and meet other scientists. The relationships established during a Fellow's tenure in the USA can extend long after he or she has returned home. The length of the fellowships helps to ensure that adequate time is available for such relationships to be developed. Evidence of these ongoing relationships can be seen in examples such as joint authorship on research articles and co-sponsored workshops.

The Borlaug Institute and Texas A&M University faculty are also active in a variety of nonacademic short-term training programs that support the USDA Cochran Fellowship Program. This program "provides US-based agricultural training opportunities for senior and mid-level specialists and administrators from public and private sectors who are concerned with agricultural trade, agribusiness development, management, policy, and marketing" (http://www.fas.usda.gov/icd/cochran/cochran.asp).

12.3.2.2 World Food Prize Youth Institute

The Borlaug Institute has created learning opportunities for high school students in Texas and Mexico in association with the Global World Food Prize Youth Institute, through establishment of the Texas Youth Institute Symposium and the Mexico Youth Institute Symposium. High school students from across Texas and Mexico are invited to submit essays and participate in these symposia. The top three students and their mentors from each of the two areas are then eligible to attend the Global World Food Prize Youth Institute in Des Moines, IA, where they are able to meet World Food Prize winners and other distinguished scholars. State Youth Institutes have also been established by universities in Indiana, Minnesota, and other states; students from states without their own Youth Institutes can participate by applying directly to the Global Youth Institute.

12.3.3 Long-Term Academic and Research Training

12.3.3.1 Borlaug Leadership Enhancement in Agriculture Program

The Borlaug Leadership Enhancement in Agriculture Program (LEAP) scholarship program is designed to help develop the next generation of international leaders in agriculture and related fields. Scholarships are available for graduate students from USAID-assisted countries who are currently studying in the USA. This program is funded by USAID and administered by the University of California–Davis. Students are supported both by their faculty mentor in the USA and by a mentor at one of the CGIAR institutions. In recent years, Texas A&M University faculties have served as mentors and major professors of several international students that have received LEAP scholarships. A representative from the Borlaug Institute serves on the Borlaug LEAP Program selection committee.

12.3.3.2 Beachell–Borlaug International Scholars Program

The Beachell–Borlaug International Scholars Program was established in 2009 by Monsanto in honor of the lifelong contributions of Dr. Henry Beachell, a pioneer in the development of high-yielding rice at the International Rice Research Institute, and Dr. Borlaug. The program, administered by Texas AgriLife Research, provides full support for students seeking Ph.D. degrees in rice or wheat breeding and is open to students worldwide. Students accepted by the program conduct at least one season of field research in a developing country. The participant selection committee is headed by Dr. Ed Runge, former head of the Soil & Crop Sciences Department at Texas A&M University. The selection committee is composed of a Monsanto representative and several very distinguished international scientists active in rice and wheat breeding.

12.3.3.3 Borlaug International Scholars Program

The International Scholars Program is intended for students outside the USA to come to Texas A&M or another land-grant university for graduate studies. Funds for this program come from a memorial fund established by the Borlaug family and administered by the nonprofit Texas A&M Foundation. The fund has received contributions from many generous supporters including the Bill & Melinda Gates Foundation. The first two scholars were named late in 2010.

12.3.4 Howard G. Buffett Foundation Chair in Conflict and Development

Agricultural development can reduce the likelihood of conflict by increasing food security, but it can also be a source of conflict if not applied appropriately. The Borlaug Institute is working to understand the relationships between agricultural development, food security, and conflict to help prevent future conflicts and assist those affected by past and present conflicts. To help meet this objective, the Howard G. Buffett Foundation Chair in Conflict and Development has been established at Texas A&M University. The first holder of this chair is Dr. Edwin Price, currently the director of the Borlaug Institute.

12.4 Reflections on Norman Borlaug

Julie Borlaug, granddaughter of Dr. Norman Borlaug, is the Assistant Director of Partnerships at the Borlaug Institute. For this chapter, she was asked to reflect on how her grandfather's life and work have influenced her own.

In many ways, Julie's early recollections of her grandfather are like those of many other grandchildren who have only a vague sense of what their grandparent does outside of the occasional visit. As a small child, Julie was told that her grandfather "was feeding starving children in Africa," but how he did that was largely a mystery to her. At the same time, Julie and the other Borlaug grandchildren were raised in an atmosphere particularly attuned to world issues, and with an understanding that each person had a responsibility to make life better for others. Some clues to Dr. Borlaug's exceptional life were evident to Julie even as a child, such as the time he and his Nobel Prize medal were the subject of her third-grade class show-and-tell.

On a typical visit, Dr. Borlaug would sit down, ask his grandchildren about their studies and sports, and then begin to read. Julie recalls working with her sisters and cousins to wash and style her grandfather's hair as he read, perplexed at what the little girls were up to but grateful that they were staying out of trouble. As a child, Julie didn't see her grandfather very often; when he was in Texas, he was generally passing through, on the way from somewhere in the world back down to Mexico. Julie speculates that in some ways, trips home might have been a letdown from the acclaim Dr. Borlaug found elsewhere. Although her grandfather was treated like a celebrity on his trips abroad, her grandmother Margaret was the "rock" and undisputed center of the family at home, even when her grandfather was home

Fig. 12.2 Dr. Norman Borlaug and his granddaughter Ms. Julie Borlaug

for a visit. Despite his busy schedule, Dr. Borlaug attended the college graduations of all five grandchildren and spoke at each one.

Julie recalls that her grandfather kept much of his work life separate from his family, who usually did not attend award events and sometimes did not even know about them. In part, this was because such honors were not important to him personally, and he preferred to use such events as a platform for the messages he wanted to convey. One notable exception to this was when Dr. Borlaug was presented the Congressional Gold Medal in 2007. The entire Borlaug family, including grandchildren and great-grandchildren, joined him for the award ceremony at the Capitol. Julie recalls Dr. Borlaug letting himself take it all in and being genuinely proud and happy that his family was present for the event (Fig. 12.2).

Dr. Borlaug's family knew very little about his views on religion or politics, though he voted regularly. He kept such opinions to himself, knowing that an apparent religious or political preference could interfere with his goals. At the same time, he made no attempt to hide his anger and disgust when he felt that not every available tool was being used to tackle the problems of hunger and poverty. The recollection of having a starving child die in his arms brought him openly to tears even decades later.

As Julie grew up and became more interested in global issues herself, she found her grandfather an invaluable source of information and perspective. She had to be careful what she wished for, as a simple question could result in an answer lasting several hours. Julie attended Texas A&M, where she earned a BA in political science and international studies, and the University of Dallas, where she received an MBA in nonprofit management. Julie worked for the Salvation Army and several other nonprofit organizations before returning to her grandfather's passion for the world's hungry. She came back to Texas A&M in 2006, where she served as Dr. Borlaug's de facto assistant. Having no agricultural background, Julie was initially surprised by the complexity of the issues surrounding agriculture and hunger. (She was later complimented by her grandfather on how much she had picked up, which was undoubtedly a source of pride for both of them.) Julie also learned that agriculture is sometimes treated as a secondary science, and she recalled one of Dr. Borlaug's favorite quotes on that topic:

> Few scientists think of agriculture as the chief, or the model science. Many, indeed, do not consider it a science at all. Yet it was the first science—the mother of sciences; it remains the science which makes human life possible; and it may well be that, before the century is over, the success or failure of Science as a whole will be judged by the success or failure of agriculture. (Mayer and Mayer 1974)

At Texas A&M, Julie's job was to schedule her grandfather's interviews and manage public relations, and she found that keeping Dr. Borlaug on a strict schedule was all but impossible. To him, it was incomprehensible that he was being asked to distill such pressing issues into 30-second sound bites, and he rarely complied. On the contrary, whenever Dr. Borlaug told a story related to agriculture, he always wanted to start at its very beginning ("at the Big Bang Theory," as Julie put it) because of his firm belief in the lessons of history. As always, Dr. Borlaug kept his focus on the message and paid little attention to administrative details such as travel expense reports, much to the dismay of those left to sort out the receipts.

Dr. Borlaug made a particular effort to meet with students, especially from outside the US. Julie recalls how much her grandfather enjoyed these meetings, and the students were thrilled to be meeting someone who was sometimes more of a legend in their own countries than in his own. Dr. Borlaug felt that it was of utmost importance for students working in any aspect of agriculture, even in areas unrelated to field work, to have hands-on field experience. Conversely, he felt that scientists needed to understand economics and to be prepared to advocate for their disciplines. Such principles were the foundation of programs such as the Borlaug LEAP Fellowship program (discussed in Sect. 12.3.3.1).

In the late 1980s and 1990s, Dr. Borlaug was disappointed that traditional sources of funding for agriculture were waning and that the public as a whole seemed to be taking less of an interest in agricultural issues, at least until food prices began to skyrocket in 2007–2008. Undaunted, Dr. Borlaug continued to champion issues he felt were critical, and he led the effort to raise awareness of the threat posed by the emergence of Ug99 wheat rust. Dr. Borlaug was encouraged by the emergence of new sources of interest and funding such as the Gates Foundation, which helped to bring issues of hunger to the forefront again.

Although Dr. Borlaug was frustrated to become increasingly dependent on others in his later years, the challenges of age and illness gave the Borlaug family 2–3 years closer to him than they had had in many years. During that time, Dr. Borlaug met with his son (Julie's uncle) to give him messages for each grandchild, which were communicated to them after Dr. Borlaug's death. Julie and the other grandchildren took comfort in these messages and felt that their grandfather noticed more about them than they might have suspected, given his many years spent away from home. Because of her ongoing role in carrying on Dr. Borlaug's legacy, Julie is often asked what it was like to grow up as a member of his family. For her, it is impossible to separate the man credited with saving a billion lives from the man who let himself be used for hairstyling practice. Her answer is simply, “He was our grandfather.”

Of all her grandfather’s traits, Julie most admired his drive and his impatience with people who didn’t understand that hungry people needed food immediately, not when some “ideal” solution could be devised in the future, and she describes his devotion to this cause as “touching and amazing.” Even in the last few days of his life, Dr. Borlaug expressed his concerns for hungry people in Africa and was troubled that he was leaving work unfinished. He urged Julie, and the many others who contacted him in those last days, to keep up the fight. His last request, spoken in reference to a new technology for Africa, was to “take it to the farmer.” In partnership with thousands of others throughout the world, the members of the Borlaug Institute strive to fulfill that mission every day.

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Chapter 13
The Water Efficient Maize for Africa Project as an Example of a Public–Private Partnership

Sylvester Oikeh, Dianah Ngonyamo-Majee, Stephen I.N. Mugo, Kingstone Mashingaidze, Vanessa Cook, and Michael Stephens

13.1 Introduction

13.1.1 Challenges and Problems Facing Sub-Saharan Africa

The two most challenging problems to improving maize yield in sub-Saharan Africa (SSA) are recurring droughts and prevalence of insect damage, especially by the maize stalk borer (*Busseola fusca*). The compounding effect of these two challenges is that during drought (see Alam et al. Chap. 5), maize that is able to survive becomes particularly susceptible to pest damage. This combination severely impacts on the ability of SSA farmers to produce enough maize to feed their families. Plant breeding practices alone will not be able to tackle these challenges.

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The complexities of breeding for a polygenic trait such as drought tolerance with a very high genotype by environment interaction (G × E) means that progress tends to be limiting the impact of any single, isolated breeding program. Hence, it is recommended that combining a breeding approach with other advanced agricultural practices and technologies, such as a transgenic approach, could ensure faster progress in improving both maize drought tolerance and insect resistance (see Stojšin et al. Chap. 9).

13.1.2 A Public–Private Partnership Solution

In 2008 the public–private partnership "Water Efficient Maize for Africa" (WEMA) was established to tackle the drought tolerance problem. The project has financial support from the Bill and Melinda Gates Foundation, Howard G. Buffett Foundation, and USAID. The initial funding (Phase 1) was for a 5-year research and development phase (2008–2012). The next funded phase of the project started in 2013 and will continue with research and development, but will also focus on deployment of the WEMA products (improved maize hybrids and traits) developed in Phase 1. The project objective is to develop and make drought tolerant maize hybrids available to smallholder farmers in SSA. Transgenic technology for insect resistance and drought tolerance as well as germplasm donated to the project by the private partner, Monsanto, is on a royalty-free basis. The partnership is led by the African Agricultural Technology Foundation (AATF) based in Kenya with collaborating partners including the International Maize and Wheat Improvement Center (CIMMYT; see Borlaug et al. Chap. 12), Monsanto Company, and five National Agricultural Research Systems (NARS); the Commission for Science and Technology (COSTECH), Tanzania; Kenya Agricultural Research Institute (KARI), Kenya; Instituto Nacional de Investigacao Agronamica (IIAM), Mozambique; National Agricultural Research Organization (NARO), Uganda; and Agricultural Research Council (ARC), Republic of South Africa.

13.1.3 The WEMA Project

In SSA, maize is the primary grain crop grown for human consumption, with more than 300 million people depending on it as their staple food (Banziger and Diallo 2001), yet the average maize yield for a farmer in SSA was reported by the Forum for Agricultural Research in Africa (FARA 2009) to average 1.7 t/ha in 2006 compared to the global average of about 5 t/ha. SSA is the only region where poverty and malnutrition are rising both as a percentage of the population and in absolute numbers (Sachs 2005). More than half of the hungry people are subsistence farmers who are unable to grow enough food to feed their families and escape from cyclic poverty.

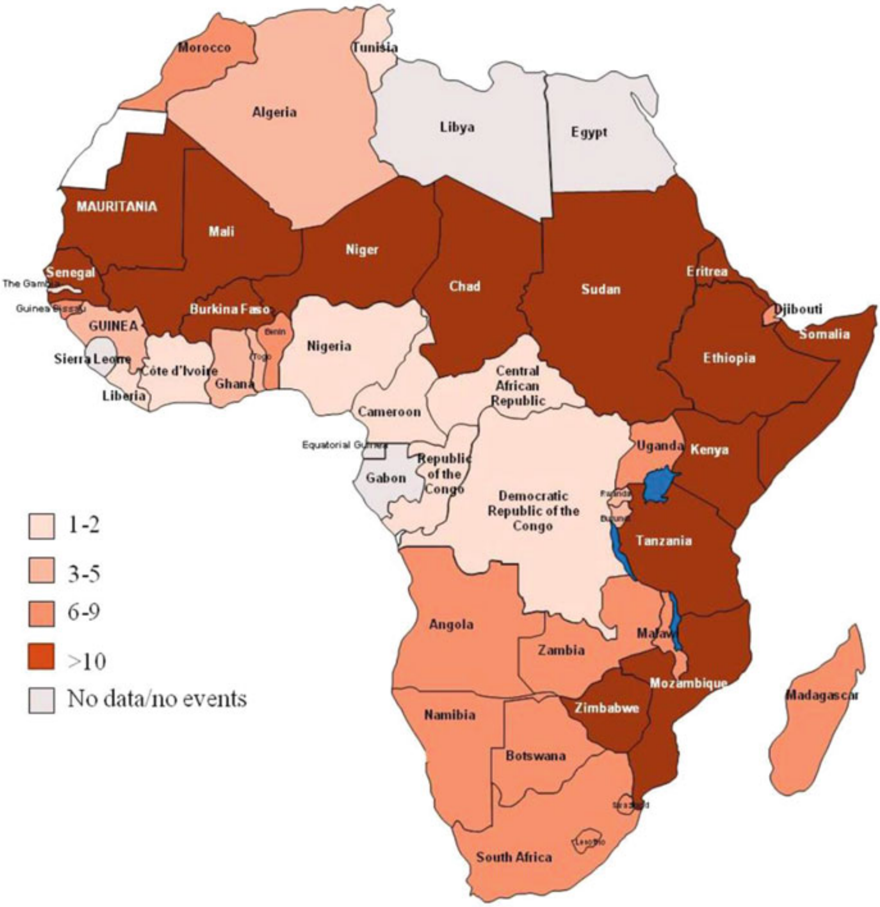

Fig. 13.1 Drought events in Africa from 1970 to 2004 (Adapted from Noojin 2006)

Most countries in SSA have experienced 5 to 10 drought events between 1970 and 2004 (Fig. 13.1). The frequency and severity of drought varies, but across SSA drought stress is one of the top two factors responsible for limiting maize production (Heisey and Edmeades 1999). It is estimated that climate warming in SSA of just 1 °C will further harm maize yields under drought conditions (Lobell et al. 2011).

The high sensitivity of maize to drought stress at critical times of the growing season discourages smallholder farmers from risking investment in best management practices including quality hybrid seed and fertilizer. The partners are identifying ways to mitigate this risk posed by drought stress in maize by both increasing and stabilizing grain yields. The drought tolerant hybrids are being developed through conventional breeding, marker-assisted breeding, and biotechnology and will be licensed to local seed companies producing and selling hybrids

Table 13.1 Contributions by each collaborating partner to the WEMA project

Organization	Expertise	Intellectual property
AATF	Public–private partnership management Project leadership	Facilitate negotiations of all agreements
CIMMYT	Conventional and abiotic stress breeding	SSA adapted drought tolerant germplasm
MONSANTO	Conventional, molecular, and doubled haploid breeding	SSA adapted germplasm; DNA marker information
	Biotechnology testing and stewardship	Transgenic insect-resistance trait and transgenic drought tolerance trait developed in collaboration with BASF
NARS	Field testing for breeding and regional trials Knowledge of farmers' product needs	Locally adapted germplasm

for SSA farmers to help reduce smallholder farmer's risk from drought and provide better food security.

The WEMA product concept is to develop drought tolerant white hybrid maize seed for smallholder[1] farmers of sub-Saharan Africa that yields at least 20 % more under drought conditions compared to commercial 2008 check hybrids. Additionally, these maize hybrids will also have the agronomic characteristics that are adapted to the region. To meet this goal each partner is contributing technology, expertise, and/or other resources to the project (Table 13.1).

For the project to be managed effectively and reach the milestones, a number of teams were established with representation from each partner organization. These are the Product Development Team, Regulatory Team, Communication Team, Deployment Team, and Intellectual Property Management Team. This same WEMA structure is repeated in each of the partner countries. The project management is supported by an Operations Committee, and high level policy oversight is provided by an Executive Advisory Board.

13.2 Drought-Tolerant Maize

Plants respond to their changing environment in a complex, integrated way that allows them to react to the specific set of conditions and constraints present at a given time. Therefore, the genetic control of tolerance to drought is very complex and highly influenced by other environmental factors and by the developmental stage of the plant (Fig. 13.2).

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[1] In South Africa this is defined as a farmer planting less than 3 ha maize.

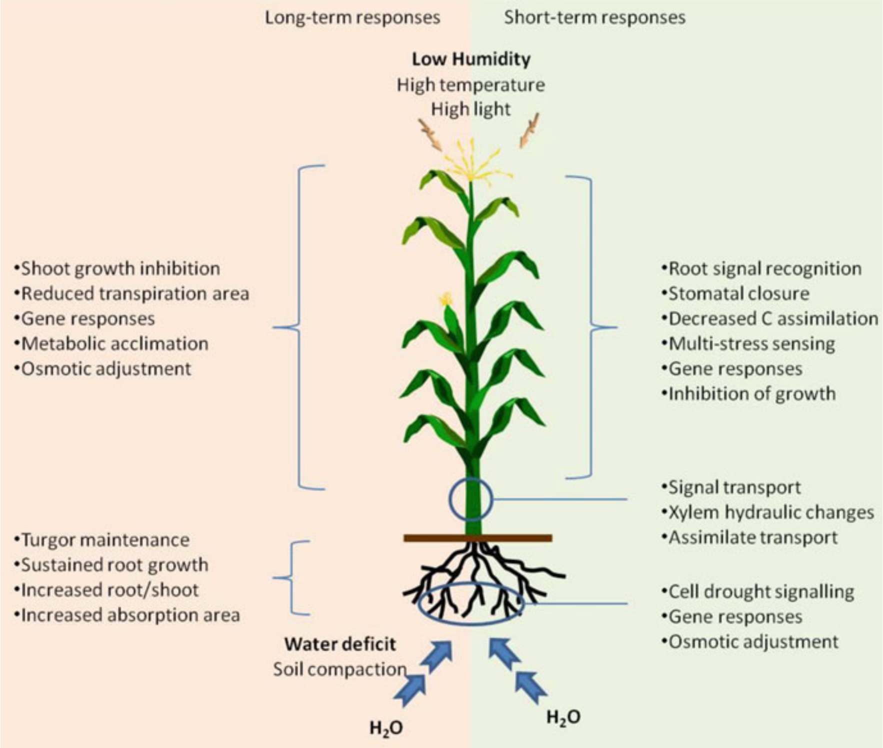

Fig. 13.2 Whole plant response to drought stress (Adapted from Chaves et al. 2003)

Drought stress triggers a series of physiological and biochemical changes in the plant, which are a result of several genes that are switched on and increased levels of several metabolites and proteins, some of which may be responsible for conferring a certain degree of protection to these stresses (Bhatnagar-Mathur et al. 2008). Due to both the complexities of drought itself and the plants' response to moisture stress, it follows that a single organization cannot address all the challenges of developing drought tolerant maize hybrids for Africa and that a single technology or methodology may provide only part of the solution. The WEMA partnership is taking multiple approaches and utilizing resources across organizations to develop a systems-based approach to reach the project's objectives.

The focus of the project is on (1) developing new germplasm using conventional breeding, doubled haploids, and Marker-Assisted Recurrent Selection (MARS); (2) to undertake discovery breeding to identify drought tolerant QTLs; (3) to introgress drought tolerance transgenes into SSA adapted germplasm; and (4) to test the germplasm introgressed with the insect-resistance and drought tolerance transgenes in the partner countries.

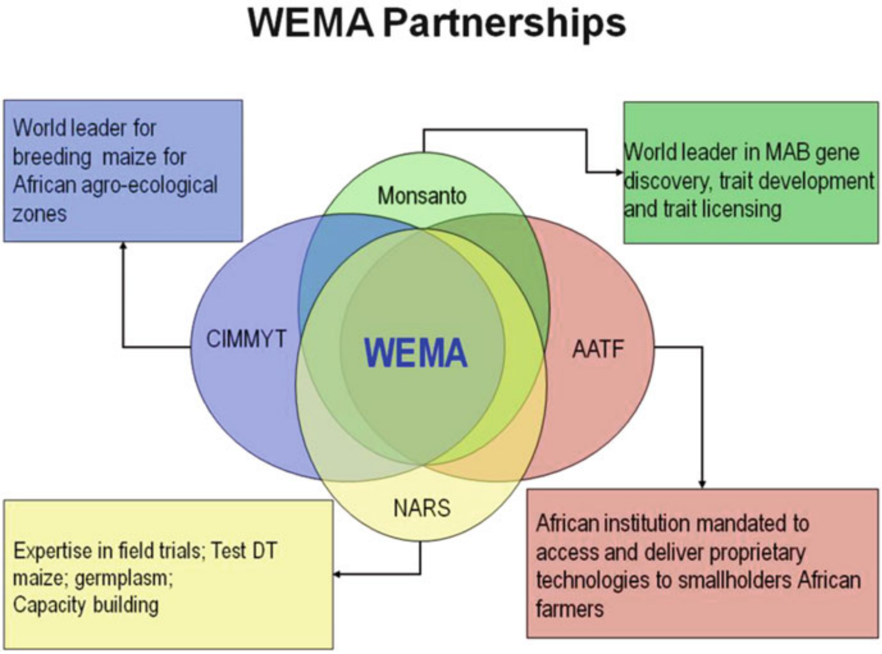

Fig. 13.3 WEMA partnerships and how they share technology, knowledge, and experience

13.3 Benefits of the Public–Private Partnership to Achieving Research Goals

The WEMA partnership is designed with a goal to harness the strength of each collaborating partner and ensure that improved drought tolerant germplasm is identified efficiently and in a cost-effective way. Hence, this can only be accomplished through good collaboration between the partners as illustrated in Fig. 13.3.

WEMA maize is evaluated under local growing conditions as well as at managed drought sites. To date WEMA has established close to 20 sites across the partner countries to test germplasm from all the WEMA programs. This includes the establishment of confined field trial sites that have the necessary facilities to impose managed drought stress. The public–private partnership has provided access to WEMA for more enabling technology than has been previously utilized in an agricultural project in Africa.

13.3.1 Collaboration Through the Breeding Approach

The partners are able to access the largest active maize germplasm resources in terms of both quality and diversity. The breeding methodologies in WEMA are equally wide-ranging and include both conventional and molecular technologies. Testcrosses are evaluated across the WEMA testing network to develop inbreds with excellent drought tolerance and general combining ability and hybrids that are tested widely before release.

A specific example of how the partners are working together on the project is in the Marker Assisted Recurrent selection (MARS) breeding program led by CIMMYT. The advantages of this system are that selection of inbreds without prior knowledge of their drought tolerance is made possible, and the inbreds selected through MARS are available immediately for use in DT hybrids. The efficiency of MARS depends on selection of the original parents, the quality of the testcross phenotyping, and the efficiency of sampling and genotyping during recombination. This is a collaborative effort where CIMMYT manages the population selection, phenotyping, and marker identification and recombination; Monsanto undertakes the genotyping; and the NARS partners provide the good testing environments.

13.3.2 Collaboration Through the Biotechnology Approach (Transgenic Drought Tolerance)

Conventional breeding and modern molecular techniques have and will improve corn plant response to drought stress, and biotechnology brings the opportunity to introduce novel drought tolerance genes into the plant. A plant's response to abiotic stresses such as drought and heat stress is due to the interaction of complex cellular regulatory processes caused by a multitude of genes (Kolodyazhnaya et al. 2009); this makes it very difficult for breeding programs to make successful marked positive gains in short (<10 years) time frames. Kolodyazhnaya et al. (2009) classified the type of genes that affect plant tolerance to abiotic stresses such as drought in several categories:

1. Genes that encode enzymes involved in the synthesis of osmotic and other protectors
2. Genes that encode proteins actively synthesized at late embryogenesis stage (late embryogenesis abundant (LEA) protein genes)
3. Regulatory genes that control stress response
4. Genes that regulate phytohormone levels
5. Genes of oxidative stress response
6. Genes of molecular chaperones

Fig. 13.4 Partners planting first transgenic drought tolerance trial at the KARI-Kiboko confined field trial site Dec 2010

7. Genes that encode ion transport proteins that are localized in the plasmalemma and in vacuoles and organelle membranes
8. Others

The Monsanto and BASF drought tolerant corn pipeline has screened thousands of genes from these categories under different drought stress conditions. The WEMA project has managed to leverage the technical and regulatory resources that Monsanto places on drought tolerance traits to ensure that the best drought gene is available to WEMA for use in Africa as soon as possible after launch in the United States. Currently WEMA is field testing Monsanto's transformation event (MON 87460[2]) that contains the cold shock protein B (cspB) gene from *Bacillus subtilis*, that has been found to confer improved stress adaptation to multiple plant species (Castiglioni et al. 2008). MON 87460 and other associated genetic elements are expected to provide gains in drought tolerance that will complement the gains obtained through the WEMA breeding programs. The tropical SSA maize inbreds included in the first round of trait introgression includes partner inbreds that are frequently in hybrid combinations today. The tropical transgenic drought tolerant hybrids are being tested in confined field trials developed and managed by the NARS partners. To date the national agricultural research systems KARI, ARC, and NARO are conducting confined field trials (CFT) with the transgenic drought tolerant event. Over the next 5–7 years required regulatory studies and multi-location testing will be performed leading towards a WEMA product launch. This collaboration has resulted in the first field testing of a drought tolerance transgene in SSA (Fig. 13.4).

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[2] MON 87460 successfully completed reviews with the US Food and Drug Administration in 2010 and with the US Department of Agriculture in 2011. Safety reviews in Canada, China, the EU, Japan, Korea, Mexico, and Taiwan were successfully completed between 2010 and 2013.

13.4 Benefits of the Public–Private Partnership to Regulatory, Compliance and Stewardship

A significant part of the WEMA project involves the testing and proposed launch of a transgenic product in SSA. South Africa is the only one of the partners that has an established regulatory framework that has allowed the development, testing, and commercialization of three transgenic crops (maize, soybean, and cotton). The other four countries range from Kenya and Uganda that have completed field trials in multiple crops to Mozambique and Tanzania that have no prior experience at reviewing applications. The regulatory teams from the partner countries have combined their experiences and expertise in order to enable the earliest possible opportunity for transgenic trials in WEMA. Part of this effort has included the development of a trial manual, handbooks, and best practices for site managers. The partners also assessed the capacity needs in regulatory skills in their countries, and, where needed:

1. Enhance the capacity for regulatory dossier compilation, filing, and timely submission of the same to regulatory authorities for review.
2. Train all personnel involved in CFTs on the best practices from seed handling through to postharvest trial site monitoring.
3. Facilitate development of CFT permit application questionnaires/forms where these do not exist.
4. Facilitate training in risk assessment for regulators in partner countries.
5. Identify key policy makers in partner countries and invite them to observe best practices via planned study tours and field visits of CFTs.

Training for scientists, site managers, and regulators has been a key activity during the first 5 years of the project. The success of the regulatory teams in WEMA is demonstrated by the successful approval of field trial applications and CFT plantings with MON87460 in South Africa (2008–2012), Kenya (2010–2012), and Uganda (2011–2012). In addition CFT plantings with the insect-resistance trait MON810 from the naturally occurring soil bacterium *Bacillus thuringiensis (Bt)* have been added in 2013 in Kenya and Uganda. The applications in Tanzania and Mozambique are currently under review by their biosafety authorities.

13.5 Communication and Outreach

A well-designed clear communication and outreach strategy has been a critical part of the partnership in realizing the project goals. The WEMA partners developed a communications strategy through a consultative process that involved both stakeholders and donors to meet the specific needs and sensitivities of different organizations. By utilizing the knowledge and experience of all the partners, the project ensured that there was a clear understanding of the operational environment, issues, and key focus areas. This strategy included country and regional stakeholder meetings that brought together participants such as policy makers, farmer group representatives, seed companies, and legislators to discuss and address any concerns on the project.

The WEMA communication strategy serves as a focal point of reference for decision and action and has ensured that the project communication is on message and aligned with partner and project interests and aims at ensuring broad stakeholder commitment to the project; facilitating the smooth conduct of trials in the countries participating in the WEMA project; and facilitating general acceptance of the maize lines resulting from the project. The strategies include capacity building; policy advocacy; project partner and stakeholder communications; strategic media relations; and proactive management of potential public opposition. The team developed clear messaging and delivery for the project that stayed on message and fitted each partner's needs. The process of openness and consideration of each partner's needs have ensured the project benefits from the partner's unique contributions and that the project communication activities are relevant and timely in the countries.

13.6 The Importance of Intellectual Property Management for Successful Partnerships

One key benefit of a public–private partnership such as WEMA is the opportunity for technology transfer and sharing of information between the partner institutes and organizations. For this to be effective, intellectual property issues must be addressed throughout the project. The WEMA partners agreed at the outset that there will be no royalty for the transgenic drought tolerance trait and its associated technology as delivered to SSA smallholder farmers. In 2011 the transgenic insect-resistance trait was added to the project with the same objectives and royalty-free license. At the same time, the technology used in the project is expected to have considerable value to commercial farmers in and outside Africa. Hence, the parties recognized the need to manage Intellectual Property so as to preserve that commercial value creation.

An Intellectual Property policy has been developed for the WEMA project. The key elements of this are: Confidentiality to meet the needs for accuracy and consistency of information when it is communicated; Patents and Plant Variety Protection to enable the partners and licensees to manage appropriate stewardship requirements to the regulated transgenic materials and to ensure seed quality and performance standards; Ownership and use of technology and property of the parties for both, technology brought to WEMA by the partners for use in the project, and for products and information developed by the project.

13.7 Maintaining the Partnership into Phase 2

The project has reached the next phase now, and the product development work will continue but the path to delivery of WEMA products will be established. This will utilize the experience of all the existing partners and potential future partners to ensure both the regulatory and seed production systems are in place. Each country will work to ensure systems are in place for effective seed production from breeder seed to certified seed for both conventional and transgenic products. The experience of existing seed companies in the region will be essential to provide quality hybrid seed to the farmers as soon as possible. The partners and WEMA teams will have co-responsibility for product stewardship to ensure production and maintenance of quality crop seeds and their proper handling and utilization for long-term benefit to the target farmers.

Stewardship considerations will encompass stakeholders' awareness creation, implementation of communications and outreach strategy, application of hybrid maize user guidelines, a monitoring and evaluation system to manage stakeholder feedback related to maize hybrid agronomic performance and utilization attributes, and address regulatory compliance issues, potential impacts on market, licensing agreements, and needs of stakeholders.

An initial assessment of the seed delivery pathway for the respective countries showed that there are limited institutional capacities and capabilities (technical skills and infrastructure) in national organizations and specific seed companies. The WEMA SSA countries also lack sufficient capacity to increase breeder seed to ensure supply for sufficient hybrid production. Emphasis in Phase 2 will be placed on the development of institutional capacities and capabilities of the national organizations and the selected seed companies that will be involved in the deployment of the products.

13.8 Conclusion

WEMA is probably the largest public–private corn breeding partnership in agriculture today and much of the success of the first 5 years is directly attributable to the efforts of the partners working closely together. The combination of partner germplasm pools and marker technologies have enabled the plans for the first conventional WEMA hybrids to be launched early in Phase 2 of the project in 2013. The joint efforts of the project's breeders and regulatory scientists have enabled transgenic drought tolerance trials in three of the partner countries to be planted from 2008 to 2012 and Bt-insect protection trait to be tested in 2013. All the partners have been involved in capacity building through the development of drought tolerance testing sites for transgenic and conventional field trials as well as in the training of WEMA scientists and the stakeholders. For WEMA to meet its objective of providing improved hybrid seeds to the farmers of SSA, so that they have more reliable yields during drought, it will be necessary for the partners to continue to work in a cohesive manner through the development and deployment phases.

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Part VI
Chemicals

Chapter 14
The Importance of Herbicides for Natural Resource Conservation in the USA

Leonard Gianessi and Ashley Williams

14.1 Introduction

Herbicides are used to reduce weed populations on approximately 220 million acres of US cropland (Gianessi and Reigner 2007). More than 90 % of the acreage of most field crops as well as vegetable, fruit, nut, and specialty crops are treated with herbicides annually. Herbicides were first introduced in the 1940s and by the 1970s had achieved a dominant role in managing weeds in crop fields. Prior to the introduction of herbicides, the dominant methods of weed control were cultivation and hand weeding. Although still practiced, cultivation and hand weeding have been greatly reduced in US crop production.

The use of herbicides has had major impacts on the conservation of soil, water, and energy resources in the USA. These impacts occurred largely due to the replacement of tillage with herbicides for weed control. Weed control methods used by organic growers, who do not use synthetic herbicides, also impact natural resources, which furthers our understanding of the role of herbicides in conservation.

14.2 Historical Aspects

14.2.1 Pre-1900

Many of the farming practices used by European settlers resulted in land exhaustion, erosion, declining yields, and abandonment. The kind of farming that paid best in the westward expansion of agriculture was exploitation of the soil. Land was

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cheap, labor was scarce, fields were large, and the best management was the application of a minimum amount of labor per acre. A common fault of almost every farmer was bringing more land into a farm than he could manage well (Bidwell and Falconer 1973).

By the early 1800s, northern Illinois and southern Wisconsin had become the new breadbasket of the nation as the wheat frontier pushed west. Farmers grew wheat until soil nutrients were depleted and fields became weed-choked. In the mid-nineteenth century, per-acre wheat yields in New York were just half of those from Colonial days (Montgomery 2007). Most eastern wheat farms were so overrun with weeds that a common practice became fallowing the land for 1 year while multiple cultivations were made (Bidwell and Falconer 1973).

In 1838 John Deere invented a steel plow capable of turning up the prairie's thick turf (Montgomery 2007). The steel moldboard plow became widely used throughout the country for removing weeds from fields before planting a crop in the spring. In the 1860s, the sulky cultivator put the farmer on a seat behind a pair of horses. Using three or four horses, 15 acres could be weeded in 1 day (Fussel 1992).

By the end of the 1800s, almost 11 million acres of American farmland had been abandoned due to erosion from excessive cultivation (Montgomery 2007).

14.2.2 1900–1950s

In the early 1900s, land was kept bare of vegetative cover after harvesting and plows were pulled through fields by horses or tractors to kill weeds before planting (Wimer 1946). Tillage required ten or more trips over the field (Triplett 1976). Use of the moldboard plow was followed by other equipments such as cultivators, harrows, and rotary hoes. In order to facilitate complete cultivation of cornfields, corn plants were planted far enough apart to allow for cultivation on all four sides of each plant (Pike et al. 1991).

Experiments in the late 1800s and early 1900s consistently showed that the only benefit of cultivation was weed control. In 125 experiments conducted before 1912, corn yields were equivalent between plots that had been cultivated and plots where weeds had been removed by hand (Cates and Cox 1912). Thus, in the early 1900s, agriculturalists realized that if a practical alternative method of weed control could be devised, they could dramatically reduce cultivation.

Several major problems were associated with tillage in the early 1900s, namely, bare soil was susceptible to water and wind erosion. The moldboard plow was at least partially responsible for the Dust Bowl of the 1930s (Triplett 1976). The Dust Bowl was as much about tillage as it was about drought (Lal et al. 2006). On April 14, 1935, known as Black Sunday, the most powerful of the dust storms, driven by 60 mile/h winds, struck Dodge City, Kansas, at noon, leaving the city in total darkness for 40 min (Helms 2010). A dust storm in May 1935 carried an estimated 350 million tons of soil into the air, dropping 12 million tons on Chicago (Lal et al. 2006).

After the Dust Bowl, it was estimated that because of erosion, 50 million acres of cropland in the USA had been essentially ruined for growing crops and an additional 50 million acres had been almost as severely damaged. Another 100 million acres, although still in crop production, had suffered such severe removal of fertile topsoil that they were only one-tenth to one-half as productive as they had been (Bennett and Loudermilk 1938). More than three quarters of original topsoil had been stripped from nearly 200 hundred million acres of land (Montgomery 2007). Approximately 300 million acres out of the 400 million acres of farm fields in America were eroding faster than soil was being formed. Two hundred thousand acres of abandoned Iowa farmland was eroded beyond redemption. More than three quarters of Missouri had lost at least a quarter of its original topsoil, more than 20 billion tons of dirt since the state was first cultivated (Montgomery 2007).

The Dust Bowl created a controversy about the usefulness of the moldboard plow. There were two strong but opposing schools of thought—no-till and plow tillage. The no-till movement was spearheaded by an extension worker in Ohio, Edward Faulkner, who wrote the book *Plowman's Folly*. Faulkner (1943) pointed out that weed control is the only reason for plowing and that if weeds could be controlled by some other method, erosion would be greatly reduced. It was not until the development of herbicides that an effective alternative method was available.

14.2.3 1950s–Today

Early research in the late 1940s with the first herbicide available for corn growers—2-4,D—indicated that a preemergence application could eliminate 1–3 cultivations while a postemergence application could eliminate one or more in-season cultivations (Slife et al. 1950). By the 1960s, the invention of new machines to plant through mulch combined with the widespread availability of chemical herbicides to control weeds set the stage for commercial adoption of conservation tillage (Montgomery 2008). As more effective herbicides were developed, farmers continued to reduce tillage before planting and in some cases completely eliminated postemergence cultivation (Triplett 1976).

The first sustained no-till development (see Hatfield, Chap. 4) for corn began in 1960 in Virginia and Ohio. It is not coincidental that the herbicide atrazine was introduced at about this time. Atrazine controlled many grasses common to the Midwest and was most effective when applied in the early spring. Atrazine also provided broad-spectrum residual control of many germinating weed seedlings. When combined with 2,4-D or dicamba to control perennial broadleaf species, growers could expect season-long vegetation control (Triplett and Dick 2008).

Rapid expansion in reduced tillage operations occurred in the 1990s with the introduction of efficient, high-residue seeding equipment and federal legislation requiring soil conservation on highly erodible land. Recent increases in diesel price and decreases in glyphosate price favored farmer acceptance of herbicide-intensive conservation tillage systems versus fuel-intensive traditional tillage systems (Nail

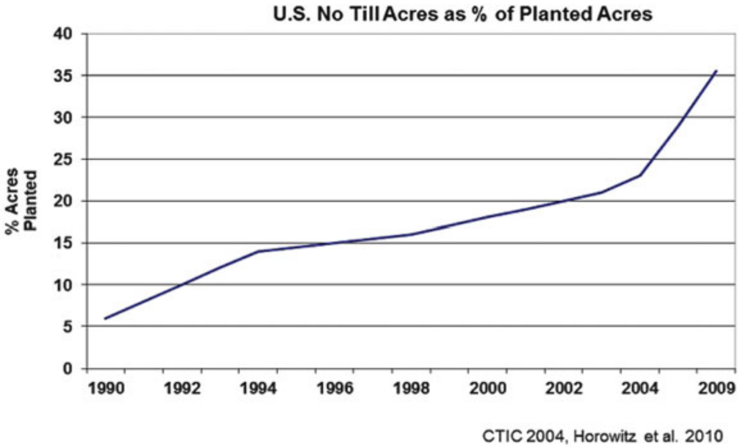


Fig. 14.1 US no-till acres as % of planted acres

et al. 2007). Between 1998 and 2005, the price of glyphosate fell by 38 % while the cost of diesel fuel went up by 160 % (Nail et al. 2007).

Approximately 36 % of US cropland planted to eight major crops—88 million acres—had no tillage operations in 2009, which represents a sixfold increase since 1990 (Fig. 14.1) (CTIC 2004; Horowitz et al. 2010). Herbicides are so crucial to conservation tillage that the National Academy of Science has concluded widespread adoption of conservation tillage would likely not have taken place without them (NRC 2000).

14.3 Soil Conservation

Herbicide use has made a significant contribution in the conservation of the nation's soil resources (see Hatfield, Chap. 4). In a no-till system, the farmer first sprays herbicides on the field to kill any growing vegetation. Seeds are planted by a machine that cuts through the plant residue on the surface, positions the seed in the soil, and covers them, all in one operation. The soil is left undisturbed except for a band made by the planter. Maintaining crop residues on the soil surface shades the soil, decreases soil water evaporation, slows surface runoff, and increases water infiltration. Thus, it simultaneously conserves soil and water (Munawar et al. 1990). Compared to the moldboard plow, no-till farming reduces soil erosion by as much as 90 % (Magleby 2003). In a 6-year experiment in North Carolina, average soil loss for no-till was 1.2 tons/acre while conventional tillage averaged 33.3 tons/acre (Raczkowski et al. 2009).

In 2007, cropland erosion in the USA averaged 5 tons/acre/year, down 44 % from the late 1930s and 32 % from 1982 (Fig. 14.2) (Magleby 2003). The total

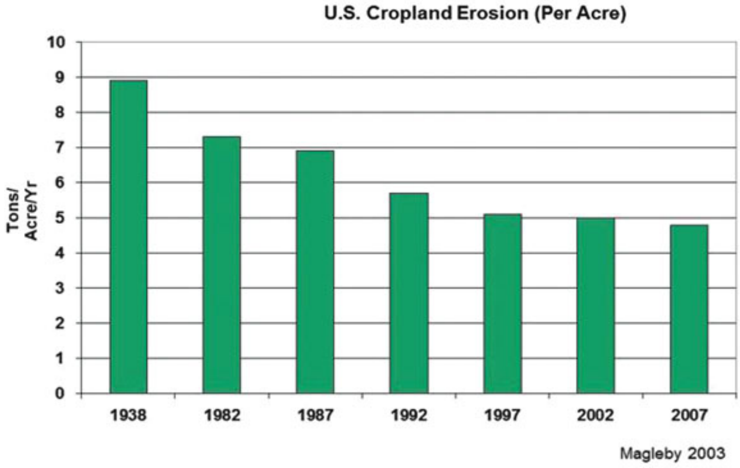


Fig. 14.2 US cropland erosion (per acre)

volume of erosion declined by 1.4 billion tons per year between 1982 and 2007 (Fig. 14.3) (USDA 2009a, b). This reduction in cropland erosion is due largely to reduction in tillage, which herbicides made possible. In the 1950s, 100 % of US corn acres were cultivated 3–4 times. In recent years only 50 % of corn acres are cultivated at all with an average of one time (USDA 1995).

14.3.1 The Pacific Northwest

The Pacific Northwest is recognized as one of the most productive, nonirrigated wheat producing areas of the world. Croplands in the Northwest are characterized by steeply rolling hills. The Northwest wheat areas have experienced some of the highest erosion rates in the USA since farming began there. By the 1970s, all of the original topsoil had been lost from 10 % of the cropland in the Palouse Basin; ¼ to ¾ had been lost from another 60 % of farmland (USDA 1979).

In the 1970s it was estimated that 110 million tons of soil were being eroded annually in the Pacific Northwest (Calvert 1990). Researchers from universities in Idaho, Oregon, and Washington and the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS) launched the Solutions to Environmental and Economic Problems (STEEP) program in 1975 to develop new approaches to control erosion and water quality degradation (Kok et al. 2009). The core strategy was to shift away from conventional moldboard plow-based tillage in favor of reduced tillage and no-till methods.

Widespread use of the herbicide glyphosate for weed control has advanced conservation efforts by replacing tillage in the Pacific Northwest (Kok et al. 2009). During the 1970s, wheat required 4–8 tillage operations. Today,

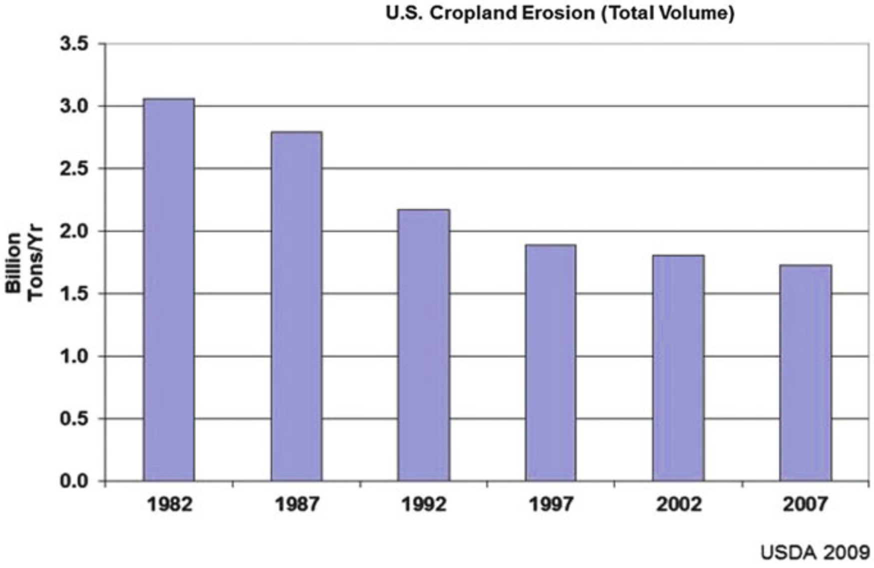


Fig. 14.3 US cropland erosion (total volume)

most growers make two glyphosate applications and two tillage passes. Prior soil loss rates of 20 tons/acre on high precipitation sites have been reduced to 5 tons/acre or less and from 12 to 6 tons/acre on intermediate precipitation sites (Kok 2007). Erosion decreased from an average of 9 tons/acre to about 4.5 tons/acre on the low precipitation sites.

14.3.2 Soil Conservation in Organic Systems

Organic farming systems mainly use tillage for weed control; therefore, soil erosion remains a concern. Organic soybean growers, for example, use up to ten tillage treatments for weeds, the same number of tillage operations used in conventional systems before the no-till era (Mutch 2008). A 2010 article (Gallagher et al. 2010) points out that organic grain production is not common to eastern Washington since a tillage-intensive organic system is not sustainable in regions with highly erodible soils (see Redick, Chap. 3).

Likewise, most crops in the Mid-Atlantic are grown on fields with steep slopes, and soil erosion is a major threat to long-term productivity (Lu et al. 1999). USDA-ARS researchers at long-term trials in Beltsville, Maryland, used the Water Erosion Prediction Model (WEPP) to compare soil erosion risks between no-till and organic corn systems (Green et al. 2005b). Chemical herbicides were applied to no-till corn while weed control for the organic system was accomplished by primary tillage, rotary hoeing, and cultivating. The WEPP model predicted greater soil loss from the organic system (43 Mg/ha/year) in comparison to the no-till system (8.5 Mg/ha/year) (Green et al. 2005a).

The soil erosion potential of no-till corn was compared to organically grown corn as part of a University of Wisconsin's Arlington Research Station research trial (WICST). Soil loss was estimated at 0.6 tons/acre in the no-till plots and at 10.0 tons/acre in the organic plots due to annual tillage and repeated cultivations (Hedtcke and Posner 2006).

14.4 Water Conservation

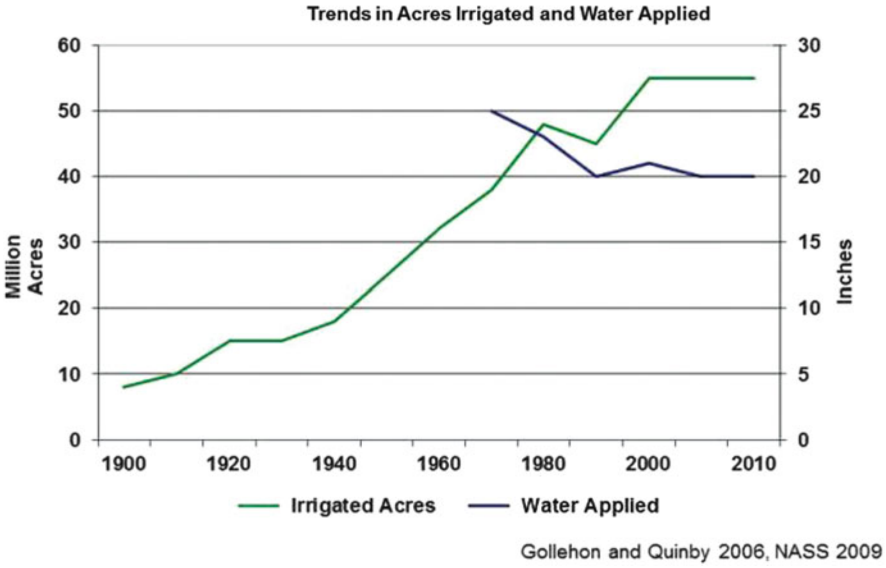
Agricultural operations, which account for about 90 % of freshwater consumption in the western states and over 80 % nationwide, are increasingly being asked to use less water in order to meet societal demands for other uses (Schaible and Aillery 2006). In recent years, national irrigated land has remained at about 55 million acres. However, since US farmers have adopted more water-conserving practices, the average depth of water applied has declined by one-fifth (5.4 in./acre) since 1969 (Fig. 14.4) (Gollehon and Quinby 2006).

Herbicide use has made a significant contribution in the conservation of water in US crop production. Herbicides have replaced multiple tillage operations in dry farming areas of the country, resulting in increased soil moisture content with less need for irrigation. Tillage dries out soil to the depth that the soil is disturbed; as a result, tillage causes 0.5–0.8 cm of evaporative water loss from each operation (Greb 1983). Soil moisture is lowest under conventional moldboard tillage. In a Kentucky experiment, soil moisture averaged 25 % higher in no-till versus moldboard plow tillage systems (Munawar et al. 1990). In California almond orchards, herbicides replaced the need to cultivate 16 times per season, which led to a 25 % reduced need for irrigation water (Meith and Parsons 1965).

Conservation tillage also reduces soil evaporative losses (see Alam et al., Chap. 5). Researchers have estimated that the reductions in water loss due to conservation tillage represent the equivalent of 2.6–4.3 days of water required for typical farms in Georgia. It has been estimated that the full adoption of conservation tillage on the state's crop acreage would save enough water (170.5 billion gallons/year) to meet the needs of 2.8 million people (Reeves et al. 2005). Conservation tillage has been shown to reduce runoff in Georgia by 29–46 %. This translates to a 29–46 % increase in total infiltrated rainfall (Sullivan et al. 2007).

14.4.1 The Ogallala Aquifer

The Ogallala Aquifer stretches 174,000 square miles beneath eight states from South Dakota to Texas. Ogallala groundwater is largely nonrenewable because its



Gollehon and Quinby 2006, NASS 2009

Fig. 14.4 Trends in acres irrigated and water applied

sources in the Rocky Mountains were cut off thousands of years ago. Americans are mining the Ogallala, drawing 5 trillion gallons of water from the aquifer annually (Ashworth 2006). At the current withdrawal rate, the Ogallala will be completely drained in 200 years; if completely drained, the aquifer would take more than 6,000 years to recharge. More than 90 % of the water pumped from this source is used to irrigate crops. Irrigation water from the Ogallala Aquifer supports nearly one-fifth of the wheat, corn, cotton, and cattle produced in the USA.

In Texas, conservation tillage with herbicides is 80 times less costly than making changes to irrigation equipment and has been identified as the most cost-effective method of conserving water from the Ogallala Aquifer for future generations (Amosson et al. 2005). A water savings of 1.75 in./acre/year has been estimated from shifting an acre of conventional systems to conservation tillage and substituting herbicide applications for tillage operations. On the Texas High Plains, increasing conservation tillage from 50 % of all irrigated acres in 2000 to 72 % by 2060 would lead to a cumulative water savings over the 60-year period of 2.1 million acre-feet (682 billion gallons) (Amosson et al. 2005).

Researchers in Kansas found that the use of herbicides substituted for 3–4 tillage operations and increased soil moisture content by 50 %, thereby reducing the need to irrigate (Unger et al. 1971; Jones et al. 1985). In another study, no-till corn and sorghum received from 7 to 11 in./acre less total irrigation than conventional tillage corn and sorghum (Harman et al. 1998).

14.4.2 The Great Plains

Since about 1900, researchers at state and federal experiment stations have worked to develop crop production systems better suited to the Great Plains (see Lee et al., Chap. 10). One of the practices that evolved for dryland crop production was the use of summer fallow, wherein no crop is grown during a season when a crop might normally be grown. Since most wheat is grown on soils capable of storing considerable amounts of water, fallowed soil can supply water to the crop in a subsequent season during prolonged periods without rainfall (Smika 1983). The primary reason for summer fallow is to stabilize crop production and reduce the chances of crop failure by forfeiting production in one season in anticipation that there will be at least partial compensation by increased crop production the next season (Nielsen and Vigil 2010).

To maximize the amount of stored water, a grower must control weeds throughout the fallow season. Undisturbed weeds remove 2–6 in. of soil water, with 800–2,700 lb./acre of weed biomass produced (Anderson and Smika 1984). Tillage systems, beginning in the spring with moldboard plowing and followed by shallow harrowing, were developed to remove weeds during the fallow season. Maximum tillage resulted in only 19 % of the fallow year's precipitation being stored in the soil. Experimentation with herbicides to remove weeds during the fallow period began in 1948 with contact types such as 2,4-D and accelerated after 1962 with the introduction of new contact and preemergence types such as atrazine, glyphosate, and paraquat (Greb 1979). Atrazine became the standard herbicide used in the fallow period for making the transition from wheat to sorghum or corn in Great Plains cropping systems (Regehr and Norwood 2008). The use of herbicides reduced the need for tillage operations to 2–4 per season and resulted in storage of 33 % of the fallow year's precipitation (Peterson and Westfall 2004). The extra water stored in the soil with the use of herbicides was reflected in an average 21 % increase in winter wheat grain yield over conventional spring tillage fallow (Greb and Zimdahl 1980).

In rainfed, dryland farming areas of the Central Great Plains, the substitution of herbicides for tillage has resulted in preserving enough soil moisture to make sustained annual production of crops possible without the need for a fallow year to store soil water. Fallow acreage in the USA has declined significantly in recent decades (Fig. 14.5). Improved herbicide options have eliminated the need for fallow years in all but the driest areas of the Great Plains (Derksen et al. 2002). Most data indicate that there can be as much or more stored water in no-tilled managed soils after a spring wheat harvest as there would be if fallow is continued until fall wheat planting (Peterson and Westfall 2004). As a result, there has been an expansion of summer corn and sorghum acreage in the Great Plains.

Sorghum grain yields more than tripled from 840 to 3,760 kg/ha in studies at the USDA-ARS Research Laboratory in Bushland, Texas from 1939 to 1997. Soil water content at planting was the dominant factor contributing to yield increases over time. Most increases in soil water content at planting occurred after 1970,

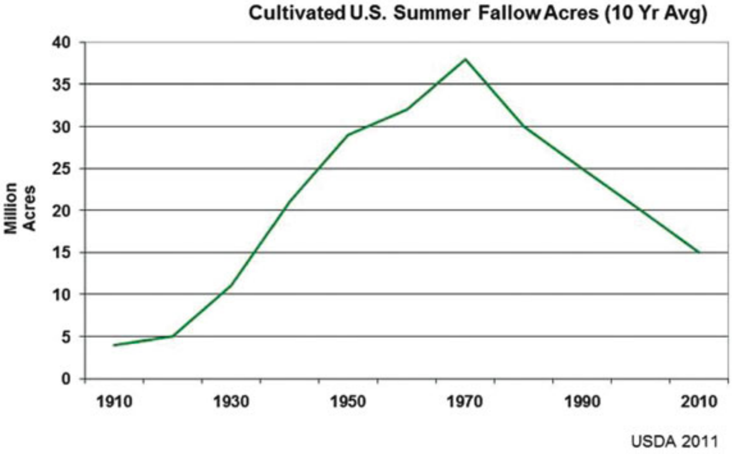


Fig. 14.5 Cultivated US summer fallow acres (10 year avg)

when improved herbicides became available and conservation tillage began receiving major emphasis (Unger and Baumhardt 1999).

14.4.3 Rice Production

During the twentieth century, the only method to suppress the weed red rice in commercial rice production was by water seeding. Rice producers were aware that if the fields could be kept flooded during the season, most of the red rice seed in the soil would not have the opportunity to germinate. Aerial application of pre-germinated rice seed was the best red rice control method available to the rice farmers at the time (Harrell 2007). After the release of Clearfield rice varieties in 2003, water seeding was no longer the only effective management practice for red rice control. Red rice could now be controlled with the use of imidazolinone herbicides; therefore, a shift toward more drill-seeded rice acres began. The Clearfield technology was used on 60 % of the southern US rice acreage in 2010 (Linscombe 2007). Drill-seeded rice fields require 0.96 acre-inches less water than water-seeded fields (Manley 2008).

Traditionally, rice production in the Southeast has involved intensive cultivation. However, new herbicides have made it possible for rice to be planted using less tillage, even no-till methods. Recently in Texas, it has been estimated that adoption of no-till rice management would save 2.5 acre-inches of water by increasing soil moisture and decreasing evaporation owing to residue cover on the soil surface (Yang and Wilson 2011).

14.4.4 Water Conservation in Organic Systems

A common practice for irrigated organic crop systems is the preplant germination of weeds. Preplant germination of weeds (pregermination) involves the use of irrigation to stimulate weed seed germination before planting the crop. The emerged seedlings are then killed by shallow cultivation, flaming, or an organic herbicide, such as vinegar. Waiting 14 days after the time of a preplant irrigation allows for weeds to emerge and for the field to dry enough to permit use of shallow tillage to control emerged weeds. This method removes up to 50 % of the weeds that would have otherwise emerged in the subsequent crop (University of California 2009). The extra irrigation application to germinate weeds before planting means that organic crop producers use more water per acre than conventional growers (Southeast Farm Press 2012). A recent survey of organic and conventional cotton farmers on the Texas High Plains showed that the organic growers used 78 % more water because of the need for additional water to maximize yield potential (Funtanilla et al. 2009).

14.5 Energy Conservation

For agricultural production, energy use is classified as either direct or indirect (embodied). Direct energy use in agriculture is primarily petroleum-based fuels used to operate tractors for preparing fields, planting, cultivating, and harvesting crops, as well as machinery for applying pesticides (Schnepf 2004). Indirect energy is consumed off the farm for manufacturing fertilizers (see Reetz, Chap. 15), pesticides, and machinery. Modern pesticides and fertilizers are almost entirely produced from crude petroleum or natural gas products. The total embodied energy input is thus both the material used as feedstock and the energy used in the manufacturing process (West and Marland 2002).

The transition from animal power (horses and mules) to machine power (tractors) occurred between 1915 and 1950 and resulted in a sixfold increase in energy use in agriculture. Energy inputs increased faster than outputs, leading to a decline in energy productivity (Cleveland 1995b). The per gallon cost of fuel for farm operations remained inexpensive and constant through the 1950s and 1960s, but increased dramatically following the energy price shocks of 1973–74 and 1980–81 and has increased again in recent years (Fig. 14.6).

Energy price increases significantly altered the pattern of energy use on US farms, resulting in a large decrease in direct energy use (Fig. 14.7). Since the late 1970s, American agriculture's direct energy use has declined by 26 %, while the energy used to produce the fertilizers and pesticides used on farms has declined by 31 % (Schnepf 2004). In the USA, the combined use of gasoline and diesel fuel in agriculture fell from its historical high of 29 billion liters in 1973 to 17 billion in

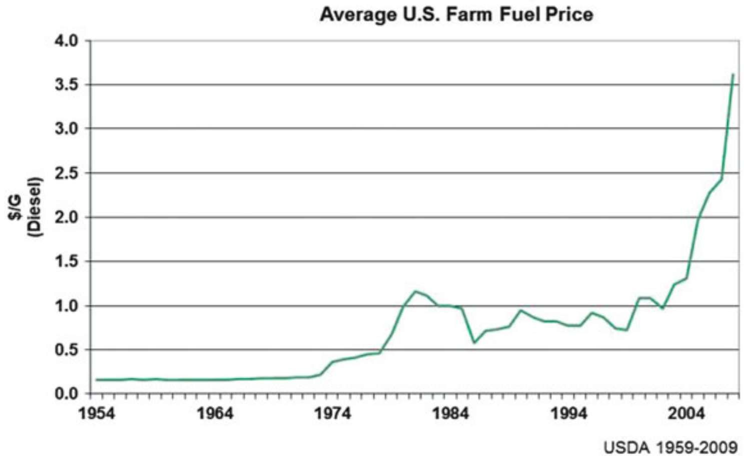


Fig. 14.6 Average US farm fuel price

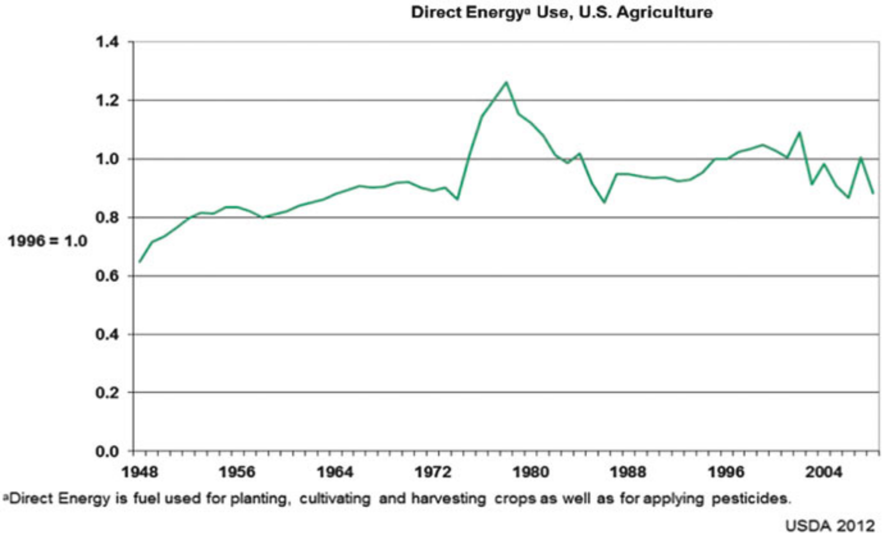
2002, a decline of about 40 %. One reason for this change was a shift to minimum and no-till practices on roughly two-fifths of US cropland (Triplett and Dick 2008).

The decline in agricultural energy use resulted in a significant reduction in agriculture's share of the nation's total energy usage. In 1978, the total direct and indirect energy use in agriculture accounted for about 5 % of US energy use (Cleveland 1995b). Currently, the direct energy use in US agricultural production (encompassing both crops and livestock) represents about 1 % of total US energy consumption while the indirect energy use in the manufacture of the pesticides and fertilizers used on US farms represents about 0.5 % (Schnepf 2004).

The large declines in agricultural energy use since the late 1970s have not come at the expense of lower output. Since 1973, farm output has grown 63 % while direct energy consumption has declined 26 %. Agriculture has made dramatic efficiency gains in energy use. As a result, direct energy use per unit of agricultural output is 50 % less today than it was in the 1970s (Fig. 14.8) (USDA 2012).

A 2010 analysis of energy use in corn production in nine Midwestern states concluded that the amount of diesel used per acre has declined by 33 % since 1996 while the embodied energy in pesticides has declined 50 % since 1991 (Shapouri et al. 2010). Because of increased corn yields, the reductions in energy required to grow a bushel of corn declined even more: 48 % less diesel and 62 % less embodied energy in the form of pesticides were needed to produce a bushel of corn.

One of the main factors accounting for the decrease in energy use in agriculture has been the substitution of herbicides for tillage to control weeds (Brown et al. 2008). The energy price increases stimulated an increase in conservation tillage that reduces fuel consumption relative to conventional tillage (Cleveland 1995a). The additional energy embodied in the herbicides used in reduced-tillage systems does not nearly offset the energy conserved by reduced tillage (Frye and Phillips 1980). Reduced tillage dramatically reduces direct fuel consumption

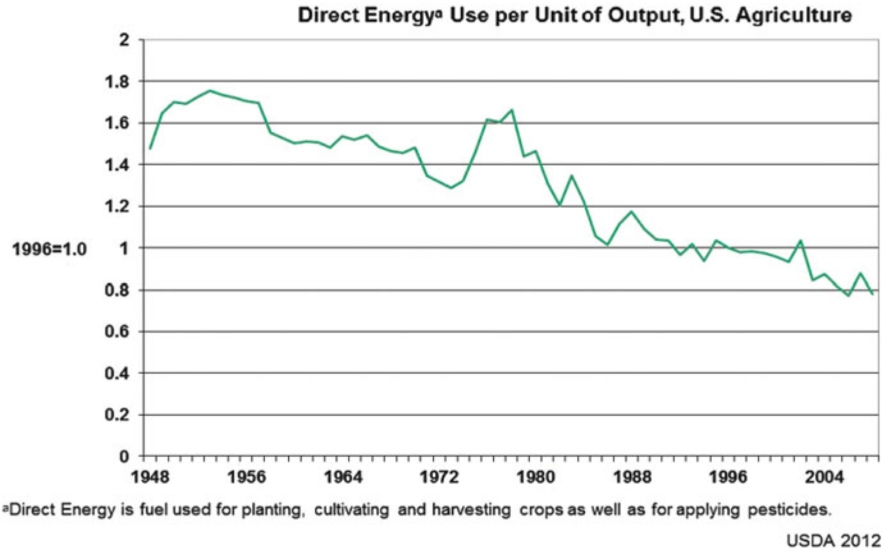


Direct Energy[a] Use, U.S. Agriculture

[a]Direct Energy is fuel used for planting, cultivating and harvesting crops as well as for applying pesticides.

USDA 2012

Fig. 14.7 Direct energy[a] use, US agriculture



Direct Energy[a] Use per Unit of Output, U.S. Agriculture

[a]Direct Energy is fuel used for planting, cultivating and harvesting crops as well as for applying pesticides.

USDA 2012

Fig. 14.8 Direct energy[a] use per unit of output, US agriculture

relative to conventional tillage with the moldboard plow. Not only does one herbicide application substitute for several tillage trips, tillage equipment is also heavier than herbicide sprayers and needs more energy to pull steel implements through the soil. A moldboard plow consumes 17 times more diesel fuel per acre than an herbicide sprayer. A row-crop cultivator requires four times more gallons per acre each trip than an herbicide sprayer (Hanna 2001).

A 2009 comparison of direct and embodied energy use between conventional tillage and no-till soybeans in Kansas indicated an overall reduction of 24 % with the no-till system (Williams et al. 2009). Direct energy consumption is 55 % lower in the no-till system, although embodied energy use is higher, primarily due to increased herbicide use.

The Conservation Technology Information Center (CTIC) has estimated a savings of 3.9 gallons of direct fuel use per acre by going from conventional tillage to no-till (USDA 2006). By 2008, the number of no-till acres reached 88 million (Horowitz et al. 2010), implying an annual fuel savings of 343 million gallons.

14.5.1 Energy Conservation in Organic Systems

Both conventional and organic agriculture depend on fossil fuels. Several long-term research trials at US locations have compared the energy inputs between growing corn and soybeans with conventional, no-till, and organic practices. These studies include comparisons of direct and embodied energy use.

In a study from 1992 to 2000 at the University of Wisconsin's WICST, no-till corn required 35 % less direct fuel for field operations than organic corn (Oosterwyk and Posner 2000). The primary difference in field operations between the no-till and organic systems was the amount of tillage needed; typically 11 tillage operations or rotary hoeings were made in organic corn versus one tillage operation in no-till corn (Oosterwyk and Posner 2000). For soybeans, the direct use fuel requirement at WICST was 68 % higher in the organic soybeans. The organic soybeans were typically cultivated 12 times in comparison to no cultivations in the no-till soybeans. The total amount of embodied energy in pesticides plus direct fuel use in no-till corn was 7 % less than the fuel use in the organic corn (Oosterwyk and Posner 2000). For soybeans, the organic system used 31 % more total energy (direct plus embodied) than the no-till system. The embodied energy requirements for the herbicides used in no-till were offset by the higher fuel use required for field operations in the organic system.

At the ARS Swan Lake Research Farm's long-term cropping systems field study in Minnesota, weed control in the organic corn and soybeans included the in-crop use of a rotary hoe two times early in the season followed by interrow cultivation 1–3 times until canopy closure. The organic treatments used 43 % more direct fuel than the conventional treatments (Archer et al. 2007).

In a study from 1989 to 2007 at Michigan State University's Long Term Ecological Research (MSU-LTER) site, direct fuel use in the MSU-LTER organic system averaged 58 %, 93 %, and 28 % more than in the no-till system for corn, soybean, and wheat, respectively (Robertson et al. 2000). The organic plots were prepared with the moldboard plow followed by 3–4 passes with cultivators and rotary hoes; weeds in the no-till plots were controlled with 2–3 herbicide applications (Davis et al. 2005).

A 2010 study in Pennsylvania modeled the energy use of a conventional no-till system and three organic crop systems (Ryan 2010). The use of diesel fuel was twice as great in the organic systems (74 l/ha) versus the no-till system (38 l/ha). The energy from direct fuel use in the organic systems averaged 67 % more than the combined total of direct fuel use and embodied energy from herbicides used in the conventional no-till system (Ryan 2010).

An organic corn system in Beltsville, Maryland, uses twice as much energy operating machinery as a no-till system uses in operating machinery and herbicide usage (Cavigelli et al. 2009).

14.6 Conclusions

Herbicide use has made a significant contribution in the conservation of natural resources in the USA. Is high-yield crop production depleting the nation's natural resources that are necessary to maintain crop production into the future? A pessimistic view is not warranted. The negative consequences of resource depletion persisted in the USA through the 1940s, with high soil loss due to tillage for weed control. Clearly, American farmers were not on a sustainable agricultural path. Since the introduction of herbicides for controlling weeds, tillage on US acres has been significantly reduced, which has resulted in more soil, water, and energy conservation and less fallow acreage.

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Chapter 15
The 4R-BMP Concept: Enhanced Nutrient Management for Agricultural Sustainability and Food and Energy Security

Harold F. Reetz Jr.

15.1 Global Framework for Nutrient Stewardship

Nutrient management is a part of the suite of crop production decisions that a farmer and his advisers must make in producing a crop. A systematic approach to these decisions has been developed by the fertilizer industry in conjunction with university and government agency scientist worldwide. The ***4R Global Framework for Nutrient Stewardship*** has been built around applying the ***right source*** of plant nutrients at the ***right rate***, at the ***right time***, and in the ***right place***. . .the core factors in the ***4R Nutrient Stewardship*** concept. This global framework for nutrient management decisions was developed by the International Plant Nutrition Institute (IPNI) scientists, in cooperation with The Fertilizer Institute (TFI), the Canadian Fertilizer Institute (CFI), and the International Fertilizer Industry Association (IFA). It has been adopted worldwide by the fertilizer industry, universities, government agencies, and NGOs as a guide for recommending and categorizing best management practices for nutrients.

Sustainable management of plant nutrition increases productivity of crops by assessing practices on the basis of these four "rights" in the context of their ***economic***, ***social***, and ***environmental*** dimensions. Figure 15.1 provides a graphic representation of 4R nutrient management in relation to these sustainability dimensions that address the interests of all stakeholders in the plant ecosystems.

The *economic* dimension includes productivity—yield, input costs, profitability, crop quality, etc. The *social* dimension includes employment opportunities and quality of life for all stakeholders. The *environmental* dimension considers how the nutrient management decisions affect such concerns as air and water quality and biodiversity. Sustainable production requires that the farmer and his advisers, as they develop the nutrient management plan for a crop field, must consider the

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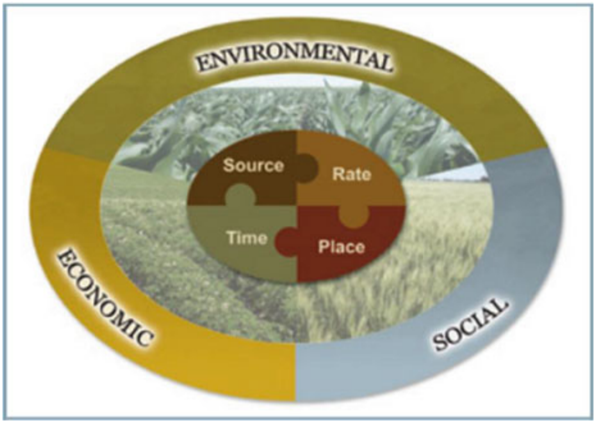


Fig. 15.1 The Global Framework for 4R Nutrient Stewardship defines the right source, right rate, right time, and right place for nutrient application producing the economic, social, and environmental outcomes desired by all stakeholders in the plant ecosystem (IPNI 2013)

interests of all stakeholders and how the three dimensions of 4R Nutrient Stewardship fit into their soil, weather, crop, and regulatory constraints.

Opportunities to reduce nutrient losses and increase nutrient use efficiency (NUE) should be taken whenever possible. In the following discussion, the focus will be on nitrogen (N) as an example of some of the most complex nutrient management decisions that must be made. Decisions around other nutrients are similar, but each has its own particular characteristics that must be considered in order to define the best management practices to be used.

15.1.1 Right Source

In recent years there has been an increase in the number of additives and enhancements farmers can choose for nitrogen fertilizer. In addition to the traditional sources, such as anhydrous ammonia (82 % N), urea ammonium nitrate solution (28 % N), ammonium nitrate (34 % N), or dry urea (46 % N), they can also choose from among several industrial byproducts, or they may select additives and inhibitors, or controlled release treatments, that may help reduce N losses or adjust the timing of availability of the N to the crop. The chemical and physical properties of each determine which source is most appropriate. The choices may be made based upon agronomic factors, logistics, environmental benefits, or even aesthetics.

15.1.1.1 Enhanced-Efficiency Fertilizers

Enhanced-efficiency fertilizers are now available, allowing farmers to change their 4R management systems, by expanding the choices available. A variety of coatings, from simple coating with sulfur, to resin-based polymers, to polyethylene coatings, are used to adjust the rate at which plant nutrients are released into the soil solution.

Most of the products are used for managing N release, but some are available for P, and there are a number of choices for various micronutrients, in which case the coatings help keep the nutrients in plant available form and prevent leaching from the soil, or prevent them from being tied up in unavailable forms with other soil minerals or organic matter. Generally, these products add to the cost, but may be the best way to improve nutrient availability and efficiency. They fit into the ***right source*** category in 4R systems.

15.1.2 Right Rate

In the 1970s, the common plan was to apply enough N to be sure it was not limiting. The price of N was low relative to the price of corn, and there was not much concern or awareness about potential environmental consequences. Applications rates were targeted at 1.2–1.5 lb. per bushel (154–193 g/m^3 of expected yield). The cost of applying too much N was relatively low compared to the cost (in lost yield) of applying too little. In recent years the prices have changed, making excess application expensive. Improved management and better genetics have made the crop more efficient. Today optimum N rates for corn are often lower. Crop N removal for corn is now in the range of 0.7 lb. of N per bushel (90 $g\ N/m^2$) of yield.

The right rate for a crop can be determined with the help of a variety of tools. Rate studies from similar soil types and climate areas are a good place to start. On-farm rate tests are especially helpful, because they match results with the farmer's own management. With modern rate controllers and yield monitors used in conjunction with soil tests, plant analysis, crop sensors, and field scouting a farmer and his advisers can design a rate program best suited to his fields and his management and implement it on a site-specific, variable-rate basis, matching the variability within each field. Such on-farm testing is important for helping farmers make better-informed decisions on their fertilizer investment.

15.1.3 Right Time

Timing of nutrient application must be based on a number of issues. For nutrients that are stable in the soil, there is considerable flexibility in selecting the time of application. Potassium (K) and phosphorus (P) can usually be applied whenever most convenient without too much concern about losses. But in the case of nitrogen (N), there are several processes through which N can be lost. To minimize losses and improve N use efficiency, the best time to apply N is just before the crop needs it. Any decisions that help to make the application as close as possible to the time of crop uptake will result in more efficient N utilization. Figures 15.2 and 15.3 illustrate the growth stages of corn and the concurrent demand for N by the growing crop.

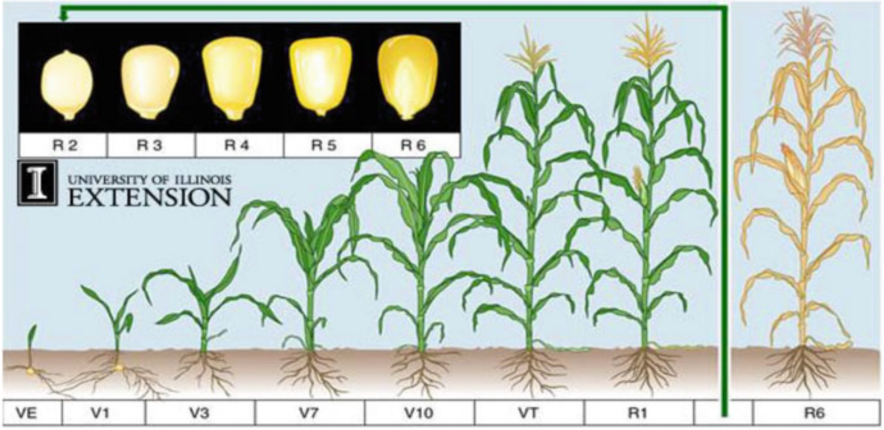


Fig. 15.2 Growth stages of corn (University of Illinois Extension)

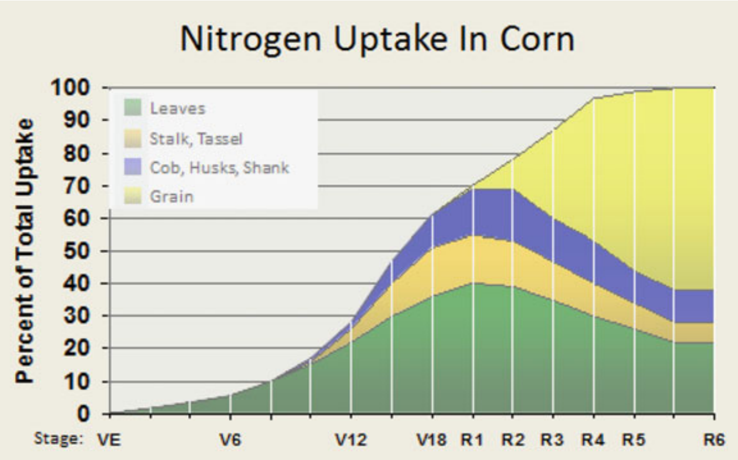


Fig. 15.3 Corn nitrogen uptake by growth stage: timing of nitrogen uptake by corn and distribution of % total uptake within the plant (adapted from "*How a Corn Plant Develops*," Special Publication 48, Iowa State University Extension)

Timing of application also must balance with soil conditions, logistics of supplying the fertilizer to the field, and coordination with the height of the crop (for sidedress and topdress applications). Corn needs a small amount of N for early growth, the large amounts in the middle of the season, and lesser amounts during later grain fill. The plant stores substantial amounts of N in the stalk and leaves (much of it in the form of the RuDP carboxylase enzyme—the main enzyme that fixes CO_2 in photosynthesis). A large percentage of this N is later transferred to the developing grain. As grain fill occurs, the root system becomes less able to actively take up and process N. Genetic improvements in corn in recent years have resulted in healthier, more vigorous root systems that effectively extend the viability of roots later into the grain filling period.

Understanding the growth stages of corn in relationship to the plant's need for N is an important step in successful N management. With such information, farmers and their advisers can make better informed decisions about the 4Rs of best management practices for N.

Nitrogen fertilizer application for any crop should be timed as close as possible to the timing of rapid crop uptake, to ensure the crop growth needs are met, but potential N losses are minimized. This must be balanced with weather and with other time-sensitive practices and with the physical and logistic constraints of fertilizer application.

15.1.4 Right Place

Normally about 30–50 % of the N applied as fertilizer is used directly by the corn crop the first season. The remainder becomes a part of the total N pool in the soil. It may be used by microbes in the breakdown of crop residues. It may be leached from the field. Some is lost as atmospheric N_2 and a smaller amount of NO_x greenhouse gases. Most is left in the soil to support future crops. The uptake of fertilizer N can sometimes be enhanced by placing the N in a concentrated zone relative to the crop roots. But since N moves in soil solution and corn crop roots are well distributed, specific placement is probably not very important beyond the first few weeks of growth. Placement can, however, affect susceptibility to N loss by runoff and volatilization. Simply incorporating the N into the soil with shallow injection or tillage can greatly reduce potential losses and improve efficiency of utilization by the crop. Maize production systems as a whole generally have low fertilizer N uptake efficiency, or recovery efficiency (RE), which is the proportion of applied fertilizer that is taken up by the plant. Through on-farm experiments in six North Central US states, average RE was determined to be 37 % with a standard deviation of 30 % (Cassman et al. 2002).

15.2 Performance Indicators of 4R Nutrient Management

The evaluation and final decisions made by the farmer can be guided by a series of performance indicators that help relate the 4Rs to the economic, social, and environmental framework dimensions, as illustrated in Fig. 15.4.

Nutrient management, and especially N management, is integrated with other crop management practices in developing a complete production system. To define the best management practices for N for a given field, it is important to use the best science available for the components of the system and their interactions. A few examples help illustrate the complexity of these management systems.

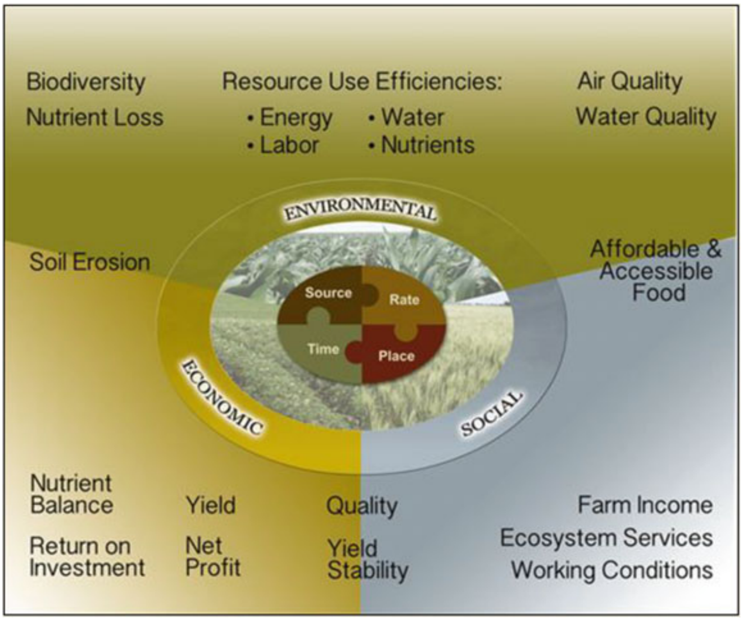


Fig. 15.4 Selected performance indicators for evaluating best management practices under the 4R-BMP nutrient management system (IPNI 2013)

15.2.1 Tillage Systems

Since the 1970s there has been a steady shift toward reduced tillage. This has in turn shifted many of the components of N management. Tillage system is one of the most important influences in how to select the 4Rs for N, and that decision is further dictated by variations in soils and climate. A summary of 442 tillage studies across the US concluded that crop yields tend to increase with reduced tillage in the southeastern states where temperatures and rainfall tend to be higher, and soils are less productive. In the Midwest, farmers tend to see yield reductions with no-till over conventional tillage due to cooler early season and higher rainfall conditions. Strip-till systems, tilling only a narrow band and leaving most of the surface undisturbed, provide a compromise, offering an opportunity for the soil in the strip to dry earlier and warm more quickly, helping to overcome the negative impact of no-till. In drier climates, reduced tillage helps hold moisture and increase yields. These soil and climate variations can be a major controlling factor in affecting the response to nutrient management. The key is for the farmer and his advisers to consider the entire system and interactions involved as they design a nutrient management plan.

15.2.2 Cover Crops

Cover crops help to trap nutrients in between the main cropping season (see Sripata et al., Chap. 8). Then the residue from the cover crops provides a slow release of the nutrients during the main crop's growing season. Another advantage of cover crops is that they provide support for soil microbes to remain active during a larger part of the year. These microbes influence the recycling rate of nutrients from soil minerals, soil organic matter, crop residues, and carryover fertilizer. Cover crops thus help support the ***right time*** and ***right place*** components of 4R nutrient management.

15.2.3 Genetic Advances

Genetic advances are helping speed up the process of crop improvement and helping enhance nutrient efficiency by producing healthier plants, more extensive root systems for water (see Alam et al., Chap. 5 and Oikeh et al., Chap. 13) and nutrient uptake efficiency, and more efficient nutrient utilization. Genetic modification supports the ***right time*** and ***right rate*** components of 4R nutrient management.

A research team at Monsanto (Yang et al. 2011) has successfully used biomarkers to monitor nitrogen status in real-time assays of field-grown maize plants under typical production conditions. They have found that about 7 % of the maize transcriptome is nitrogen responsive and have identified gene expression profiles that can quantitatively assess response of corn plants to nitrogen stress. Using a composite gene expression scoring system, they can use these biomarker genes to provide an accurate assessment of nitrogen responses independent of genotype, environment, or growth stage, and under either controlled environment or field conditions. Their results suggest that biomarkers have the potential to be used as agronomic tools to monitor and optimize nitrogen fertilizer usage to help achieve maximal crop yields.

These results indicate that gene expression biomarkers can quantitatively measure the response of plants to differing nitrogen levels and may provide a new tool to more carefully manage nitrogen application rates and to mitigate limiting nitrogen conditions in real time in production fields. Early evaluation showed that these biomarkers have potential to be used across a range of genotypes and environments, making them potentially more useful than phenotypic comparisons for determining nitrogen responsiveness.

15.3 The Nitrogen Cycle

15.3.1 The N Cycle: What It Means to Global Crop Production

Life cycle analysis is a popular way of evaluating all of the interactions of a particular nutrient. The nitrogen cycle (Fig. 15.5) is one of the world's major chemical–physical–biological systems. Nitrogen plays a major role in the physiological processes of all living things. It is a primary component of the genetic code of all cells, a building block of all amino acids and proteins, and is involved in other chemical and structural functions in all living organisms. N is the largest component (78 %) of Earth's atmosphere as N_2 gas, is a key component of soil organic matter, and exists in other chemical forms in the soil. Nitrogen is involved in many processes beyond plant and soil systems, and it is in a constant state of flux between various fixed and reactive forms. The reactive forms used by plants are primarily nitrate and ammonia forms. These and other reactive forms, particularly NO_x gases, are environmentally active, as contributors to water quality concerns as biologically active pollutants and to air quality concerns as greenhouse gases.

15.3.2 Key Management Points of Control Where We Can Improve the System

The ubiquitous occurrence of N in nature, and its existence in multiple chemical and biological forms, provides unique opportunities to manage N. Many points in the N cycle offer control sites that can be used to adjust the amount of N in various forms and to regulate the rate of change among these forms. These are the management opportunities in agricultural production, points where altering management practices can affect not only the utilization of N for crop growth and yield but also the process by which the N is used by the crop, moves in the soil, or is lost from the field. These losses potentially affect water and air resources and ultimately impact development of hypoxic zones in water bodies and global warming potential (GWP) in the atmosphere.

Leaching loss is probably the most important source of N contamination of water supplies by crop production. The rate of loss is increased with tile drainage because the water flowing from the fields carries dissolved nitrate. The source of that nitrate is mineralization of organic compounds in soil organic matter (see Hatfield, Chap. 4), direct loss of fertilizer N applied to the crop, or existing soil nitrate—all of these sources changing as a result of time of the year, soil conditions, and water supply. All represent points where BMP intervention can help reduce environmental impact. Atmospheric N loss is also in various forms, including ammonia, nitrous oxide (N_2O), and other NO_x gases. The nitrous oxide is of most concern

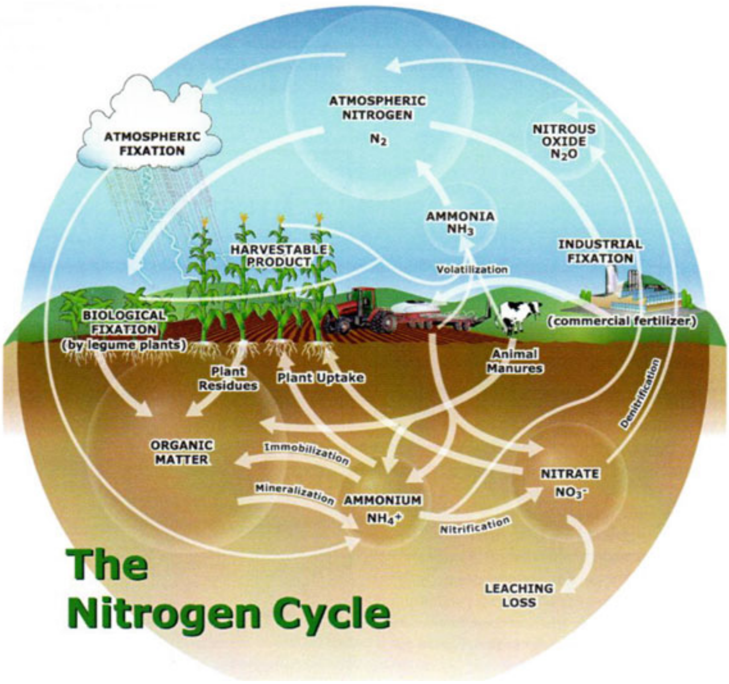


Fig. 15.5 The nitrogen cycle (2012) (International Plant Nutrition Institute)

because its GWP is 296 times the GWP of CO_2. Implementing BMPs that reduce NO_x losses helps to reduce impact of crop production systems on global climate change.

Many studies have shown that when N application rates are in balance, N losses via N_2O emissions and leached nitrate are reduced to a minimum, depending on the cropping system. Fine-tuning N rates is an important strategic management practice to help reduce the environmental consequences of N use. Selection of the proper rate of application is probably the first step toward reducing N loss and improving efficiency.

15.4 Plugging Technology into the Nitrogen Cycle

15.4.1 Site-Specific Management Offers Some New Opportunities

Since the mid-1990s, farmers have increasingly adopted various components of site-specific management, where the rate of fertilizer applied is carefully adjusted within the field to the specific needs of the growing crop. Plant and soil analysis, previous crop yield, and various electronic sensor systems are among the tools used to determine the crop needs. Data from these measurements are combined with computer models to interpret the results and guide rate controllers for site-specific variable-rate application of the nutrients. This technology can greatly increase the N use efficiency of applied fertilizer. It has resulted in about a 20 % reduction in the amount of N fertilizer applied to corn crops. The N fertilizer applied per unit of corn yield has gone from nearly 1 kg N/37 kg corn in 1995 to 1 kg N/62 kg of corn produced in 2010. These gains were a result of better placement and timing and other agronomic management, as well as genetic gains in N use efficiency in corn.

15.4.2 Sensors to Determine N Status on a Real-Time Basis

Sensor systems to identify crop N needs are based upon a system where specific wavelengths of light are targeted on the crop and the reflectance back to the unit is measured by optical sensors. These systems measure specific wavelengths of light reflected from the leaf surface from a standard light source of specific wavelengths. The result is an index of the "greenness" of the leaves which can be calibrated to nitrogen status of the plant. These sensors are either hand-carried or mounted on the fertilizer applicator. In the latter case the sensing and application are done in real time as the fertilizer is being applied. Various other sensor systems or digital camera technologies are available at a range of prices for scouting N status of plants and can often serve as a guide for in-season application of additional N fertilizer. Using such tools will help farmers and their advisers to fine-tune N management in support of the 4R system.

Variable-rate technology provides the means to take action. The availability of such sensor and application systems has made it possible to much more precisely match fertilizer rates to the crop needs of a particular spot in the field. . ..no more, no less. . .resulting in greatly increased fertilizer use efficiency and reduced potential for yield losses from N deficiency or environmental losses from excess N application.

15.4.3 The Elusive N Test

Several different N tests have been developed for either testing the soil or testing the plant to help determine the N requirement for fertilizer application. Each of the available test procedures has its potential to help identify N needs, but each also has its limitations. Since N occurs in different chemical forms and is especially impacted by weather, the N status of the soil is constantly changing. So several tests potentially could be used in formulating the N recommendation for a crop. No one test can tell the complete N status at any given time. The soil profile in the root zone may contain several tons of N/hectare. The amount managed by farmers and used by crops is a small part of the total N in the environment. It is in different chemical forms and in different states of mineralization by physical and biological processes. How much of that N is readily available to the plant roots at any given time depends upon a wide range of plant, soil, and climate conditions. Microbial activity in the soil is a major, though poorly understood, factor in total soil N availability to plants. Finding a test that can give the best estimate of *plant-available* N is a real challenge.

15.4.3.1 Why N Tests Are Difficult to Implement

The N status of the soil and the crop are dynamic; they vary considerably at different stages of the growing season and are significantly impacted by rainfall patterns. So determining when to do the N tests is a difficult decision. N is constantly changing from nitrate to ammonia form, as well as some intermediate forms, is subject to changing form, and being lost from the system by leaching or volatilization. Several biological relationships are involved in these changes, as shown in the N cycle (Fig. 15.5) discussed earlier. The changes occur so rapidly that the tests taken may no longer be valid by the time results are returned from the lab.

15.4.3.2 Different Test for Different Decisions: Soil Tests, Plant Analysis, Grain Analysis

The test to be used depends on the purpose. Soil tests are useful in determining the amount of N and form of N in the soil at any point in time. The Pre-Sidedress Soil Nitrogen Test (PSNT) (Purdue University Extension 2003) can be used in-season to determine whether sufficient N remains in the soil to meet the crop needs after winter and spring rains have taken their toll. This is especially useful if there has been excess rainfall resulting in unusually high leaching or denitrification losses. Stalk nitrate tests are used at the end of the growing season to indicate how much excess N was left at the end of the season. While this test may not be a good predictor of how much N will remain in the soil for the next year, it can be used as a guide to determine if the amount available during the current season was sufficient to carry the crop to maturity, or if the supply was running out. Grain analysis can provide information on amount of N (and other nutrients) that was removed at harvest.

15.5 Sustainable Nitrogen Management Must Be Built on Solid Science

Nitrogen management is subject to a lot of political pressure and emotional positioning. The best approach in the long run for all interested stake holders, and for farmers in particular, is to let solid science be the guide for decision-making. Replicated, scientifically sound field studies are the best way to collect data upon which to base management decisions. Studies should be conducted on commercial farms under the conditions that N will be used. Initial testing of products, procedures, and practices will often need to be done under more controlled conditions, but the ultimate evaluation must be at the field level using on-farm comparisons.

15.5.1 Food and Energy Security Dependence on Best N Management Practices

While N, as one of the 17 essential elements of plant nutrition, is no more important to the crop than any other nutrient, it is the one that is usually given the most attention and the one that has the most opportunities for management input decisions. For the objectives of increasing crop production and for addressing environmental issues related to crop production, management of N is among the most critical components. Production of N fertilizer has a high energy requirement. All manufactured N fertilizer is produced by combining N_2 from the atmosphere with natural gas under high heat and pressure. So more efficient use of N fertilizer directly means more efficient use of natural gas resources. Anything we can do to employ management practices that make more efficient use of N fertilizer and improve crop production with less N input or reduced N losses will contribute directly to saving natural resources as enhanced N use efficiency allows us to produce higher yield from the same unit of land, it also protects resources and increases our food security.

15.5.2 How Efficiency Leads to Security

With a finite supply of food production resources and limited opportunities for expanding productive farmland, making most efficient use of these resources is critical to future food security (see Buchanan and Orbach, Chap. 1). The concern is not so much that the supply of N is limited, but rather that supplying adequate N to meet production needs requires use of limited resources (such as natural gas) and potentially contributes to degradation of our environment if not properly and efficiently managed.

15.6 Science Surviving Politics of Nitrogen Management

15.6.1 Importance of Separating Science and Politics to Define Sustainable Management

In the long run, having a sustainable crop production system means one that maintains productivity to meet the food, feed, fiber, and fuel requirements of society and minimizes loss of environmental resources and ecosystem services. Sound science must be the guiding force in the quest for sustainable production systems. Eventually systems guided by political agendas at the expense of good science will fail because their false basis will become too expensive to maintain. Building a nutrient management plan around good science will provide the best economic and environmental outcome, and political interests should play a secondary role.

15.6.2 Key Research Needs to Provide the Science

There has been a trend since the 1980s away from providing funding in support of fundamental management research. Funding from government agencies and industry sources has been directed more to basic discovery and development in largely laboratory research. That has provided us with some amazing progress in new products, genetics, and technology. But to fully utilize those advances we need a concurrent expansion of the adaptive research that defines the management systems to best utilize those new developments from science. There is a growing need for integrated production systems research to identify how to make the best use of new genetics, new technology, and new agronomic practices to link them together.

15.6.3 Selling the Scientifically Sound Systems to Producers, Regulators, and the Public

Because N management is such a vital component of profitable crop production, and because it is an integral component of environmental concerns and ecosystem services, it follows that there are a lot of interests, often with conflicting goals in how N is managed. The best way to resolve these issues is to base analysis, interpretations, and decisions relative to N management on sound science. A good example is the growing popular opinion that farmers are over-applying N fertilizer and that this overapplication is a major factor in causing environmental problems. Actually, the opposite is true. N use efficiency has greatly increased through better management in recent years. Use of N and increased use of agricultural drainage are often assumed to be responsible for the increasing nutrient load in the major rivers, such as the Missouri River and the Mississippi River, and eventually contributing to the hypoxic "dead zone" in the Gulf of Mexico. However it is difficult to draw direct cause-effect correlations between increasing nutrient use and increasing water quality degradation. In fact, a decline in N use in relation to crop production over the past 20 years has had little effect on these water quality problems.

The overall nutrient balance in the Mississippi River Basin is so highly buffered that major changes—higher or lower—in application rate have little impact on water quality. The amount of N that is managed by the farmer is a minor part of the total N in the soil, including the amount that is tied up in organic matter, microorganisms, and other components of the system. It is likely to take many years for management changes to impact water quality, and our ability to measure those changes is very limited. Given that, it is still important to recognize that nutrient management does contribute to water quality, even if we can't document the magnitude, and farmers should make whatever reasonable management changes they can to reduce that contribution.

15.7 Putting Data Collection and Data Interpretation Tools to the Task of Gleaning Information

15.7.1 Corn Nitrogen Rate Calculator

Current N use by farmers is actually below recommended levels for most corn growing areas, as demonstrated by a recent N use assessment by the International Plant Nutrition Institute (Snyder 2012). The ***Corn Nitrogen Rate Calculator*** (2012) (Iowa State University) was used to compute an estimate of the maximum economic return to N (MRTN) for seven states (Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin) in the Midwest US Corn Belt, using data submitted by the Land Grant universities. This estimate was compared to the actual nitrogen use for the same area as reported by the public reports from the USDA (based upon the Agricultural Resource Management Survey and the Agrichemical Usage Data).

Table 15.1 summarizes these comparisons for the most recent available data—2000, 2005, and 2010 (Snyder 2012) This summary used data for corn following soybeans, which would generally generate a lower recommendation for N than that for continuous corn. Even with this conservative estimate of N required for optimum production, the actual use is considerably less on average than the Land Grant universities' recommendations. This confirms that Midwest corn farmers on average *are not using excessive nitrogen*, and in many cases are under-applying N compared to official university recommendations. These data refute misguided

Table 15.1 Comparison of recommended N rates to actual fertilizer used as reported by USDA survey for selected states/regions in the USA for 2000, 2005, and 2010

	Rate prescribed by "Corn N Rate Calculator" for MRTN			USDA surveyed state fertilizer N rate on corn land receiving N			Difference (recommended N minus applied N)		
	2000	2005	2010	2000	2005	2010	2000	2005	2010
	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
Iowa	156	137	160	147	158	159	9	−21	1
Illinois (Central)	195	174	202	180	164	187	15	10	15
Indiana (West and Northwest)	192	177	196	171	165	199	21	12	−3
Michigan	151	139	156	123	143	137	28	−4	19
Minnesota	127	115	134	128	156	140	−1	−41	−6
Ohio	203	180	211	181	180	158	22	0	53
Wisconsin (VH/VHP Soils)	140	120	146	149	155	103	−9	−35	43
Average	166	149	172	155	160	155	11	−11	17

Note: Data for anhydrous ammonia (NH_3) prices paid by farmers between March and April 2000, 2005, and 2010 and average corn prices received by farmers between August and October in the same years were used as input data for the ***Corn Nitrogen Rate Calculator*** (2012), available on a website maintained by Iowa State University. Representative field rate study data are submitted by state Land Grant Universities to keep the associated database current. MRTN is the *Maximum Return To N* based upon that calculator

popular opinions that Midwest corn producers are over-fertilizing, and need to reduce N rates.

Table 15.1 essentially says that the amount of N used by Midwest farmers is LESS than the amount recommended by the official Land Grant universities' recommendation.

Data on actual crop use of N, and subsequent crop removal from the system, in comparison to N applied in fertilizer and manure, show that crop nitrogen use efficiency has steadily increased over the past 20 years and that harvested grain is removing more N from the system than is being applied in N fertilizer and manure. Data on actual fertilizer application in the major corn producing states show that fertilizer applications have been less than removal for a number of years.

15.7.2 NuGIS

The International Plant Nutrition Institute (IPNI) has developed a ***Nutrient Use Geographic Information System for the U.S.*** (NuGIS IPNI) to provide a detailed accounting of nutrient use on all major crops in the USA. It is based upon industry and government databases on fertilizer and manure usage and crop production for each county in the USA. The NuGIS data can be summarized on a county-by-county basis or summarized for larger geographic areas or individual watersheds, including fertilizer and manure use and crop removal for up to 21 different crops.

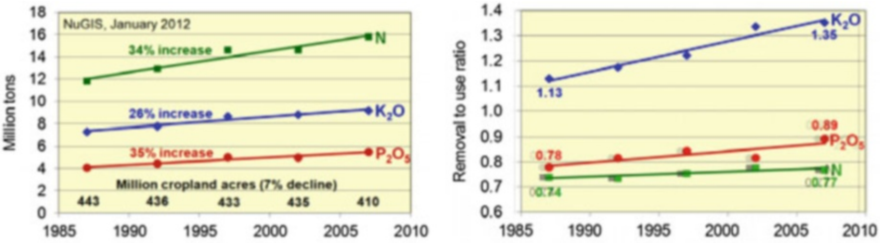


Fig. 15.6 Nutrient removal in crop harvest and nutrient removal to use ratios for the USA

The NuGIS information is available on the Internet as an interactive program at http://www.ipni.net/NuGIS.

From this NuGIS data analysis, it can be shown that nutrient removal in crop harvest for the USA increased dramatically from 1987 to 2007 for all three primary nutrients, with N and P climbing about 35 % and K about 26 % (Fig. 15.6), while total cropland acres declined by 7 %. Nutrient removal to use ratios also increased during this same period with K showing the largest increase and N the smallest. Increasing the nutrient removal to use ratio, as crop yields continue to increase, means that the crop management systems are becoming more efficient, generating more yield per unit of nutrient use.

These data can be more useful for management decisions if they are interpreted for a smaller geographic area. Care needs to be used in interpreting national figures on nutrient balance due to the great variability existing among regions within the USA. Table 15.2 illustrates the diversity in nutrient budgets and the resulting balances among states. Cropping systems are becoming more efficient in nutrient use, but nutrient applications in many cases are not increasing enough to maintain soil nutrient levels. In those cases, farmers are mining the soil of nutrient reserves. This will eventually lead to reduced productivity if not corrected.

The first columns in Table 15.2 show the 2007 N and P applications and crop removal rates for four representative states. The final two columns (BALANCE) show the ratio of crop removal to total nutrient input and the rate per acre of nutrients left after the crop season. The summary shows that crop removal for N is 77 % of total N applied, and crop removal for P is 89 % of P applied. Illinois farmers are removing 154 % of the P that is applied—they are effectively mining the soil P reserves.

This spatial and temporal analysis of partial nutrient balances in the USA leads to the following general observations:

- Crop nutrient removal in the USA is increasing faster than nutrient use.
- Great variation exists across the country in major nutrient (N, P, K) balances.
- The most positive P balances are found in the South Atlantic, Gulf, New England, and California watershed regions. (*Nutrient application exceeds crop removal*)

Table 15.2 N and P budgets for four states and the USA in 2007

						Balance	
	Nutrient	Fertilizer	Recoverable manure	N fixation	Harvest removal	Removal/	Per cropland acre
State	Thousand tons					use	lb./A
Florida	N	167	13	4.5	102	0.55	56
	P_2O_5	56	13		33	0.47	25
Illinois	N	1,018	21	727	1,531	0.87	19
	P_2O_5	332	37		567	**1.54**	−16
North Carolina	N	187	94	75	197	0.55	61
	P_2O_5	101	148		69	0.28	70
South Dakota	N	450	17	333	679	0.85	13
	P_2O_5	212	29		219	0.91	2
U.S.	**N**	**12,594**	**1,405**	**6,643**	**15,847**	**0.77**	**23**
	P_2O_5	**4,337**	**1,809**		**5,484**	**0.89**	**3**

IPNI (2013)

Note: 1 short ton (US) = 0.90718474 metric tons. 1 hectare = 2.47105 acres

- Much of the Corn Belt has negative P balances (e.g., **the Illinois data shows P removal is 1.54 times P application**), and the entire western half of the country has highly negative K balances (not shown in Table 15.2). (*Crop removal exceeds nutrient application—Soil P and K levels in these areas are being depleted.*) This mining of nutrients will reduce yield potential and value of the land for crop production.
- Removal to use ratios appear unsustainably high in some regions and unsustainably low in others calling for intensive monitoring of soil fertility and more intensive nutrient management with greater adoption of 4R Nutrient Stewardship.
- Substantial uncertainty exists in these aggregate data and points to a need for farm level measurement of nutrient balance and removal to use ratios as a basis for indicating progress in nutrient management.

Focusing again on N management, it is clear that loss of N from crop fields is more often a result of timing of application in relationship to crop N use, than of excess N application rates. When excess N losses occur, they are most often associated with improper timing of application or improper selection of N source. More farmers are adopting the practice of split-application—dividing total needed into two or three application times—and sometimes using different sources, to more closely match timing of crop N use.

There is no doubt that crop production systems contribute to the N losses from fields to the downstream water bodies. Increased tile drainage in the major corn production areas of the Midwest coincide with the major nitrogen fertilizer application areas. The system is leaky. Water flowing through the soil carries dissolved N as it exits the field in tile drainage, runoff, or groundwater percolation. New technologies of drainage water management are helping control these losses.

Systems that turn drainage water on and off (drainage water management) and control the depth of the water table at different levels during the growing season have been shown to reduce water loss by 35 % or more during the growing season, and have equally reduced nitrate losses in tile water by over 35 % (Agricultural Drainage Management Coalition 2010). Special filtering systems such as saturated buffers, bioreactors, and constructed wetlands can help to reduce nitrate losses from fields by 90 % or more. Use of cover crops may also help by keep the nutrients in plant material during the time period between the commercial crops.

Natural decomposition of soil organic matter releases N into the soil solution. In fact N was being lost from fields long before crops were grown there. Some of the highest N and P losses measured in monitored streams in Wisconsin are not from cropland or livestock operations, but from forests. Historical records and river sediments show that the nitrate levels in the Illinois River were as high or higher in the mid-1800s as they are today, due to decaying organic matter from natural areas. There are several thousand pounds of N in the root zone of most crop fields in various stages of plant availability. The 150–200 kg/ha of N that farmers manage is just a small part of the total N available for mineralization, leaching, denitrification, etc., in addition to use for crop growth. So being able to significantly affect N loss through the farmer's management is a real challenge. Even so, following 4R-BMP management helps farmers do what they can to reduce environmental losses.

As shown is Fig. 15.5, the N cycle is very dynamic. It involves a complex system of chemical, physical, and biological forces, with man's activity in growing crops thrown into the mix. All of these forces interact. Some can be managed to our benefit. Those are the ones on which scientists and farmers and policymakers need to focus their attention, so that they can become more of a positive influence. This is the goal of a new global program being promoted by industry, farmers and their advisers, and government agencies around the world. Selecting the right fertilizer products for the given crop-soil-climate region is an important first step. Then basing the rate used on good scientific research to avoid under- or overapplication is next. Then looking at details to adjust timing and placement to best fit crop rooting patterns and uptake needs throughout the growing season will help improve nutrient use efficiency and reduce losses.

15.8 Nutrient Use Efficiency

While the simple solution to nutrient problems is sometimes proposed to be cutting back on nutrient applications, a better approach is to make decisions on the basis of output per unit of nutrient input. One of the best ways to evaluate nutrient management is through calculation of ***Nutrient Use Efficiency*** (NUE). In its simplest forms, NUE can be calculated from fertilizer application rates and crop yields on any field or any larger geographic area. More information can be gleaned, and thus more helpful management guidance, by conducting rate comparisons, including a

Table 15.3 Definitions, calculations, and some examples for the four NUE determinations discussed above

NUE Term	Calculation	Reported examples
PEP Partial factor productivity of applied nutrient	Y/F	40–80 units of cereal grain per unit of N
AE Agronomic efficiency of applied nutrient	$(Y - Y_0)/F$	10–30 units of cereal grain per unit of N
PNB Partial nutrient balance (removal to use ratio)	U_H/F	0 to greater than 1.0—depends on native fertility and fertility maintenance objectives <1 in nutrient deficient systems (fertility improvement) >1 in nutrient surplus systems (under-replacement) Slightly less than 1 to 1 (system sustainability)
RE Apparent crop recovery efficiency of applied nutrient	$(U - U_0)/F$	0.1–0.3—proportion of P input recovered first year 0.5–0.9—proportion of P input recovered by crops in long-term cropping systems 0.3–0.5—N recovery in cereals—typical 0.5–0.8—N recovery in cereals—best management

Dobermann (2007)

F, amount of nutrient applied (as fertilizers, manure, etc.); Y, yield of harvested portion of crop with applied nutrient; Y_0, yield in control with no applied nutrient; U_H, nutrient content of harvested portion of crop; U, total nutrient uptake in aboveground crop biomass with nutrient applied; U_0, total nutrient uptake in aboveground crop biomass with no nutrient applied

plot without the subject nutrient applied. The following discussion of NUE again uses N as an example, but the procedure can be used for any nutrient.

Improving NUE benefits the farmer by providing more yield for each unit of inputs. . .not just nutrient inputs, but also land, labor, machinery, and other inputs. NUE also benefits the environment by helping avoid unnecessary application of nutrients that might otherwise contribute to water and air quality problems. Perhaps most important, NUE practices produce more for each acre of land in production, thereby reducing the need to destroy fragile ecosystems in order to meet crop production needs.

Snyder and Bruulsema (2007) summarized four common components of NUE. The two ***production efficiency*** calculations refer to efficiency based in the harvested crop. The two ***recovery efficiency*** calculations deal relate to the nutrients removed by the crop (Table 15.3).

Production efficiency

Partial factor productivity (PFP)—The simplest production efficiency calculation is one which computes units of crop yield per unit of nutrient applied. PFP compares the productivity of the cropping system with its nutrient input.

Agronomic efficiency (AE)—calculated as units of **yield increase** per unit of nutrients applied. AE requires a comparison plot with no nutrient applied, but it better reflects the impact of the applied fertilizer, measuring how much productivity was improved by addition of the nutrient.

Recovery efficiency

Partial nutrient budget (PNB)—the simple form is calculated as nutrient output per unit of nutrient input. PNB can be computed for multiple growing seasons.

Recovery efficiency (RE)—a more complex term, defined as increase in crop uptake of the nutrient (usually above ground only) per unit of nutrient applied. Like AE, RE requires a research plot without the nutrient applied. RE is limited to a single nutrient application or a single growing season.

15.8.1 NUE Analysis of a Nitrogen Rate Study

An example of these four NUE calculations for a Nebraska N rate comparison trial is illustrated in Table 15.4. An additional column is added to show the economic analysis for these treatments. For this study, 134 kg/ha of N resulted in the highest net return to applied N.

While these calculations seem simple, their interpretation requires deeper analysis. As an example, computing the PFP for N on corn for the USA over the period from 1964 to 2006 showed the N use efficiency first declined then rose over time, increasing by 50 % from 1975 to 2006. But this was not simply from changing the rate of N. During that time, N rates actually increased by 24 %, but genetics and other management improvements resulted in an 86 % increase in corn yield. Also, prior to 1975 more of the N for the crop was coming from mineralization of soil organic matter, which has been stabilized by improved conservation practices since that time (Snyder and Bruulsema 2007).

Many researchers report that as crop yields are increasing, the nutrient content of the grain, and thus nutrient removal per unit of yield, is decreasing for many crops. This is likely due to the relative increase of carbohydrates relative to mineral nutrients as yields increase. There are also some distinct geographic differences in grain nutrient content, probably due to differences in soils and climate that must be taken into account in studying nutrient management and nutrient balance over time.

15.8.2 Crop Nutrient Response Tool

The data shown in Table 15.4 are based upon the ***Crop Nutrient Response Tool*** (CNRT) (IPNI 2010) developed by the International Plant Nutrition Institute

Table 15.4 Efficiency values calculated from N responses reported for an irrigated corn field in Nebraska (mean of 3 years)

N rate		Yield		Total N uptake		Grain uptake		Production efficiencies		Recovery efficiencies		Net return to applied N	
lb./A	kg/ha	bu/A	kg/ha	lb./A	kg/ha	lb./A	kg/ha	PFP	AE	PNB	RE	$/A	$/ha
0	0	120	7,525	108	121	73	82	–	–	–	–	–	–
60	67	137	8,591	132	148	85	95	128	16	1.42	0.39	37	91
90	101	143	8,968	141	158	90	101	89	14	1	0.36	45	111
120	**134**	**147**	**9,218**	**148**	**166**	**94**	**105**	**69**	**13**	**0.78**	**0.33**	**47**	**116**
150	168	149	9,344	153	171	97	109	56	11	0.64	0.3	43	106
180	202	149	9,344	157	176	98	110	47	9	0.55	0.27	32	79

Shapiro and Wortmann (2006)

PFP, partial factor productivity (yield per unit of N applied); AE, agronomic efficiency (yield increase per unit of N applied); PNB, partial nutrient balance (units of N uptake in grain per unit of N applied); RE, recovery efficiency (units of increase in N uptake per unit of N applied); Net return calculated based upon corn priced at $3.50/bu ($138/mT) and N priced at $0.40/lb. ($884/mT)

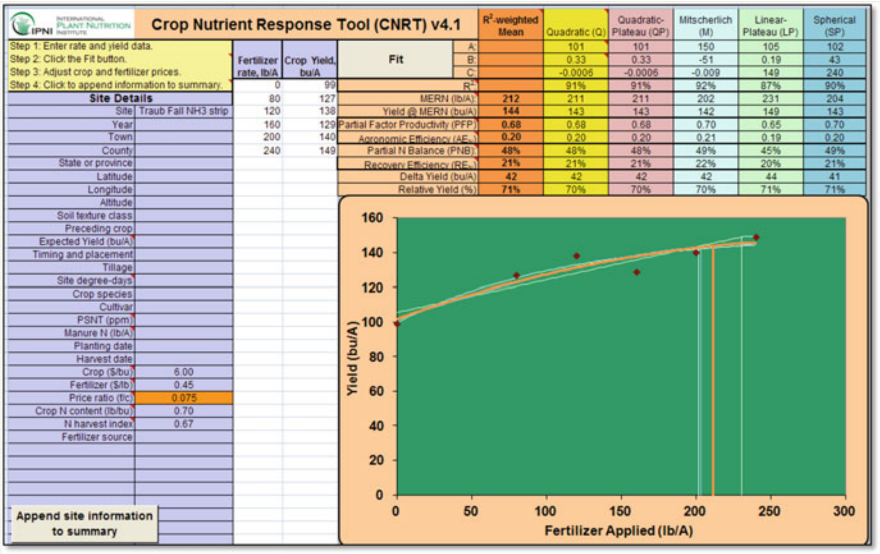
(IPNI). This computer worksheet is available on the IPNI web site at http://www.ipni.net. This tool can guide farmers and their advisers in improving their BMPs for improved NUE.

Figure 15.7 illustrates the information calculated with the CNRT using data from a central Illinois N rate demonstration on corn. The calculations were based upon the yields produced at six different N rates, the respective current prices for N fertilizer, and the local grain price for corn. Five different models are used to find the best statistical fit for the data.

15.9 Making Fertilizer BMPs Work

Fertilizer BMPs that improve NUE are centered around the 4R concept. Most of those practices work toward keeping more of the nutrients in the field to benefit crops and avoiding losses in drainage, surface run-off, denitrification, etc. Grassed waterways, stream bank buffers, drainage water management, cover crops, and other conservation practices also help improve NUE.

Fertilizer use worldwide must increase if crop production needs are to be met. But steps taken to improve NUE for those nutrients applied can result in meeting the crop production needs without negative environmental consequences and without destroying wildlife habitat and fragile ecosystems. NUE management improvements can, and should, be applied in any cropping system, anywhere in the world, regardless of farm size or economic status—improvements at all levels contribute to a better aggregate global improvement in nutrient management.



Crop Nutrient Response Tool (CNRT) v4.1

Step 1: Enter rate and yield data.
Step 2: Click the Fit button.
Step 3: Adjust crop and fertilizer prices.
Step 4: Click to append information to summary.

Fertilizer rate, lb/A	Crop Yield, bu/A
0	99
80	127
120	138
160	129
200	140
240	149

Fit	R²-weighted Mean	Quadratic (Q)	Quadratic-Plateau (QP)	Mitscherlich (M)	Linear-Plateau (LP)	Spherical (SP)
A:		101	101	150	105	102
B:		0.33	0.33	-51	0.19	43
C:		-0.0006	-0.0006	-0.009	149	240
R^2:		91%	91%	92%	87%	90%
MERN (lb/A):	212	211	211	202	231	204
Yield @ MERN (bu/A)	144	143	143	142	149	143
Partial Factor Productivity (PFP)	0.68	0.68	0.68	0.70	0.65	0.70
Agronomic Efficiency (AE_N)	0.20	0.20	0.20	0.21	0.19	0.20
Partial N Balance (PNB):	48%	48%	48%	49%	45%	49%
Recovery Efficiency (RE_N)	21%	21%	21%	22%	20%	21%
Delta Yield (bu/A)	42	42	42	42	44	41
Relative Yield (%)	71%	70%	70%	70%	71%	71%

Site Details	
Site	Traub Fall NH3 strip
Year	
Town	
County	
State or province	
Latitude	
Longitude	
Altitude	
Soil texture class	
Preceding crop	
Expected Yield (bu/A)	
Timing and placement	
Tillage	
Site degree-days	
Crop species	
Cultivar	
PSNT (ppm)	
Manure N (lb/A)	
Planting date	
Harvest date	
Crop ($/bu)	6.00
Fertilizer ($/lb)	0.45
Price ratio (f/c)	0.075
Crop N content (lb/bu)	0.70
N harvest index	0.67
Fertilizer source	

Fig. 15.7 Use of IPNI Crop Nutrient Response Tool to computer various nutrient use efficiency factors, and determine the most economical return to nutrients (IPNI 2010). Note: 1 short ton (US) = 0.90718474 metric tons. 1 hectare = 2.47105 acres

15.9.1 Global Application of the 4R Nutrient Management Concept

The 4R concept works anywhere in the world for any crop production system. The tools will vary and some of the best practices will vary, but all farmers, from a half-hectare rice farmer in Southeast Asia to a 5,000-hectare corn farmer in Illinois, can use the 4R concept to guide management decisions. Getting 4R management in place for more farms throughout the world is the best way to meet the global crop demand in the most sustainable way (see Redick, Chap. 3). Implementing more efficient production systems built around 4R nutrient management is the only way to reduce the need to move fragile lands into production, which would destroy important natural resources ecosystem services. Higher yielding, more efficient production systems help protect natural resources and wildlife habitats by focusing crop production on the most productive lands that are already under cultivation.

15.9.2 Future Nutrient Sustainability

As agricultural production is expanded to meet the growing global demand for food, feed, fiber, and fuel in the coming years, the amount of fertilizer applied must be increased. These demands cannot be met with reduced fertilizer inputs, and they cannot be met through organic production systems. The amount of organic nutrients available in the USA, for example, is sufficient to supply only about 10 % of the total nutrients needed from fertilizer. In many cases, the location of the organic nutrients is not near the area of the crop needs. Meeting this demand through sustainable production systems will be possible through broader adoption of fertilizer BMPs defined under the 4R concept. Management under the 4R-BMP concept will lead to higher yields, more efficient use of fertilizer and other inputs, greater profitability, and reduced environmental degradation. In short, 4R-BMP nutrient management leads to more sustainable nutrient management.

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