CAST

The Science Source for Food, Agricultural, and Environmental Issues

Sustainability of U.S. Soybean Production:

Conventional, Transgenic, and Organic Production Systems

CAST®

The Science Source for Food, Agricultural, and Environmental Issues

Council for Agricultural Science and Technology
4420 West Lincoln Way, Ames, IA 50014-3447, USA
Telephone: (515) 292-2125; Fax: (515) 292-4512
E-mail: cast@cast-science.org
CAST Website: www.cast-science.org

Mission and Policies

CAST assembles, interprets, and communicates credible science-based information regionally, nationally, and internationally to legislators, regulators, policymakers, the media, the private sector, and the public. CAST is a nonprofit organization composed of scientific societies and many individual, student, company, nonprofit, and associate society members. CAST's Board of Directors is composed of representatives of the scientific societies and individual members, and an Executive Committee. CAST was established in 1972 as a result of a meeting sponsored in 1970 by the National Academy of Sciences, National Research Council.

The primary mission of CAST is the publication of task force reports, special publications, issue papers, and commentaries written by scientists from many disciplines. The CAST National Concerns Committee screens proposals from all sources and recommends to the board topics for approval as publication projects.

The CAST Board of Directors is responsible for the policies and procedures followed in developing, processing, and disseminating the documents produced. Depending on the nature of the publication, the society representatives may nominate qualified persons from their respective disciplines for participation on the task force. Aside from these involvements, the member societies have no responsibility for the content of any CAST publication.

Diverse writing groups and active participation by all task force authors and reviewers assure readers that a balanced statement on the topic will result.

The authors named in each publication are responsible for the contents. Task force members serve as independent scientists and not as representatives of their employers or their professional societies. CAST publishes and distributes the documents.

Copies of *Sustainability of U.S. Soybean Production: Conventional, Transgenic, and Organic Production Systems* are available from CAST, 4420 West Lincoln Way, Ames, IA 50014-3447, or (515) 292-2125. The 96-page report is $18.00 plus shipping. For more information, visit the CAST website at www.cast-science.org

This publication was made possible through funding provided by the United Soybean Board (USB) Biotechnology Initiative. USB is made up of 68 farmer-directors who oversee the investments of the soybean checkoff on behalf of all U.S. soybean farmers. Checkoff funds are invested in the areas of animal utilization, human utilization, industrial utilization, industry relations, market access and supply. As stipulated in the Soybean Promotion, Research and Consumer Information Act, USDA's Agricultural Marketing Service has oversight responsibilities for USB and the soybean checkoff. The opinions expressed are those of the authors based on a comprehensive review of the published literature.

USB
UNITED SOYBEAN BOARD
Making Your Checkoff Pay Off.

Sustainability of U.S. Soybean Production: Conventional, Transgenic, and Organic Production Systems

Layout and cover design by Richard Beachler, Information Technology Services, Iowa State University, Ames
Cover photo sources:
Soybeans, courtesy of USDA Agricultural Research Service Image Gallery
Young soybean field, courtesy of USDA Agricultural Research Service Image Gallery
Summer soybean field, courtesy of the Image Archive, CHS, Inc., St. Paul, Minnesota
Crimping roller, courtesy of USDA Agricultural Research Service Image Gallery
Close-up soybean plants, courtesy of the Image Archive, CHS, Inc., St. Paul, Minnesota
Mature soybeans, courtesy of the Image Archive, CHS, Inc., St. Paul, Minnesota

ISBN 978-1-887383-32-5
ISSN 0194-407x
13 12 11 10 09 5 4 3 2 1

Special Publication
No. 30 June 2009

Council for Agricultural Science and Technology
Ames, Iowa, USA

Task Force Members

Larry Heatherly, Project Manager/Lead Author, Agronomic Advisor, Seymour, Tennessee

Anne Dorrance, Department of Plant Pathology–OARDC, The Ohio State University, Wooster

Robert Hoeft, Department of Crop Sciences, University of Illinois, Urbana

David Onstad, Department of Crop Sciences, University of Illinois, Urbana

James Orf, Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul

Paul Porter, Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul

Stan Spurlock, Department of Agricultural Economics, Mississippi State University, Mississippi State

Bryan Young, Department of Plant, Soil, and Agricultural Systems, Southern Illinois University, Carbondale

Reviewers

Allan Felsot, Entomology & Environmental Toxicology, Washington State University–TriCities, Richland

Leonard Gianessi, CropLife Foundation, Washington, D.C.

Matt Liebman, Department of Agronomy, Iowa State University, Ames

Gyles Randall, Soil Scientist, University of Minnesota Southern Research & Outreach Center, Waseca

CAST Liaisons

John Havlin, Department of Soil Science, North Carolina State University, Raleigh

Todd Peterson, Pioneer Hi-Bred International, Johnston, Iowa

Contents

Figure

Tables

Foreword

In June 2008, the Board of Directors of the Council for Agricultural Science and Technology (CAST) approved entering into a collaborative agreement with the United Soybean Board to conduct a critical literature review on the topic of sustainability in U.S. soybean production. An eminent group of eight experts was chosen as the writing task force, led by Dr. Larry Heatherly as project manager. Four highly qualified scientists were invited to review and comment on the document, and two members of the CAST Board of Directors served as project liaisons.

The authors prepared an initial draft of this document and reviewed and revised all subsequent drafts based on reviewers' comments. The CAST Executive Committee and Editorial and Publications Committee reviewed the final draft, and all task force members reviewed the galley proofs. The CAST staff provided editorial and structural suggestions and published the document. The task force authors are responsible for the publication's scientific content. If the document is copied in any manner, credit to the authors and to CAST would be appreciated.

On behalf of CAST, we thank the project manager, authors, and reviewers whose expertise made it possible to prepare this publication as a contribution by the scientific community to public understanding of the issue. We also thank the employers of the scientists who made the time of these individuals available to CAST, thus making the project a reality.

CAST appreciates the opportunity to work collaboratively with the United Soybean Board on this important publication.

Henry L. Shands
CAST President

John M. Bonner
Executive Vice President, CEO

Linda M. Chimenti
Director of Council Operations

In an effort to assess the sustainability of U.S. soybean production, the United Soybean Board (USB) requested that the Council for Agricultural Science and Technology (CAST) conduct a comprehensive literature review. The purpose of this review was to evaluate U.S. soybean production systems currently in use with respect to their environmental and economic sustainability.

A 2002 USB-sponsored CAST publication compared the environmental impacts of biotechnology-derived and traditional soybean, corn, and cotton crops. At that time, 68% of the 75.4 million U.S. soybean acres were planted to transgenic varieties compared with 92% of the 75.7 million soybean acres planted in 2008.

With this dramatic change in mind, USB approached CAST to conduct a literature review that would evaluate the impacts of this new production system on environmental and economic sustainability. The primary focus of the review was to determine the relative impacts of traditional, organic, and transgenic soybean production systems on soil erosion, water and pesticide runoff, crop productivity, and economic returns.

The USB is made up of 68 farmer-directors who oversee the investments of the Soybean Checkoff on behalf of all U.S. soybean farmers. USB recognizes the efforts of the authors to provide a comprehensive, objective review of the published literature applicable to U.S. soybean production. The authors selected the literature reviewed and the data presented. The conclusions drawn are those of the authors.

The USB appreciates the opportunity to work with CAST on this project.

Chuck Myers
Soybean Farmer
USB Chairman

Richard Fordyce
Soybean Farmer
Team Lead—USB Biotechnology Initiative

Doug Goehring
Soybean Farmer
Team Lead—USB Sustainability Initiative

Executive Summary

This comprehensive review of soybean (*Glycine max* L.) research findings leads to the conclusion that all three of the soybean systems discussed in this report—conventional, transgenic, and organic—are environmentally sustainable and can be managed for profit when proper practices and technologies are used. This report identifies practices and technologies and describes their proper use and application to achieve sustainable and profitable soybean production.

Results of this comprehensive literature review indicate that production practices are evolving to ensure the continued environmental and economical sustainability of soybean production in the United States. These evolutions include improved production and management practices; advances in breeding and variety development; new or improved materials and methodology for disease, nematode, insect, and weed management; and increased interest in organic soybean production because of growing demand for organic food products.

Production and Management Practices—All Systems

Most production and management practices used in current and future U.S. soybean production are applied the same or nearly the same way regardless of the production system (conventional, transgenic, or organic). The summary points in this section follow this premise.

Increased yields coupled with decreases in erosion, water runoff, and fuel use support the premise that soybean produced with conservation tillage is more economically and environmentally sustainable regardless of the production system. In fact, conservation tillage is the only tillage approach that realistically supports environmentally sustainable soybean production in most regions of the United States.

Cover crops used in a soybean production system provide positive environmental benefits. There usually is no income, however, to offset the cost of their establishment and culture, and this discourages their use. This lack of income can be remedied by (1) developing technologies that lower costs associated with their use, and/or (2) putting into effect a program of government incentive payments to encourage their use to achieve the environmental benefits they provide.

Crop rotation provides positive production and environmental benefits to both soybean and the rotated crop in most systems. A rotation of a grain crop with soybean decreases erosion potential. The nitrogen fertilizer requirement for a grain crop following soybean can be reduced by an estimated 40 to 80 lb/acre compared with the grain crop following itself. Energy output:input ratios favor rotating soybean and a grain crop. Crop rotation and rotation of resistant soybean varieties are used to manage soybean cyst nematode (SCN) (*Heterodera glycines* L.) populations effectively. The soybean–corn rotation in the Corn Belt should be monitored to determine whether additional rotations or other practices within the standard biennial rotation are needed to mitigate nitrogen loss to the environment and adaptation of pest species to the rotated crop.

Sustainable and environmentally sound soil nutrient management continues to rely on the tried and true process of accurate soil sampling and soil tests. Some fertilizers should be applied using variable rate technology to prevent overfertilization that may result in environmental contamination. Application of nitrogen fertilizer to soybean is unjustified and incurs an unnecessary expense with no benefit. Maintaining soil pH in the range of 6.0 to 7.0 will enhance availability of fertilizer nutrients, decrease availability of toxic elements, and improve microbial activity.

Irrigated soybean systems are the most productive in the United States. Irrigation provides consistent and sustainable soybean production in the long term, especially in regions that receive too little or too erratic rainfall to ensure stable and profitable yields without irrigation. Government-sanctioned regulatory bodies provide the only reasonable governance and oversight to ensure adequate water supplies for future soybean irrigation in these regions. These regulatory bodies also can be chartered to address environmental concerns that may result from irrigation management practices.

Breeding and Variety Development—All Systems

Breeding and variety development will continue to provide advances that will have a major impact on U.S. soybean production. The U.S. soybean germplasm collection contains a large amount of variation in genetic material. This material can be screened for new traits and genes that will provide enhanced genetics for improved yield potential, host-plant resistance, and enhanced seed traits in new varieties that will be developed. Augmenting this collection will be access to global germplasms that may have additional genes to provide resistance to plant pathogens and insects, and management of abiotic stresses.

Most public soybean breeding programs likely will continue to emphasize conventional breeding rather than transgenic methodology. This idea suggests that conventional varieties will continue to be developed, but the availability of seed will depend on both demand from domestic and international markets that specifically seek seed from conventional varieties and success of conventional breeding programs to increase yields and effectively manage stresses that reduce yield potential.

Conventional breeding strategies have been and will continue to be successful in developing soybean varieties with traits that improve productivity, quality, and resistance to pests, especially SCN. Varieties that possess specialty or value-added traits that improve or enhance seed quality are available, and more are forthcoming. Breeding lines that offer potential drought tolerance have been developed recently and are available for incorporation into variety-development programs. Organic producers will rely on the continual development of conventional, nontransgenic varieties, especially for varieties with value-added traits.

Many soybean breeding programs currently use transgenic varieties as parent material for future variety development. As the private sector moves to include multiple transgenic events or different transgenic events in the same variety, some private programs are contemplating doing their basic genetic improvement using conventional breeding techniques and then backcrossing the transgenic trait(s) into the lines for eventual release as a variety.

Presently, there are no transgenic disease management traits in soybean; however, disease management through molecular genetic approaches may be forthcoming. Transgenic insecticidal soybean has been evaluated in the United States and found to be efficacious against defoliating insects. It is generally agreed, however, that the present U.S. market for varieties that are developed with this transgenic trait may be too small to justify its commercialization in this country.

Recent breeding efforts have resulted in the development of transgenic varieties with resistance to nonselective herbicides. Forthcoming transgenic traits will impart resistance to both nonselective and selective herbicides, and varieties with these traits will be the foundation of weed management strategies in the United States.

Disease, Nematode, and Insect Management—All Systems

The most effective and widely used management strategy for soybean pathogens in soybean production systems is host-plant resistance. Increased screening of potential varieties in disease nurseries is needed to ensure that released varieties have the disease resistance necessary to withstand pathogen infection in the area of their intended major use. For fungal diseases where host-plant resistance has not been identified, many recently labeled fungicides are available for effective management of disease outbreaks in nonorganic systems. These materials should be used in an integrated management approach to mitigate development of resistance in fungal populations and avoid secondary environmental impacts. Presently, there are no transgenic disease management traits in soybean.

Soybean cyst nematode is the most damaging pest to U.S. soybean, and it is managed effectively with crop rotation and resistant varieties. Effective management of future SCN populations depends on identifying new types of resistance through either breeding or biotechnology for incorporation into high-yielding varieties.

Integrated pest management has been promoted and used for insect management in U.S. soybean and has resulted in significant cost savings and limited environmental impact. Host-plant resistance is available, and high-yielding insect-resistant varieties may be developed as evidenced by recent progress in identifying aphid resistance genes that can be incorporated into new varieties. Scouting fields to determine insect pressure, relying on and protecting natural insect predators, and applying chemical insecticides when warranted (in nonorganic systems) provide consistent and effective control. Synthetic insecticides are used on a low percentage of U.S. soybean acres and therefore pose minimal threat to human health or the environment. Rotation of insecticide chemistries that offer similar control will retard selection for resistance in insect species. Transgenic insecticidal soybean based on *Bacillus thuringiensis* (*Bt*) endotoxins has been introduced. Subsequent *Bt* lines were developed and evaluated and found to have significant insecticidal activity against some insect species. The U.S. market, however, may be too small to justify commercialization in this country.

Weed Management—Conventional and Transgenic Systems

Sustainability of conventional or nontransgenic weed management in a soybean production system will be limited in the future because of few new nonglyphosate herbicide chemistries, disappearance of available nonglyphosate chemistries, and the decreasing number of conventional varieties. In fact, future soybean breeding efforts likely will use transgenic, herbicide-resistant parents to develop new varieties.

Development of transgenic glyphosate-resistant (GR) soybean is arguably the most significant step toward a sustainable weed management system for soybean production. The future sustainability of transgenic soybean for weed management will rely on using a combination of herbicides that are used in conventional soybean and the development and commercialization of new transgenic soybean such as Liberty Link, Optimum GAT, and varieties with dicamba and 2,4-D resistance. Using conventional herbicides with current and new transgenic herbicide-resistant varieties in an integrated approach will ensure that glyphosate and GR soybean will continue to be a major component in a sound, sustainable, and environmentally acceptable system for weed management in soybean.

Organic System

Organic producers will rely on conventionally developed, nontransgenic varieties. Diseases will be managed mostly with varietal resistance, whereas nematodes will be managed with varietal resistance and crop rotation. Tillage will be used for cover crop management and weed control. Where mechanical weed control is not effective, hand weeding will be necessary. Crop rotation and rotation sequence will be fundamental, as will applying animal manures and legume cover crops as fertilizer sources. These inputs indicate that sustainability of organic soybean production will rely on availability of seed of conventional varieties, management of weeds using only organic methods and hand weeding, availability of a reliable and cheap source of manure, and a strong market to ensure a price premium.

1 Introduction

Sustainable agriculture is an integrated system of plant and animal production that should (1) meet the rapidly expanding human food, animal feed, and fiber needs; (2) enhance environmental quality by maintaining or improving the soil, air, and water resource base that supports agriculture; (3) make the most efficient use of nonrenewable resources such as fossil fuels and mineral fertilizers, and integrate, where appropriate, natural biological cycles and controls; (4) be commercially competitive to maintain the economic viability of farm operations; and (5) enhance the quality of life for producers and be viable enough to support the rural socioeconomic infrastructure (Feenstra, Ingels, and Campbell 1997; Gold 2007a, 2008).

Sustainable agriculture can be described briefly as farming systems that incorporate practices that result in the commensurate maintenance or enhancement of environmental quality and profitability. A production system that is environmentally sound must be profitable for it to be adopted and used by producers over the long term. Soybean production in the United States is a significant enterprise involving large acreage and intense management with myriad inputs. Thus, it follows that the definition of sustainable soybean production mimics that of sustainable agriculture in general.

The objective of this report is to document the ecological and economical implications of U.S. soybean production in conventional, transgenic (biotech[1]), and organic production systems, with special emphasis on environmental sustainability and strategies to mitigate environmental impacts resulting from soybean production. The report presents major components or inputs for the three systems, along with a discussion of how the management of those inputs affects the environmental stewardship and sustainability associated with each production system. New and/or forthcoming developments that will affect the future sustainability of soybean production in the United States regardless of the production system also are discussed.

[1] For purposes of this document, the term "transgenic" is used in place of "biotechnology-derived" or "biotech."

The context of this report is based on the premise that a conventional soybean system is one that uses conventional varieties that have been developed using traditional or nontransgenic breeding methods, a transgenic system is one that uses transgenic varieties that contain a gene or genes from another species, and an organic system is one that uses conventional varieties and nonsynthetic fertilizers and pesticides. Thus, this presentation is separated into chapters (3, p. 37; 4, p. 53; and 5, p. 60) that are delineated accordingly. This terminology for the systems seems to ignore the fact that glyphosate-resistant (GR) varieties are now the "conventional" ones (>92% of U.S. planted acres), but takes into account that glyphosate resistance is presently the only transgenic trait that is used in soybean production. In other words, soybean production is still "conventional" in all categories except for the use of GR varieties.

Before these three sections, an overview of production and management factors (Chapter 2, p. 7) that are common to all three systems is provided. Management components and/or factors that affect soybean production in any system are presented here. This chapter contains the most detail because of the aforementioned fact that the majority of all soybean production systems employ these "conventional" inputs and practices, and their application and use are basically for the same purposes in all production systems.

Soybean Production in the United States

Soybean production in the United States has changed since the time of its initial introduction into the Corn Belt in the mid-1800s. Initially, the crop was produced mainly for forage and received only minimal inputs. Its husbandry evolved to become a grain crop that is a major source of both protein in animal diets and vegetable oil for human consumption.

Today, soybean production in the United States is a significant agricultural enterprise. From 2000 to 2008, soybean was grown on more than 72 million acres in 31 states (except 2007 with 63 million acres; USDA–NASS 2008a). Soybean production generally occupies approximately 22% of the roughly 340 million acres of harvested cropland in the United States (Lubowski et al. 2002), second only to corn. Thus, management of land cropped to soybean and production practices used in its production are significant components related to the impact and sustainability of overall U.S. agriculture.

Farm gate value[2] from soybean during the 2000 to 2008 period ranged from $12.6 billion in 2001 to $26.75 billion in 2007 (USDA–NASS 2008a). Annual exports typically are approximately one-half of total U.S. production (USDA–OCE 2008). The magnitude of this income and the importance derived from soybean trade are important factors in the overall U.S. agricultural economy.

The majority of U.S. soybean production is located in three distinct regions: the Midwest or Corn Belt, the midsouthern United States or lower Mississippi River Delta, and the Southeast or Atlantic coast (Heatherly 2007; USDA–NASS 2008b). Producers in these three regions manage and produce soybean differently because of soil and climate differences; however, the same basic inputs and practices (i.e., tillage, crop rotation, soil nutrient management, pest and weed control, etc.) are used in each region but in varying degrees.

The Midwest (generally above 37 deg. N latitude–Cairo, IL) is characterized by rolling terrain with deep topsoil, consistent summer rain, and moderate temperatures. Soybean generally is planted in May (USDA–NASS 2008c) because earlier plantings are at risk from frost injury. Virtually all the soybean is grown in *dryland production systems* in rotation with corn (*Zea mays* L.). Kansas and Nebraska in the western Corn Belt have significant irrigated soybean acreage (USDA-NASS 2008a), and a dryland rotation of soybean with grain sorghum (*Sorghum bicolor* [L.] Moench) is an important production system in that region. Average yield across representative Midwestern states for the 2002 to 2006 period was 44.0 bushels per acre (Heatherly 2007). The 2008 average yield across the same states was 43.1 bushels per acre (USDA–NASS 2008a). In 2008, 79% of the 75.9 million U.S. soybean acres were in the Midwest (USDA–NASS 2008a).

The midsouthern United States (generally below 37 deg. N latitude and west of Alabama) has both alluvial and upland soils, summer drought with high temperatures, and infrequent inundating rainfall events from late-summer tropical storms. A significant portion of the crop is planted in April (USDA–NASS 2008c). There is both significant irrigated acreage and significant acreage that is *doublecropped* with wheat (*Triticum aestivum* L.) (USDA–NASS 2008b). Planting is spread over a 2.5- to 3-month period (late March through mid-June), with maturity occurring over a same-length period (late July through mid-October). Average yield across representative midsouthern states for the 2002 to 2006 period was 35.6 bushels per acre (Heatherly 2007). The 2008 average yield across the same states was 36.6 bushels per acre (USDA–NASS 2008a).

The Southeast has sandy soils, summer drought and high temperatures, and sporadic inundating rainfall events from late-summer hurricanes. Virtually no soybean is planted before May (USDA–NASS 2008c), and only a low percentage of the acreage is irrigated. A large portion of the crop is doublecropped with a winter grain crop (USDA–NASS 2008b). Approximately half of the crop is planted after June 1, and maturity of all plantings occurs after mid-September. Average yield across representative southeastern states for the 2002 to 2006 period was 29.0 bushels per acre (Heatherly 2007). The 2008 average yield across the same states was 30.6 bushels per acre (USDA–NASS 2008a).

Egli (2008) analyzed soybean yield trends from 1972 to 2003 in four states: Iowa, Nebraska, Kentucky, and Arkansas. His findings are the following:

- harvested soybean acreage increased dramatically during the 32-year period;
- yields during the 32-year period increased in 79% of the analyzed areas;
- yield increases were concurrent with increased harvested acreage;
- permanent yield plateaus since 1972 were common in low-yield, high-stress environments;
- rate of yield increase was enhanced by irrigation in Nebraska and Arkansas;
- stagnant soybean yields and doublecropping were associated with each other;
- high-yield systems had the greatest increases in yield;
- irrigation could greatly increase yields in drier areas; and
- the challenge for the future of soybean production in the United States is not only to keep yields increasing in productive environments, but also

[2] Italicized terms (except genus and species names) are defined in the Glossaries at the end of sections and chapters.

to develop and apply technology to increase yields in high-stress, low-yield environments.

Glossary

Doublecrop. Growing two crops consecutively during a 12-month period.

Dryland production system. Growing a crop without supplemental water.

Farm gate value. Value of an agricultural crop when it leaves the farm, usually synonymous with the selling price of the product.

Literature Cited

Egli, D. B. 2008. Soybean yield trends from 1972 to 2003 in midwestern USA. *Field Crops Res* 106:53–59.

Feenstra, G., C. Ingels, and D. Campbell. 1997. What is sustainable agriculture? Sustainable agriculture research and education program, University of California, Davis, http://www.sarep.ucdavis.edu/Concept.htm

Gold, M. V. 2007a. Sustainable agriculture: Definitions and terms. Alternative Farming Systems Information Center. U.S. Department of Agriculture–National Agricultural Library, Washington, D.C., http://www.nal.usda.gov/afsic/pubs/terms/srb9902.shtml

Gold, M. V. 2008. Sustainable agriculture: Information access tools. Alternative Farming Systems Information Center. U.S. Department of Agriculture–National Agricultural Library, Washington, D.C., http://www.nal.usda.gov/afsic/pubs/agnic/susag.shtml

Heatherly, L. G. 2007. "Boosting soybean yields requires attention to local conditions." *Success Farming*, March 12, http://www.agriculture.com/ag/story.jhtml?storyid=/templatedata/ag/story/data/1173711714526.xml

Lubowski, R. N., M. Vesterby, S. Bucholtz, A. Baez, and M. J. Roberts. 2002. Major uses of land in the United States. EIB-14. U.S. Department of Agriculture–Economic Research Service, Washington, D.C., http://www.ers.usda.gov/publications/EIB14/eib14d.pdf

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008a. Quick stats: agricultural statistics data base. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/QuickStats/

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008b. Acreage. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-30-2008.pdf

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008c. National crop progress. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/Publications/National_Crop_Progress/index.asp

U.S. Department of Agriculture–Office of the Chief Economist (USDA–OCE). 2008. World agricultural supply and demand estimates. WASDE-463. USDA–OCE, Washington, D.C., http://www.usda.gov/oce/commodity/wasde/latest.pdf

2 Major Components in Soybean Production

Varieties, tillage, *cover crops*, *crop rotation*, soil nutrient management, pest and weed management, and drought and irrigation are management components or factors that affect or can be used to alter all soybean production environments in the United States. The tenets presented here for each component or factor generally will apply to all three of the aforementioned production systems. Therefore, these topics are discussed in this section without specificity to a particular production system because it is assumed that one or more of them will affect or will be applied or used to affect each system. Where any of these factors is managed in a specific way to alter or affect one of the three systems, further details will be presented in the individual chapters for each production system.

Breeding and Variety Development

Conventional breeding strategies have been very successful in improving soybean productivity and quality (Orf, Diers, and Boerma 2004). The majority of past breeding efforts in the United States were directed toward improving seed yield because of its importance in maintaining producer profits which in turn sustained the continuation of soybean production. In addition to yield, significant progress has been made in developing *germplasm* and varieties with resistance to pathogens and insects. Varietal improvements also have been made in seed quality traits such as protein and oil, and agronomic characteristics such as lodging resistance and canopy structure. Recent efforts in breeding have resulted in the development of transgenic varieties with resistance to nonselective herbicides. The availability of new conventional and molecular technologies, along with the availability of new technologies already in use, will result in a substantial increase in the rate of genetic gain in soybean production potential, resistance to pests, improvements in seed quality, and herbicide resistance.

The soybean germplasm collection maintained by the U.S. Department of Agriculture–Agricultural Research Service (USDA–ARS) at Urbana, Illinois, contains more than 20,000 accessions (second to China), and contains a large amount of the natural variation in the genus *Glycine* (Carter et al. 2004). As challenges in U.S. soybean production have arisen, variation within the soybean germplasm collection has been identified and used in the development of new varieties with traits that have provided genetic solutions to those challenges.

Additional variation in soybean has been induced using mutagensis when natural variation has not been identified in the germplasm. The advent of genetic transformation has provided another avenue for introducing variation in soybean to meet challenges that have arisen and will continue to arise. With the recent completion of the sequencing of the soybean genome, additional information is available to geneticists via the genome sequence to allow even further variation to be identified and introduced. With all these genetic materials and tools, soybean germplasm resources are available to address expected and unexpected future challenges.

Specialty traits or *value-added traits* that need to be segregated or *identity-preserved* (IP) have been incorporated into varieties grown for commercial production, and more are forthcoming (Table 2.1). In almost all cases, these varieties are grown under contract and a premium price is paid for their seed. The development of varieties with IP seed traits such as high oleic oil, high stearate oil, reduced raffinose and stachyose, and low phytate as well as the production of soybean with these traits are anticipated to enhance the sustainability of future soybean production, especially organic production, by increasing or enhancing the uses of soy products for human consumption and animal feed. The precise acreage devoted to these varieties in the United States is unknown due to the contractual nature of the production and the number of both small and large companies involved in IP soybean. The acreage devoted to these specialty varieties probably will not approach the acreage devoted to commodity soybean varieties in the near future, but premium prices will promote their use and aid

Table 2.1. Value-added traits in soybean and approximate year when seed were/will be available for commercial production (those past 2009 are projected[a])

Trait	Projected Advantages	Year
Large seed	Desirable for tofu/soy milk production	1960
Small seed	Desirable for natto/sprout production	1983
Lipoxygenase-free	Eliminates bitter taste	1995
Low saturated oil	Healthier oil with less saturated fat	1996
Enhanced sulfur amino acids	Dietary advantage	1999
Low-linolenic oil	Low saturated fat content; more stable oil; reduces need for hydrogenation; reduces/eliminates trans fats	2004
Mid-oleic oil	More stable oil, especially for frying	2007
High-oleic oil	More stable oil; reduces/eliminates rancidity of oil; higher monounsaturated and lower saturated fat in oil; no trans-fatty acids; increased industrial uses for oil	2009
High-stearate oil	Trans-free alternative that provides solid fat functionality that does not raise cholesterol; industrial uses; increased uses in prepared foods	>2011
Reduced raffinose and stachyose	More digestible carbohydrates in soybean meal; reduces flatulence	2011
Low phytate	More digestible phosphorus resulting in less excretion of phosphorus to surrounding environment	>2010
High isoflavones	Relief of menopausal symptoms in women and increased prostate health in men; reduces cholesterol; beneficial antioxidant	>2010
High omega-3 (steridonic acid)	Plant based source that enriches omega-3 levels in human tissues (heart health) and maintains food flavor quality and shelf life	2011
High-oleic/low-saturate/low-linolenic oil	More stable oil for use in frying and baking applications, low saturated fat; no trans fatty acids	>2011
High-oleic/low-saturate oil	Trans-free oil with low saturated fats for use in high stability heat applications providing foods with lower saturated fat content	>2011
Improved protein soybean	Better functionality in some foods (improved taste and solubility); health benefits	2011

[a]Information obtained from various company publications and announcements.

in sustaining those producers that grow value-added soybean varieties for specialty markets.

Section Summary

Conventional breeding strategies have been successful in developing soybean varieties with increased yield potential and resistance to pests. Recent breeding efforts have resulted in the development of transgenic varieties with resistance to nonselective herbicides. Forthcoming transgenic traits will impart resistance to both nonselective and selective herbicides. These transgenic varieties will continue to be the foundation of weed management strategies in the United States.

The U.S. soybean germplasm collection contains a large amount of variation in genetic material that can be screened for new traits and genes that can be used in the development of new varieties with improved yield and *host-plant resistance* traits. Value-added traits that have recently been incorporated into soybean varieties, plus forthcoming varieties with value-added traits, will improve soybean's marketability as a premier source of products for human and animal consumption, as well as enhance its production sustainability by increasing its usage beyond a commodity grain.

Glossary

Cover crop. A crop grown to provide soil cover during seasons when an annual grain crop is absent.

Crop rotation. The practice of growing two or more annual crops in a given field in a planned pattern or sequence in successive crop years.

Germplasm. A collection of diverse genetic resources (i.e., soybean seed) that is available to be used in the development of improved breeding lines and varieties.

Host-plant resistance. A genetically controlled innate or bred phenotypic or physiological property of a plant that enables it to withstand injury from insect feeding and pathogenic infection.

Identity preserved (**IP**). Identification and maintenance through marketing channels (usually through contract-growing for a higher or premium price) of seed with specific traits or characteristics that are sought or preferred by users.

Value-added trait. A quality trait or characteristic that increases the value of a crop product relative to its typical or commodity version and that requires a uniform and uncontaminated end product; in soybean, commonly referred to as specialty varieties with specific physical or chemical characteristics that are required for specific markets.

Literature Cited

Carter, T. E. Jr., R. L. Nelson, C. H. Sneller, and Z. Cui. 2004. Genetic diversity in soybean. Pp. 303–416. In J. Specht and R. Boerma (eds.). Soybean: *Improvement, Production, and Uses*. Agronomy Monograph, 3rd ed. American Society of Agronomy, Madison, Wisconsin.

Orf, J. H., B. W. Diers, and H. R. Boerma. 2004. Genetic improvement: Conventional and molecular-based strategies. Pp. 417–450. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*. Agronomy Monograph, 3rd ed. American Society of Agronomy, Madison, Wisconsin.

Table 2.2. Approximate amount of diesel fuel required for indicated tillage operations according to Iowa State University (ISU) and Colorado State University (CSU), and soybean residue remaining after use of each implement

	Diesel Fuel Use		
Tillage Operation	ISU[a]	CSU[b]	Residue[c]
	gallons per acre		%
Moldboard plow	1.70	1.68	0–5
Subsoiler/ripper	1.70	—	60–85
Chisel plow	1.10	1.10	40–60
Tandem disk	0.55	0.55	10–50
Field cultivate	0.65	0.60	30–75
Bedder/hipper	—	—	5–20
Planter-row crop	0.55	0.50	75–95
No-till planter	0.45	0.35	50–90
Rotary hoe	0.20	0.25	80–90
Sprayer	0.10	0.10	—
Cultivate-post plant	0.40	0.45	—

[a]Hanna 2001

[b]Downs and Hansen 2007

[c]McCarthy, Pfost, and Currence 1993

Tillage

Tillage in soybean production systems is used to prepare a seedbed, remedy soil compaction, incorporate fertilizers and herbicides, influence water movement both within and out of a production field, and control weeds. A *tillage system* is made up of operations that use a variety of implements to achieve a particular production environment and/or to remedy a defined problem that limits production potential. Hoeft and colleagues (2000) give a detailed narrative of tillage systems, as well as a pictorial description of tillage implements used in soybean production and how their use affects the production environment.

Implements used to accomplish varied tillage goals differ in the fuel requirements for their use and operation (Rathke et al. 2007; Table 2.2). Use of different tillage implements also results in different amounts of soybean plant residue left on the soil surface after their use (USDA–NRCS 2000; Table 2.2). Thus, tillage implements directly affect the agronomic environment for soybean production and, consequently, its economic potential.

Overview of Tillage Systems

For purposes of this publication, tillage definitions will be based on the effect of a particular tillage operation on soil loss, fuel consumption, and water runoff because these are three major components related to the impact of tillage on the economic and environmental sustainability of soybean production.

Conventional Tillage System

A *conventional tillage system* is synonymous with clean tillage. Operations involve primary tillage with moldboard plows, heavy disks, and chisel plows. These operations are followed by one or more secondary tillage operations with a tandem disk harrow or field cultivator. Essentially no previous crop plant residue remains on the soil surface (McCarthy, Pfost, and Currence 1993). All the soil is disturbed and exposed to maximal water runoff and *erosion* (Table 2.3). The total energy input and cost for conventional tillage systems is the highest among all systems (Table 2.4). In 2002, an estimated 17% of U.S. soybean acres were grown using conventional methods (USDA–ERS 2002a).

Reduced Tillage System

Reduced tillage system operations are conducted with secondary tillage implements (no moldboard or deep plow) that require less fuel than primary tillage

Table 2.3. Measured surface cover and soil loss for various tillage systems used for corn and soybean production in Kansas and Nebraska (Heatherly and Elmore 2004)

Residue Type/Tillage System	Residue Cover	Erosion	Erosion Reduction Relative to Moldboard Plow
	%	ton/acre	%
		Corn Residue[a]	
Moldboard plow, disk 2X, plant	7	7.8	—
Chisel plow, disk, plant	35	2.1	74
Disk 2X, plant	21	2.2	72
Rotary-till, plant	27	1.9	76
Till-plant	34	1.1	86
No-till, plant	39	0.7	92
		Soybean Residue[b]	
Moldboard plow, disk 2X, plant	2	14.3	—
Disk 2X, plant	5	14.3	0
Chisel plow, disk, plant	7	9.6	32
Disk, plant	9	10.6	26
Field cultivate, plant	18	7.6	46
No-till, plant	27	5.1	64

[a]After tillage and planting on a silt loam soil having a 10% slope and 2 in. water applied in 45 min.

[b]After tillage and planting on a silty clay loam soil having 5% slope and 2 in. water applied in 45 min.

implements (Table 2.2) and leave 15 to 30% of the soil covered with crop plant residue. This system can be termed a hybrid of the previously described conventional tillage system and the following conservation tillage system. It is the most flexible of the three systems in that limited tillage is used as needed to remedy an identified problem associated with continuous cropping of a site. An example of a reduced tillage system is the *stale seedbed planting system* used for soybean production in the midsouthern United States (Heatherly 1999a). Using a reduced tillage system increases dependence on both pre- and post-planting chemical weed control, but it does decrease erosion (Ditsch and Murdock 1987; Table 2.3) and fuel use (Tables 2.2, 2.4). In 2002, an estimated 18% of U.S. soybean acres were grown with a reduced tillage system (USDA–ERS 2002a).

Conservation Tillage System

Conservation tillage systems include those commonly referred to as mulch-till, strip-till, ridge-till, and no-till. Definitions of these sometimes difficult-to-distinguish systems provide the nuances for their delineation (USDA–ERS 2007a; USDA–NRCS 2000).

Table 2.4. Estimated fuel use (FU) in gallons per 10 acres and fuel cost (FC) in dollars per 10 acres for various tillage systems used for soybean production, and potential cost savings (CS) over conventional tillage in dollars per 10 acres in six USDA–NRCS crop management zones that produce soybean. Diesel cost for this energy estimate is $4.50/gallon (all estimates[a] will change slightly with increasing acreage) (USDA–NRCS 2008)

	Conventional		Mulch-till			Strip-till			Ridge-till			No-till		
Region	FU	FC	FU	FC	CS	FU	FC	CS	FU	FC	CS	FU	FC	CS
Lower Delta	31	140	28	126	14	—	—	—	—	—	—	21	94	46
Upper Delta	49	220	41	184	36	—	—	—	—	—	—	21	94	126
Piedmont	56	252	47	212	40	—	—	—	—	—	—	19	86	166
Atlantic Coast	75	338	70	315	22	55	248	90	—	—	—	37	166	171
Lower Corn Belt	49	220	41	184	36	—	—	—	33	148	72	19	86	135
Upper Corn Belt	49	220	31	140	81	—	—	—	33	148	72	19	86	135

[a]Different acreage and fuel cost assignments can be made to obtain results for a specific situation.

Fertilizer application and planting are done in narrow strips, with minimal soil disturbance outside the application and planting zone. The U.S. Department of Agriculture–Natural Resources Conservation Service (NRCS) (2000) standard for qualification of a conservation tillage system is more than 30% coverage of the soil with plant residue at any given time.

Plant residue cover is credited as the major factor for decreasing soil loss with conservation tillage. Erosion can be decreased by as much as 50% if 30% of the soil surface (compared with bare soil) is covered with residue (McCarthy, Pfost, and Currence 1993). Fuel consumption and cost are minimal (Table 2.4). In 2002, 64% of U.S. soybean acres were grown using a conservation tillage system (USDA–ERS 2002a). Conservation tillage is recognized as one of the most important developments that has positively impacted crop production agriculture (Crookston 2006).

A strict no-till system may be the hardest to maintain on a continuing basis. Results from Minnesota research (Randall and Vetsch 2005a; Vetsch, Randall, and Lamb 2007) indicate that to maintain yield potential some form of rotational full-width tillage (even shallow row cultivation) may be needed to disrupt surface soil consolidation and/or disturb surface residues that accumulate in a continuous no-till soybean–corn rotation. This occasional tillage does not compromise the long-term goals of a no-till system to reduce soil erosion and water runoff, nor does it release any significant amounts of carbon from the topsoil.

Conservation tillage frequently is used with a narrow row spacing that better shades between-row areas and precludes postplanting cultivation of the field. This practice places total dependence on herbicides for both pre- and postplant weed management; however, the fuel requirement for spraying herbicides is low (Rathke et al. 2007; Table 2.2) and the energy input from their use is proportionately small because of low application rates (Rathke et al. 2007). Using a conservation tillage system results in soil and water conservation, decreased fuel consumption and fuel costs (Tables 2.2, 2.3, 2.4), and a lower total energy input (Rathke et al. 2007).

Deep Tillage

Deep tillage (sometimes termed “subsoiling” or “deep ripping”) refers to primary tillage operations that affect soil deeper than about 10 inches. These operations are used to fracture or loosen deep soil barriers, improve rainfall infiltration, and mix residue and nutrients deep into the soil profile. Deep tillage can be part of a conservation tillage system if it minimally disturbs the soil surface and leaves more than 30% of the soil covered by residue. The fuel requirement for deep tillage is high (essentially the same as for moldboard plowing; Table 2.2), so it should be incorporated into a conservation tillage system only to remedy subsurface soil problems. In some problematic soil environments, deep tillage results in increased yields (Frederick et al. 1998; Popp et al. 2001; Wesley, Elmore, and Spurlock 2001; Table 2.5) and net returns (Wesley, Elmore, and Spurlock 2001). The economic return of yield increases, however, must be balanced against the cost of the operation because high equipment and fuel costs will affect profitability.

Table 2.5. Yield (bu/acre) of soybean grown in numerous tillage studies in the southern United States (Heatherly and Elmore 2004)

State	Soil Series/Texture	Tillage Treatment[a]	Yield
Arkansas	Sharkey clay[b]	Conventional	40.4
		DT	48.1
Mississippi	Tunica silty clay[b]	Conventional	36.2
		DT	51.3
Mississippi	Sharkey clay[b]	Conventional	27.7
		DT	33.1
Mississippi	Sharkey clay[b]	Conventional	30.5
		DT	36.7
	Sharkey clay[c]	Conventional	24.6
		DT	26.6
Mississippi	Tunica silty clay[b]	Conventional	29.8
		DT	47.1
South Carolina	Eunola loamy sand[c]	No-till	32.1
		DT	35.9

[a]Conventional = shallow tillage (< 6 in.) with chisel plow, disk harrow, or spring-tooth cultivator; DT = deep-tilled to 15 to 18 in. depth.

[b]April-planted.

[c]May and later-planted (South Carolina study followed wheat harvest).

Fuel Use and Cost

A tillage system that minimizes use of nonrenewable fuel resources and associated costs while concurrently maintaining or enhancing productivity will be the most sustainable. An online calculator for estimating fuel consumption and cost for various tillage systems is available on the USDA–NRCS website (USDA–NRCS 2008).

Based on the NRCS calculator, estimates of fuel use, costs, and savings associated with using different tillage systems in six USDA–NRCS crop management soybean-producing zones are shown in Table

2.4. As expected, a conventional tillage system for soybean production results in the greatest use of fuel and therefore the highest fuel cost. A no-till system results in at least a one-third decrease in fuel use and dollars spent for fuel. In five of the six indicated zones (Table 2.4), decreases in fuel use and dollars spent for fuel were 50% or more. Mulch-till, strip-till, and ridge-till decreased fuel use and cost below that for conventional tillage, but not as much as for the no-till system. This fuel cost savings may be offset somewhat by higher herbicide costs in conservation tillage systems (Yiridoe et al. 2000).

Tillage, Erosion, and Soil Loss

It is recognized that soil erosion in excess of soil production will lead to decreased agricultural potential (Montgomery 2007). Implementation of a no-till crop production system decreases water runoff and soil erosion (Rhoton, Shipitalo, and Lindbo 2002) by leaving increased amounts of plant residue on the soil surface. The decrease in soil loss can be dramatic (Tables 2.3, 2.6).

Soybean residue is fragile, and even light tillage, especially in the fall, can break up a large amount of the soybean residue after harvest (USDA–NRCS 2000). A no-till system for soybean may be the only one that meets the standard of 30% surface residue cover required for a conservation tillage system (USDA—NRCS 2000; Table 2.3). This result is depicted in excellent graphic fashion by the USDA–NRCS (2000) reference.

Table 2.6. Annual soil loss from plots with 5% slope in the brown loam soil region of Mississippi (Heatherly and Elmore 2004)

	Conventional Tillage Soil Loss/Year		No-till Soil Loss/Year	
Crop	C Factor[a]	Ton/Acre	C Factor[a]	Ton/Acre
Sorghum	0.04	4.2	0.005	0.6
Corn (grain)	0.09	7.2	0.005	0.4
Corn (silage)	0.14	11.2	0.003	0.3
Soybean	0.12	21.1	0.006	1.2
Soybean	0.10	19.6	0.008	1.4
Cotton	0.31	31.2	0.053	5.4

[a]Factor used in the Universal Soil Loss Equation to reflect influence of soil management and cropping methods on water erosion. Kind and time of tillage, implements used, time of planting, crops planted, postemergence cultivation, crop sequence, residue cover on the soil surface, and changes in soil organic matter all affect *C factor.*

Tillage and Yield

DeFelice, Carter, and Mitchell (2006) conducted an extensive review of the effect of tillage on soybean yields in the United States and found that (1) the national average difference in yield between no-tillage and conventional tillage soybean is small, and (2) no-till yields improve over time with continuous no-till. They concluded that soybean producers in most of the United States will not suffer a yield disadvantage when switching to a conservation tillage-based production system. Results from other research conducted in Texas, Kansas, and the Corn Belt support this conclusion (Franzluebbers, Hons, and Saladino 1995; Kelley and Sweeney 2008; Randall and Vetsch 2005a; Randall et al. 2002; Vetsch, Randall, and Lamb 2007).

Section Summary

Increased yields coupled with decreases in erosion and water runoff and lower fuel use and fuel cost strongly support the premise that soybean produced with conservation tillage in any production system is more economically and environmentally sustainable. In fact, considering the generally accepted 30% minimum residue cover and the 3 to 5 tons/acre/year tolerable soil loss for a sustainable soybean production system, conservation tillage is the only system that seems to support sustainable soybean production from an environmental standpoint. A recent summary of global soil erosion by Montgomery (2007) supports the conclusion that conservation tillage systems used to produce soybean in the United States can provide a foundation for sustainable soybean production.

Glossary

C factor. Cover management factor used in the Revised Universal Soil Loss Equation that reflects the effect of cropping and management practices on erosion rates.

Conservation tillage system. Limited mechanical operations with implements that result in the soil surface being covered with >30% plant residue.

Conventional tillage system. A combination of mechanical operations with implements that effectively results in a seedbed free of weeds and plant residue cover.

Deep tillage. Mechanical operations with implements that affect soil properties below 10 inches.

Erosion. Undesirable displacement of soil from a site by wind and/or water.

Plant residue cover. Plant material remaining on the soil surface after crop harvest.

Reduced tillage system. Limited mechanical operations with implements that result in the soil surface being covered with 15 to 30% plant residue.

Stale seedbed planting system. A seedbed that has received no seedbed preparation tillage just before planting. It may or may not have been tilled since harvest of the preceding crop. Any tillage conducted in the fall, winter, or early spring will have occurred sufficiently ahead of planting time to allow the seedbed to settle or become stale. A crop is planted in this unprepared seedbed, and weeds present before or at planting are killed with herbicides. This system does not preclude tillage because it is a minimum or reduced tillage concept rather than a no-till concept.

Tillage system. A combination of mechanical operations with implements that alter the soil environment to affect crop production.

Literature Cited

Crookston, R. K. 2006. A top 10 list of developments and issues impacting crop management and ecology during the past 50 years. *Crop Sci* 46:2253–2262.

DeFelice, M. S., P. R. Carter, and S. B. Mitchell. 2006. Influence of tillage on corn and soybean yield in the United States and Canada. *Crop Mgmt* 26 June, http://www.plantmanagementnetwork.org/sub/cm/research/2006/tillage/CornSoybean.pdf (online only; limited access)

Ditsch, D. C. and L. W. Murdock. 1987. Soil erodibility: How is it determined and used. AGR-125. University of Kentucky Cooperative Extension Service, Lexington, http://www.ca.uky.edu/agc/pubs/agr/agr125/agr125.htm

Downs, H. W. and R. W. Hansen. 2007. Estimating farm fuel requirements. Pub. No. 5.006. Colorado State University Extension, Fort Collins, http://www.ext2.colostate.edu/pubs/farmmgt/05006.html

Franzluebbers, A. J., F. M. Hons, and V. A. Saladino. 1995. Sorghum, wheat, and soybean production as affected by long-term tillage, crop sequence, and N fertilization. *Plant and Soil* 173:55–65.

Frederick, J. R., P. J. Bauer, W. J. Busscher, and G. S. McCutcheon. 1998. Tillage management for doublecropped soybean grown in narrow and wide row width culture. *Crop Sci* 38:755–762.

Hanna, M. 2001. Fuel required for field operations. PM 709. Iowa State University Extension, Ames, http://www.extension.iastate.edu/Publications/PM709.pdf

Heatherly, L. G. 1999a. The stale seedbed planting system. Pp. 93–102. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Heatherly, L. G. and R. W. Elmore. 2004. Managing inputs for peak production. Pp. 451–536. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*. Agronomy Monograph, 3rd ed. American Society of Agronomy, Madison, Wisconsin.

Hoeft, R. G., E. D. Nafziger, R. R. Johnson, and S. R. Aldrich. 2000. *Modern Corn and Soybean Production*. 1st ed. MCSP Publications, Savoy, Illinois. 353 pp.

Kelley, K. W. and D. W. Sweeney. 2008. Influence of tillage, row spacing-population system, and glyphosate herbicide timing on soybean production in the eastern Great Plains. *Crop Mgmt* 14 November, http://www.plantmanagementnetwork.org/sub/cm/research/2008/production/ (online only; limited access)

McCarthy, J. R., D. L. Pfost, and H. D. Currence. 1993. Conservation tillage and residue management to reduce soil erosion. Pub. G1650. University of Missouri Extension, Columbia.

Montgomery, D. R. 2007. Soil erosion and agricultural sustainability. *Proc Nat Acad Sci* 14:13268–13272, http://www.pnas.org/content/104/33/13268.full.pdf

Popp, M. P., T. C. Keisling, C. R. Dillon, and P. M. Manning. 2001. Economic and agronomic assessment of deep tillage in soybean production on Mississippi River valley soils. *Agron J* 93:164–169.

Randall, G. W. and J. Vetsch. 2005a. Optimum tillage systems for corn and soybean production and water quality protection in south central Minnesota–Minnesota River Basin. BU-08315. University of Minnesota, St. Paul, http://www.extension.umn.edu/distribution/cropsystems/DC8315.html

Randall, G. W., T. L. Wagar, N. B. Senjem, L. M. Busman, and J. F. Moncrief. 2002. Tillage best management practices for water quality protection in southeastern Minnesota. WW-07694. University of Minnesota Extension, St. Paul, http://www.extension.umn.edu/distribution/cropsystems/DC7694.html

Rathke, G. W., B. J. Wienhold, W. W. Wilhelm, and W. Diepenbrock. 2007. Tillage and rotation effect on corn–soybean energy balances in eastern Nebraska. *Soil Tillage Res* 97:60–70.

Rhoton, F. E., M. J. Shipitalo, and D. L. Lindbo. 2002. Runoff and soil loss from midwestern and southeasthern U.S. silt loam soils as affected by tillage practice and soil organic matter content. *Soil Tillage Res* 66:1–11.

U.S. Department of Agriculture–Economics Research Service (USDA–ERS). 2002a. Crop residue management practices, for soybeans, by tillage system, for all available states, for 2002. USDA–ERS, Washington, D.C., http://www.ers.usda.gov/Data/ARMS/app/Crop.aspx

U.S. Department of Agriculture–Economics Research Service (USDA–ERS). 2007a. Agricultural chemicals and production technology: Glossary–crop residue management and tillage definitions. USDA–ERS, Washington, D.C., http://www.ers.usda.gov/Briefing/AgChemicals/glossary.htm

U.S. Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS). 2000. Residue management choices: A guide to managing crop residues in corn and soybeans. GWQ029. USDA–NRCS and University of Wisconsin Extension, Madison, http://clean-water.uwex.edu/pubs/pdf/farm.hiresid.pdf

U.S. Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS). 2008. Energy Estimator for Tillage. USDA–NRCS, Washington, D.C., http://ecat.sc.egov.usda.gov/Fuel.aspx

Vetsch, J. A., G. W. Randall, and J. A. Lamb. 2007. Corn and soybean production as affected by tillage system. *Agron J* 99:952–959.

Wesley, R. A., C. D. Elmore, and S. R. Spurlock. 2001. Deep tillage and crop rotation effects on cotton, soybean, and grain sorghum on clayey soils. *Agron J* 93:170–178.

Yiridoe, E. K., T. J. Vyn, A. Weersink, D. C. Hooker, and C. Swanton. 2000. Farm-level profitability analysis of alternative tillage systems on clay soils. *Can J Plant Sci* 80:65–73.

Cover Crops

Cover crops are grown to conserve environmental quality and enhance soil productivity (Clark 2007), and should be considered for inclusion as a component of a cropping system that seeks to be sustainable (Sullivan 2003). Integrating cover crops into a crop production system should be considered a long-term investment for conserving and/or improving soil and water resources. The benefits come from

- providing soil cover to prevent erosion (Hively and Cox 2001; Kessavalou and Walters 1997; Langdale et al. 1991; Ruffo, Bullock, and Bollero 2004);
- increasing water infiltration into the soil and soil organic matter (Villamil et al. 2006);
- decreasing nutrient loss and leaching from the soil profile and/or lowering residual soil nitrogen (Dinnes et al 2002; Kaspar et al. 2007, 2008; Kessavalou and Walters 1997, 1999; Ruffo, Bullock, and Bollero 2004; Strock, Porter, and Russelle 2004);
- decreasing herbicide runoff in a corn–soybean rotation (Shipitalo, Edwards, and Owens 1997);
- suppressing or decreasing early-season weeds and weed biomass (Moore, Gillespie, and Swanton 1994; Reddy 2003);
- and, for legumes, increasing nitrogen supply for the following summer grain crop (Clark 2007; Decker et al. 1994).

A cover crop can consist of annual weeds, a single crop species, or a mixture of crop species. Planted cover crops are seeded before harvest (overseeding or interseeding) or immediately after harvest of a summer crop. Cover crops usually are destroyed by tillage or herbicides before planting of a following summer row crop with no short-term economic gain from their use; that is, they are not grazed by livestock or harvested for a saleable product (Singer 2008).

Cover Crops in Soybean Production Systems

In the Corn Belt, cover crop use between grain crops (assumed to be predominantly corn, soybean, or grain sorghum) is only approximately 10%; winter wheat, cereal rye (*Secale cereale* L.), and oat (*Avena sativa* L.) are the species most used (Singer 2008; Singer, Kaspar, and Pedersen 2005). A cover crop of cereal rye planted after soybean harvest in Nebraska resulted in as much postplanting plant residue cover as a crop of corn (Kessavalou and Waters 1997). Cover crops have suppressed early-season weeds for the first 3 to 5 weeks after soybean planting (Williams, Mortensen, and Doran 1998). Efficacy of other integrated weed management tactics possibly is enhanced when used in conjunction with cover crops (Williams, Mortensen, and Doran 1998). Cover crops planted in the fall and killed with herbicides before soybean planting the following spring favored soybean emergence and growth over that of weeds (Williams, Mortensen, and Doran 1998). Winter cover crops offer the potential to overcome weed problems that otherwise may be unmanageable in the winter and spring (Reddy, Heatherly, and Blaine 1999). An established grass cover crop following corn in a soybean–corn rotation in the Midwest reduces nitrate N loss through subsurface tile-drainage discharge (Kaspar et al. 2007; Kladivko et al. 2004; Strock, Porter, and Russelle 2004).

In the southern United States, using volunteer winter weeds as a cover crop in the stale seedbed system has merit (Heatherly 1999a). There is no expense associated with their establishment and they can be killed in the spring with preplant, foliar-applied herbicides. Winter weeds serve as poor hosts for soybean cyst nematode (*Heterodera glycines* L.) in midsouthern fields (Donald, Hayes, and Walker 2007). Successful use of winter weeds as cover crops may depend on the amount and time of fall tillage, because some winter annual species emerge in late summer/early fall and tillage after this time may jeopardize volunteer stands of weeds. Label restrictions on the latest date for late winter/early spring aerial application of some preplant, foliar-applied herbicides may decrease the value of winter weeds as cover crops if they must be killed too far ahead of planting soybean.

A cover crop may have some disadvantages in a soybean or soybean–corn production system. Interseeding some cover crop species before harvest can result in the production of more dry matter in the fall than for those planted after harvest (Johnson et al. 1998), but may interfere with soybean harvest (Hively and Cox 2001). If a grass or cereal cover crop is used, a higher rate of nitrogen (N) fertilizer may be required for a following corn crop. If a legume cover crop is used, the decreased N requirement (and thus lower N fertilizer expense) for corn following the legume cover crop must be weighed against the higher estimated cost for the legume cover crop compared with that for a cereal cover crop (Table 2.7). In drier areas, allowing the cover crop to grow too long in the spring can deplete soil moisture that will be needed for the summer crop's germination and emergence (Varvel 1995).

In the Midwest, Karlen and Doran (1991) found that a winter cover crop resulted in a 10% lower corn yield, which they attributed to the depletion of soil nitrate levels by cover crop decomposition that was not overcome by postemergence broadcast application of N. Cover crops can impede soil warming in the spring (Hoeft et al. 2000), thus delaying planting of the sum-

Table 2.7. Estimated costs associated with using indicated cover crops following soybean[a]

Operation/Input	Cover Crop			
	Legume	Wheat	Cereal Rye	
	$/acre			
Tandem disking—once	9.20	9.20	9.20	No-till
Seeding	4.76	4.76	4.76	11.40
Seed (lb/acre planted)	50.00 (25 lb)	16.20 (90 lb)	22.50 (90 lb)	11.00 (60 lb)
Inoculant	2.00	—	—	—
Glyphosate—1 qt/acre + application	10.57	10.57	10.57	6.70
Miscellaneous	4.07	1.72	2.14	3.30
Total	80.60	42.45	49.17	36.40

[a]Entries in first three columns are calculated using Mississippi State Budget Generator (Laughlin and Spurlock 2007) and are estimated costs for representative inputs that include tillage before seeding bagged seed with a spin spreader. Entries in last column are estimates for Iowa (Kaspar, T. 2009. Personal communication) and include no-till seeding of bulk cereal rye seed.

mer crop. Abnormally heavy cover crop residues can interfere with soybean or corn seed placement and decrease crop plant densities (Williams, Mortensen, and Doran 1998). Cover crop growth and development is slow due to the shorter and cooler growing season (Dinnes et al. 2002; Strock, Porter, and Russelle 2004), and thus may provide inadequate cover to protect soil from erosion and/or mitigate nutrient leaching and loss.

Cover Crops and Yields

The preponderance of research results leaves little doubt that using cover crops in a soybean system does not result in increased yield of either soybean or corn (De Bruin, Porter, and Jordan 2005; Hively and Cox 2001; Johnson et al. 1998; Moore, Gillespie, and Swanton 1994; Reddy 2001, 2003; Singer and Kohler 2005; Thelen and Leep 2002). Thus, net returns are lower (De Bruin, Porter, and Jordan 2005; Heatherly 1999a; Reddy 2001, 2003) when cover crops are part of a soybean production system because their use results in an added expense (Table 2.7) with no increased return. This, then, leads to the conclusion that using cover crops is an environmentally sustainable practice, but is not an economically sustainable one in nonorganic soybean production systems.

Strategies for Cover Crop Use in Soybean

The negative economic impact from using cover crops may be mitigated in several ways. Put another way, cover crop use in a soybean production system will more nearly approach economic sustainability if significant portions of the expense for their use can be offset in some way.

- First, allowing volunteer winter weeds to become established as a cover crop after harvest of a summer crop is practical in the midsouthern United States and is an integral part of the stale seedbed system used there (Heatherly 1999a). This practice will have to be combined with no- or limited fall tillage to ensure the maintenance of the weed cover that may emerge before soybean harvest.
- Second, a government program of incentive payments could be used to encourage growing cover crops to achieve the environmental benefits they can provide. This practice was suggested by De Bruin, Porter, and Jordan (2005) and is exemplified by the state of Maryland's efforts to protect the Chesapeake Bay (Maryland 2008).
- Third, growing a cover crop species that is winter-killed will negate the expense for killing it before planting the summer crop (Johnson et al. 1998).
- Fourth, adopting a system that perpetuates a winter cereal cover crop through self-seeding shows promise in the upper Midwest (McDonald, Singer, and Wiedenhoeft 2008; Singer, Kohler, and McDonald 2007).
- Fifth, using the winter cover crop for a harvestable product such as forage (hay or grazing) (Thelen and Leep 2002) or grain (doublecropping) (Wesley 1999) can provide income to offset

the cost of cover crop establishment. These income-generating practices may affect the yield of the following soybean crop; thus, returns to the total system must be used to evaluate the economic effect of the cover crop that is used for forage or grain.

Section Summary

Including cover crops in a soybean production system lowers short-term profitability, thus discouraging their use. But, cover crops provide positive environmental benefits when used in a soybean or soybean–corn production system. Developments needed to encourage cover crop usage in soybean systems to overcome the above-mentioned financial obstacle are to (1) identify technologies that will lower the costs associated with cover crop establishment and culture, (2) use environmental benefits to support providing financial incentives to producers to integrate cover crops into soybean production systems, (3) identify cover crops that can be used to generate income without detracting from their benefits or from yield of the following summer crop, and (4) identify crop species and/or crop varieties that will be self-seeding and/or winter-hardy.

Literature Cited

Clark, A. (ed.). 2007. *Managing Cover Crops Profitably*. 3rd ed. Handbook Series Book 9. Sustainable Agriculture Research and Education (SARE), USDA–CSREES, Beltsville, Maryland, http://www.sare.org/publications/covercrops/covercrops.pdf

De Bruin, J. L., P. M. Porter, and N. R. Jordan. 2005. Use of rye cover crop following corn in rotation with soybean in the upper Midwest. *Agron J* 97:587–598.

Decker, A. M., A. J. Clark, J. J. Meisinger, F. D. Mulford, and M. S. McIntosh. 1994. Legume cover crop contributions to no-tillage corn production. *Agron J* 86:126–135.

Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agron J* 94:153–171.

Donald, P. A., R. Hayes, and E. Walker. 2007. Potential for soybean cyst nematode reproduction on winter weeds and cover crops in Tennessee. *Plant Health Progress* 26 Feb, http://www.plantmanagementnetwork.org/pub/php/research/2007/scn/ (online only; limited access)

Heatherly, L. G. 1999a. The stale seedbed planting system. Pp. 93–102. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Hively, W. D. and W. J. Cox. 2001. Interseeding cover crops into soybean and subsequent corn yields. *Agron J* 93:308–313.

Hoeft, R. G., E. D. Nafziger, R. R. Johnson, and S. R. Aldrich. 2000. *Modern Corn and Soybean Production*. 1st ed. MCSP Publications, Savoy, Illinois.

Johnson, T. J., T. C. Kaspar, K. A. Kohler, S. J. Corak, and S. D. Logsdon. 1998. Oat and rye overseeded into soybean as fall cover crops in the upper Midwest. *J Soil Water Cons* 53:276–279.

Karlen, D. L. and J. W. Doran. 1991. Cover crop management effects on soybean and corn growth and nitrogen dynamics in an on-farm study. *Amer J Sustain Ag* 6:71–82.

Kaspar, T. C., D. B. Jaynes, T. B. Parkin, and T. B. Moorman. 2007. Rye cover crop and gamagrass strip effects on NO3 concentration and load in tile drainage. *J Environ Qual* 36:1503–1511.

Kaspar, T. C., E. J. Kladivko, J. W. Singer, S. Morse, and D. Mutch. 2008. Potential and limitations of cover crops, living mulches, and perennials to reduce nutrient losses to water sources from agricultural fields in the upper Mississippi basin. Pp. 129–148. In *Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop*, Ames, Iowa, 26–28 September 2005. ASABE, St. Joseph, Michigan.

Kessavalou, A. and D. T. Walters. 1997. Winter rye as a cover crop following soybean under conservation tillage. *Agron J* 89:68–74.

Kessavalou, A. and D. T. Walters. 1999. Winter rye cover crop following soybean under conservation tillage: Residual soil nitrate. *Agron J* 91:643–649.

Kladivko, E. J., J. R. Frankenberger, D. B. Jaynes, D. W. Meek, B. J. Jenkinson, and N. R. Fausey. 2004. Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system. *J Environ Qual* 33:1803–1813.

Langdale, G. W., R. L. Blevins, D. L. Karlen, D. K. McCool, M. A. Nearing, E. L. Skidmore, A. W. Thomas, D. D. Tyler, and J. R. Williams. 1991. Cover crop effects on soil erosion by wind and water. Pp. 15–22. In W.L. Hargrove (ed.). *Cover Crops for Clean Water*. Soil and Water Conservation Society, Ankeny, Iowa.

Laughlin, D. H. and S. R. Spurlock. 2007. User's guide for the Mississippi State Budget Generator, Version 6.0 for Windows. Department of Agricultural Economics, Mississippi State University, http://www.agecon.msstate.edu/laughlin/msbg/userguide6.pdf

Maryland Department of Agriculture. 2008. Maryland's Winter Cover Crop Program, http://www.mda.state.md.us/resource_conservation/financial_assistance/cover_crop/index.php

McDonald, P. B., J. W. Singer, and M. H. Wiedenhoeft. 2008. Establishment and growth of self-seeded winter cereal cover crops in a soybean-corn rotation. *Agron J* 100:432–439.

Moore, M. J., T. J. Gillespie, and C. J. Swanton. 1994. Effect of cover crop mulches on weed emergence, weed biomass, and soybean development. *Weed Technol* 8:512–518.

Reddy, K. N. 2001. Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean. *Weed Technol* 15:660–668.

Reddy, K. N. 2003. Impact of rye cover crop and herbicides on weeds, yield, and net return in narrow-row transgenic and conventional soybean. *Weed Technol* 17:28–35.

Reddy, K. N., L. G. Heatherly, and A. Blaine. 1999. Weed management. Pp. 171–195. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Ruffo, M. L., D. G. Bullock, and G. A. Bollero. 2004. Soybean yield as affected by biomass and nitrogen uptake of cereal rye in winter cover crop rotations. *Agron J* 96:800–805.

Shipitalo, M. J., W. M. Edwards, and L. B. Owens. 1997. Herbicide losses in runoff from conservation-tilled watersheds in a corn–soybean rotation. *Soil Sci Am J* 61:267–272.

Singer, J. W. 2008. Corn belt assessment of cover crop management and preferences. *Agron J* 100:1670–1672.

Singer, J. W. and K. A. Kohler. 2005. Rye cover crop management affects grain yield in a soybean–corn rotation. *Crop Mgmt* 24 Feb, http://www.plantmanagementnetwork.org/pub/cm/research/2005/rye/ (online only; limited access)

Singer, J., T. Kaspar, and P. Pedersen. 2005. Small grain cover crops for corn and soybean. PM 1999. Iowa State University Extension, Ames, http://www.extension.iastate.edu/Publications/PM1999.pdf

Singer, J. W., K. A. Kohler, and P. B. McDonald. 2007. Self-seeding winter cereal cover crops in soybean. *Agron J* 99:73–79.

Strock, J. S., P. M. Porter, and M. P. Russelle. 2004. Cover cropping to reduce nitrate loss through subsurface drainage in the northern U.S. Corn Belt. *J Environ Qual* 33:1010–1016.

Sullivan, P. 2003. Overview of cover crops and green manures. Appropriate Technology Transfer for Rural Areas–National Center for Appropriate Technology (ATTRA–NCAT), Fayetteville, Arkansas, http://www.attra.ncat.org/attra-pub/PDF/covercrop.pdf

Thelen, K. D. and R. H. Leep. 2002. Integrating a double-cropped winter annual forage into a corn–soybean rotation. *Crop Mgmt* 18 Dec, http://www.plantmanagementnetwork.org/pub/cm/research/winterforage/ (online only; limited access)

Varvel, G. E. 1995. Precipitation use efficiency of soybean and grain sorghum in monoculture and rotation. *Soil Sci Soc Am J* 59:527–531.

Villamil, M. B., G. A. Bollero, R. G. Darmody, F. W. Simmons, and D. G. Bullock. 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. *Agron J* 70:1936–1944.

Wesley, R. A. 1999. Double cropping wheat and soybeans. Pp. 143–156. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Williams, M. M. II, D. A. Mortensen, and J. W. Doran. 1998. Assessment of weed and crop fitness in cover crop residues for integrated weed management. *Weed Sci* 46:595–603.

Crop Rotation

Crop rotation is the growing of two or more crop species in a given field in some consecutive order. In the United States, soybean is commonly rotated with corn, wheat, rice (*Oryza sativa* L.), or grain sorghum. The benefits of growing soybean in rotation rather than continuously include

- higher yields of one or both crops,
- decreased need for nitrogen (N) fertilizer on the crop following soybean,
- increased plant residue cover,
- mitigation of pest and weed cycles, and
- improved economic potential.

In the Corn Belt, the majority of soybean is rotated biennially with corn (Wiebold and Belt 2006). This rotation does not always give maximum soybean yields compared with other rotations or rotation sequences with soybean (Mallarino, Ortiz-Torres, and Rueber 2006; Porter et al. 1997); however, it does provide the greatest economic benefit (Porter et al. 1997). In the western Corn Belt, grain sorghum is commonly rotated with soybean (Wortmann, Mamo, and Dobermann 2007) because its production costs are lower than those for corn (Staggenborg, Dhuyvetter, and Gordon 2008). Furthermore, corn is less able than sorghum to withstand low moisture conditions and high temperatures that are common in the region (Staggenborg, Dhuyvetter, and Gordon 2008; Yamoah, Clegg, and Francis 1998).

In the midsouthern states, there is a lack of long-term research that documents how a *biennial rotation* of soybean and a grain crop will perform. But, approximately 2.3 million acres of rice can potentially be rotated with soybean (USDA–NASS 2008b). Doublecropping of soybean with a winter grain crop is practiced on a significant acreage in the southeastern and midsouthern states (Heatherly 2007) and may be applicable in the southwestern Corn Belt (Kelley 2003).

Yield

Yields of both corn and soybean increase when planted in rotation with each other in the Midwest or Corn Belt (Table 2.8). The increase is greatest when the crops are rotated biennially and in the first year of either crop following consecutive years of the other (Pedersen and Lauer 2003; Porter et al. 1997). Corn grain yield variability over the long term in the western Corn Belt is decreased by rotation with soybean (Varvel 2000). Rotations of corn and soybean generally are more profitable than either crop grown in monoculture (DeWitt et al. 2002; Katsvairo and Cox 2000a; Pedersen and Lauer 2003; Stanger, Lauer, and Chavas 2008). The energy output:input ratios for corn and grain sorghum are greater when grown in rotation with soybean than when grown in monoculture (Franzluebbers and Francis 1995; Rathke et al. 2007).

Yields of both soybean and grain sorghum are increased when grown in rotation in the western Corn Belt (Table 2.9). The increase in yield of sorghum following soybean is greatest when they are rotated biennially and in the first year of sorghum following consecutive years of soybean (Kelley 2005). Yamoah, Clegg, and Francis (1998) measured a greater rotation effect on sorghum yield in cooler, wetter years. Varvel (1995) determined that soybean and grain sorghum are less affected by the previous crop in a nonirrigated rotation than corn is in the limited-rainfall western Corn Belt. Thus, grain sorghum will have a much more stable production (i.e., reduced yield variability

Table 2.8. Corn and soybean yields when grown continuously and in rotation with each other in long-term studies, and advantage from rotation

		Yield of Corn Following:			Yield of Soybean Following:		
State	Site-Yr No.	Corn	Soybean	Adv.[a]	Soybean	Corn	Adv.[a]
		- - - - - - bu/acre - - - - - -		%	- - - - - - bu/acre - - - - - -		%
				Hoeft et al. (2000)			
IL	17	144	170	18	—	—	—
IN	20	166	179	8	45.7	50.9	11
IA	8	128	145	13	31.9	35.8	12
MN	20	122	136	12	36.0	40.8	13
NY	12	127	139	9	—	—	—
WI	9	131	152	16	52.2	55.0	5
				Erickson (2008)			
KY	14	125	136	9	—	—	—
IA	25	131	154	18	38.7	45.3	17
SD	10	96	112	17	—	—	—
MN	11	115	131	14	35.4	40.9	16
MN	10	130	142	9	36.8	40.6	10
MN	9	131	152	16	52.2	55.1	6
WI	15	145	161	11	—	—	—
IN	10	181	190	5	—	—	—
IN	21	168	180	7	—	—	—
				Pedersen and Lauer (2003)			
WI	15	140	168	20	—	—	—
				DeWitt et al. (2002)			
IA	20	128	148	16	36.0	43.0	19
				Varvel and Wilhelm (2003)			
NE	20	117	137	17	—	—	—
NE	10	168	184	10	—	—	—
				Wilhelm and Wortmann (2004)			
NE	16	95	112	18	34.2	38.7	13
				Katsvairo and Cox (2000b)			
NY	5	121	142	17	—	—	—

[a]Advantage to rotation.

Table 2.9. Grain sorghum (GS) and soybean yields when grown continuously and in rotation with each other in rotation studies, and advantage from rotation

		Yield of GS Following:			Yield of Soybean Following:		
State	Site-Yr No.	GS	Soybean	Adv.[a]	Soybean	GS	Adv.[a0]
		------ bu/acre ------		%	------ bu/acre ------		%
			Varvel and Wilhelm (2003)				
NE	20	99	104	5	—	—	—
			Roder et al. (1989)				
NE	7	96	101	6	38.2	41.4	8
			Yamoah, Clegg, and Francis (1998)				
NE	18	93	105	13	—	—	—
			Kelley (2005)				
KS	5	75	97	29	24.5	30.3	24
			Leikam et al. (2007)				
KS	5	79	88	11	—	—	—
KS	5	103	120	16	—	—	—
			Watson (2003)				
KS	18	76	90	18	31	41	32
			Gordon, Whitney, and Fjell (2001)				
KS	19	88	101	15	—	34	

[a]Advantage to rotation.

over the long term) in rotation with soybean than corn will in dryland production systems in this region (Varvel 2000).

In the midsouthern United States, the analysis of net returns to eight cropping systems over an 8-year period (Heatherly and Elmore 2004) provided the following conclusions:

- Without irrigation, grain sorghum was the more desirable component crop for rotation with soybean and in rotation with a wheat–soybean doublecropping sequence.
- With irrigation, net returns to cropping systems that included corn rotated with soybean and in rotation with a wheat–soybean doublecropping sequence were greater than those from continuous single-crop systems.
- In both nonirrigated and irrigated systems, rotated crop sequences provided greater net returns than a continuous soybean system.

In a midsouthern U.S. study, yield and net return from nonirrigated soybean that followed rice were greater than yield and net return from soybean grown continuously (Heatherly and Elmore 2004). Rice yield and net return also were increased by rotation with nonirrigated soybean. Overall average net return from a rice–nonirrigated soybean rotation exceeded that from both continuous nonirrigated soybean and continuous rice. Where soybean was irrigated, which is usually the case in a biennial rotation with rice, yield and net return were similar to those from continuous irrigated soybean. Thus, yield of irrigated soybean following rice is not enhanced by the rotation with rice. The advantages of rotating soybean with rice where both are irrigated must accrue from benefits such as enhanced rice yields and disruption of pest and weed cycles in both crops rather than a yield benefit to the soybean.

The preceding discussion often identifies the "highest yielding" and/or "most profitable" rotations, which obviously have the greatest chance of being the most sustainable over the long term. This does not imply that monocropped soybean or soybean grown in rotations other than those identified here are neither profitable nor sustainable. On the contrary, a producer may decide that another soybean cropping system is more manageable within local production constraints. An example of a successful and sustainable soybean production system that does not involve rotation is in the midsouthern United States. During the 2003 to 2007 period, 87% of Arkansas's soybean acreage was monocropped (USDA–NASS 2008b). It is common knowledge that the same proportion of the soybean acreage in the other states in the region falls into the same category. This practice is not considered a risk in this region because analysis of long-term yields indicates that high and consistent yields are sustainable over a long period (Heatherly 2005a). Also, the millions of acres of clay-textured soils where soybean monocropping is practiced will not maintain soybean cyst nematode (SCN) populations (Heatherly and Elmore 2004) and are not considered conducive to sustainable corn and cotton production.

Nitrogen

Soybean preceding a grain crop in a rotation is considered to provide an "N credit" to the grain crop. The N contribution from soybean is an important aspect of decreasing yield variability in the following grain crop (Varvel 2000). Late-fall or early-spring soil tests have not been able to detect or reflect this soybean N credit (Varvel and Wilhelm 2003). Green and Blackmer (1995) suggest that differences in N fertilizer requirement for the grain crop in the rotation compared with a continuous grain crop are explained by differences in amount of N that is immobilized during residue decomposition rather than by mineralization of biologically fixed N associated with the soybean.

Results from several soybean/grain crop rotation studies have estimated the soybean N credit. Results from a long-term study by Varvel and Wilhelm (2003) indicated a soybean N credit of 58 and 71 lb N/acre for a following corn or sorghum crop, respectively. An N credit from soybean to corn of 70 to 80 lb/acre was extrapolated from the results of Bergerou and colleagues (2004), DeWitt and colleagues (2002), Mallarino, Ortiz-Torres, and Pecinovsky (2005), and Stanger, Lauer, and Chavas (2008). Roder and colleagues (1989) determined the soybean N credit to a succeeding grain sorghum crop was approximately 80 lb/acre. Yamoah, Clegg, and Francis (1998) estimated an N contribution of 55 lb/acre from soybean to sorghum. In an 11-year rotation study in Texas, 40% more N fertilizer was required to achieve optimal grain yield from continuous sorghum than from rotated sorghum (Franzluebbers, Hons, and Saladino 1995). Grain sorghum producers in the western Corn Belt can decrease fertilizer N by 40 lb/acre when sorghum follows soybean vs. itself (Kelley 2005). Nitrogen fertilizer replacement values of soybean for corn in a soybean-corn rotation from various studies are presented by Swink, Ketterings, and Cox (2007).

The decrease in the amount of N fertilizer that should be applied to a grain crop following soybean is a significant economic and environmental consideration. Accounting for this N credit will prevent excessive N fertilizer application to the grain crop, thus decreasing expense and potential N loss to the surrounding environment (Franzluebbers, Francis, and Walters 1994). A decrease in N fertilizer application to a grain crop following soybean also decreases the total energy input for the production of the grain crop, which is particularly important for corn because N fertilization accounts for approximately half of the total energy input for its production (Rathke et al. 2007). This decrease in N fertilization of the grain crop also contributes to a higher output:input energy ratio from rotated crops (Franzluebbers and Francis 1995; Rathke et al. 2007).

Subsurface drainage ("tiling") is a water management practice used to remove excess water from poorly drained soils in the Midwest; it can result in the transport of significant amounts of nitrate from cropped areas to surface waters. Soybean grown in a rotation with corn does not mitigate this nitrate leaching (Randall and Vetsch 2005b; Randall, Vetsch, and Huffman 2003; Randall et al. 1997; Zhu and Fox 2003). In fact, nitrate losses through subsurface drainage in soybean years can be similar to or above losses in corn years. Losses in soybean years apparently are related to rate of N fertilizer applied to corn, annual precipitation, and residual soil nitrate following corn. Thus, when evaluating the effect of N fertilizer management practices for corn on nitrate losses to subsurface drainage in a soybean-corn rotation, both crop phases should be included in the assessment. Management practices that can reduce nitrate leaching in a soybean–corn rotation are discussed by Dinnes and colleagues (2002). The practices include

- proper timing and rate of N fertilizer application to corn,
- accurately crediting nitrogen mineralization,
- diversifying crop rotations,

- using cover crops,
- reducing autumn and early-spring tillage, and
- using N removal strategies such as riparian buffers and wetlands. Riparian buffers provide an added benefit of reducing atrazine and other herbicide transport to shallow groundwater and in runoff, which is an important consideration in a soybean–corn rotation (Flores 2009; Lin et al. 2003, 2007, 2008).

Residue Cover/Erosion Control

Crops such as corn and sorghum that are rotated with soybean generally produce more dry matter and subsequent plant residue following harvest and maintain more surface residue following tillage and/or planting operations than soybean does (Table 2.3). This increased plant residue resulting from rotation of soybean with other crops may lead to improved water infiltration, soil tilth, and organic matter. Over the long term, soil organic carbon levels and crop residue produced and returned to a field are greater in a soybean–corn rotation than in a continuous soybean system (Omay et al. 1997; Varvel and Wilhelm 2008).

Crop rotation can be used to decrease erosion potential. As shown in Table 2.6, culture of some crops results in a greater erosion hazard than others. Soils planted to soybean may have as much as 10 to 100% greater soil loss potential than soils planted to corn or grain sorghum (Triplett and Dabney 1999). Reasons for this difference are that soybean does not produce a large volume of plant residue that covers the soil during the off-season and soybean residue decomposes more rapidly than the stalks, leaves, and roots of nonleguminous crops.

Rotation of corn or grain sorghum with soybean, and with soybean planted no-till, allows the grain crop residue cover to persist into the soybean growing season, thus decreasing erosion potential. Small grain straw also provides extensive, persistent cover, making a soybean–small-grain doublecrop system effective in controlling soil loss. For this system to function well, the small-grain straw should not be baled or burned and soybean should be planted no-till.

Pest and Weed Management

Nematodes are a serious pest of soybean in the United States. In areas with severe infestations, producing soybean without control measures is not economically feasible. Heatherly and Elmore (2004) provide a summary (with references) of how crop rotation can be used to control or mitigate the effects of nematodes.

The SCN is the most serious nematode pest. Major damage to soybean by SCN infestation occurs primarily when the crop is grown on medium- and coarse-textured soils. Combining the use of SCN-resistant varieties and rotation with nonhost summer crops such as corn, cotton (*Gossypium hirsutum* L.), and grain sorghum is the most successful strategy for decreasing SCN populations on infested soils and producing the greatest soybean yields from infested fields. Rotating soybean varieties with different sources of resistance in a rotation with a nonhost crop slows the adaptation (race shift) of SCN in the field (Niblack and Tylka 2008). A susceptible variety may be grown in the rotation in a single year if SCN population densities are low, but SCN density will increase.

Root-knot nematodes (*Meloidogyne incognita, M. arenaria*, and *M. javanica*) and reniform nematode (*Rotylenchulus reniformis*) are significant pests of soybean grown in the southeastern United States, especially in the drought-prone soils of the Atlantic Coastal Plain. Soybean varieties resistant to *M. arenaria* and *M. javanica* have not been widely developed. Therefore, rotation of soybean with other crops may be the only way to avoid serious damage from these nematodes. Use of resistant varieties is effective for managing reniform nematode; however, rotation to grasses, which are poor hosts for the pest, also is an effective management tool.

According to a review by Heatherly and Elmore (2004), soybean grown in rotation with corn can disrupt pest cycles and may result in less expenditure for control of insects and diseases. Rotation, however, is not a guaranteed long-term control measure for pests as indicated by the discovery that the western corn rootworm (*Diabrotica virgifera virgifera*) has circumvented this strategy in Illinois by increasing to economic significance the density of eggs laid in soybean fields (Levine et al. 2002). Thus, pest management by a crop rotational strategy should be monitored periodically for effectiveness and to determine if a third rotational crop may be needed in the future to sustain cultural control of rootworms in a soybean–corn rotation.

The continuous growing of either corn or soybean maximizes the opportunities to increase those weed species best adapted to compete with the monocultured crop. Rotation of corn and soybean allows the rotation of herbicides, which may limit occurrence of resistant weed species. In New York, Katsvairo and Cox (2000a) found that a soybean–corn rotation resulted in decreased fertilizer, herbicide, and pesticide use compared with a continuous corn system.

Section Summary

When soybean is rotated with either corn or grain sorghum in the Midwest, yield of each crop following the other is greater than yield of each crop following itself. The N fertilizer requirement for a grain crop following soybean is less than for the crop following itself, and the N contribution from soybean is an important aspect of decreasing yield variability in the grain crop. Economic and agronomic incentives and energy output:input ratios favor a 2-year soybean–grain crop rotation in the Corn Belt. A majority of soybean in the southern United States is monocropped, and there is little long-term research to evaluate the effects of rotating soybean in that region. Doublecropping soybean and a small grain without irrigation in the South may be a high-risk enterprise.

Rotation of soybean with a crop that is not a host to nematode pests of soybean as well as the use and rotation of resistant soybean varieties can be effective in alleviating damage to soybean by these pests. In addition, these practices can delay or prevent the buildup of new SCN races. The soybean–corn rotation, however, is not a guaranteed long-term control measure for all pests in this rotation, as indicated by the discovery that western corn rootworm has adapted to this system by laying its eggs in soybean crop and by extended dispause.

Soils planted to soybean have greater soil loss potential than soils planted to a grain crop. A grain crop results in more dry matter production and subsequent plant residue, as well as decreased erosion potential. A rotation of a grain crop with soybean, and with soybean planted no-till, decreases erosion potential to acceptable levels. Subsurface drainage used to remove excess water from poorly drained soils can result in the transport of significant amounts of N from cropped areas. Soybean grown with corn does not mitigate this action; therefore, management practices that can reduce nitrate leaching in a soybean–corn rotation should be adopted.

Long-term commodity price prospects should be used to project the potential net returns to different cropping systems that may involve rotation. The decision to rotate soybean with other crops should be evaluated from both agronomic and economic perspectives. In most instances, soybean rotated with another summer crop will enhance economical and sustainable production.

Glossary

Biennial rotation. The practice of growing two different crops in alternating years

Literature Cited

Bergerou, J. A., L. E. Gentry, M. B. David, and F. E. Below. 2004. Role of N_2 fixation in the soybean N credit in maize production. *Plant and Soil* 262:383–394.

DeWitt, J., M. Duffy, G. Miller, J. Sawyer, J. Creswell. 2002. Crop rotation. NMEP 5. Iowa State University Extension Service, Ames, http://www.extension.iastate.edu/Publications/NMEP5.pdf

Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agron J* 94:153–171.

Erickson, B. 2008. Corn/soybean rotation literature summary, http://www.agecon.purdue.edu/pdf/Crop_Rotation_Lit_Review.pdf

Flores, A. 2009. ARS-developed riparian zones reduce atrazine contamination in water. *Agric Res Magazine* 57(1):20, http://www.ars.usda.gov/is/AR/archive/jan09/zones0109.htm?pf=1

Franzluebbers, A. J. and C. A. Francis. 1995. Energy output:input ratio of maize and sorghum management systems in eastern Nebraska. *Ag Ecosys Environ* 53:271–278.

Franzluebbers, A. J., C. A. Francis, and D. T. Walters. 1994. Nitrogen fertilizer response potential of corn and sorghum in continuous and rotated crop sequences. *J Prod Agric* 7:277–284.

Franzluebbers, A. J., F. M. Hons, and V. A. Saladino. 1995. Sorghum, wheat, and soybean production as affected by long-term tillage, crop sequence and N fertilization. *Plant Soil* 173:55–65.

Gordon, B., D. A. Whitney, and D. L. Fjell. 2001. Effects of cropping system and nitrogen fertilization on no-tillage grain sorghum production. Pp. 60–63. In *2001 Agric Res Report Progress 876*. Kansas State University, Manhattan, http://www.oznet.ksu.edu/library/crpsl2/srp876.pdf

Green, C. J., and A. M. Blackmer. 1995. Residue decomposition effects on nitrogen availability to corn following corn or soybean. *Soil Sci Soc Am J* 59:1065–1070.

Heatherly, L. G. 2005a. Midsouthern USA soybean yield affected by maturity group and planting date. *Crop Mgmt* 12 Nov, http://www.plantmanagementnetwork.org/cm/ (online only: limited access)

Heatherly, L. G. 2007. "Boosting soybean yields requires attention to local conditions." *Success Farm*, March 12, http://www.agriculture.com/ag/story.jhtml?storyid=/templatedata/ag/story/data/1173711714526.xml

Heatherly, L. G. and R. W. Elmore. 2004. Managing inputs for peak production. Pp. 451–536. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*, 3rd ed. Agronomy Monograph 16. American Society of Agronomy, Madison, Wisconsin.

Hoeft, R. G., E. D. Nafziger, R. R. Johnson, and S. R. Aldrich. 2000. *Modern Corn and Soybean Production*. 1st ed. MCSP Publications, Savoy, Illinois. 353 pp.

Katsvairo, T. W. and W. J. Cox. 2000a. Economics of cropping systems featuring different rotations, tillage, and management. *Agron J* 92:485–493.

Katsvairo, T. W. and W. J. Cox. 2000b. Tillage x rotation x management interactions in corn. *Agron J* 92:493–500.

Kelley, K. W. 2003. Double-cropping winter wheat and soybean improves net returns in the eastern Great Plains. *Crop Mgmt*

12 Nov, http://www.plantmanagementnetwork.org/sub/cm/research/2003/plains/kelley.pdf (online only; limited access)

Kelley, K. W. 2005. Grain sorghum and soybean cropping sequence affect yield and fertilizer N requirement. *Crop Mgmt* 22 Sept, http://www.plantmanagementnetwork.org/sub/cm/research/2005/sequence/cropping.pdf (online only; limited access)

Leikam, D., R. E. Lamond, L. C. Bonczkowski, J. S. Hickman, and D. A. Whitney. 2007. Using legumes in crop rotations. L-778. Department of Agronomy, Kansas State University, Manhattan, http://www.oznet.ksu.edu/library/crpsl2/l778.pdf

Levine, E., J. L. Spencer, S. A. Isard, D. W. Onstad, and M. E. Gray. 2002. Adaptation of the western corn rootworm to crop rotation: Evolution of a new strain in response to a management practice. *Amer Entomol* 48:94–107.

Lin, C. H., R. N. Lerch, H. E. Garrett, W. G. Johnson, D. Jordan, and M. F. George. 2003. The effect of five forage species on transport and transformation of atrazine and isoxaflutole (Balance) in lysimeter leachate. *J Environ Qual* 32:1992–2000.

Lin, C. H., R. N. Lerch, H. E. Garrett, C. J. Gantzer, and S. H. Anderson. 2007. Utilizing vegetative buffer strips to remove dissolved and sediment-bound atrazine, metolachlor and glyphosate from surface water runoff. *Proc 10th North American Agroforestry Conf*, June 9–14, Quebec City, Quebec, Canada.

Lin, C. H., R. N. Lerch, H. E. Garrett, and M. F. George. 2008. Bioremediation of atrazine-contaminated soil by forage grasses: Transformation, uptake, and detoxification. *J Environ Qual* 37:196–206.

Mallarino, A. P., E. Ortiz-Torres, and K. Pecinovsky. 2005. Effects of crop rotation and nitrogen fertilizer on crop production. Publ. ISRF04-13. *Annual Progress Report*, Northern Research and Demonstration Farm, Iowa State University, Ames, http://www.agronext.iastate.edu/soilfertility/info/NERF_AnnRepo2004_Nrotation_Publ-2005.pdf

Mallarino, A. P., E. Ortiz-Torres, and D. Rueber. 2006. Grain yield of corn, soybeans, and oats as affected by crop rotation and nitrogen fertilization for corn. Publ. ISRF05-22. *Annual Progress Report*, Northern Research and Demonstration Farm, Iowa State Univ., Ames, http://www.ag.iastate.edu/farms/05reports/n/GrainYield.pdf

Niblack, T. L., and G. L. Tylka (eds.). 2008. *Soybean Cyst Nematode Management Guide*. 5th ed. North Central Soybean Research Program, Urbandale, Iowa, http://www.planthealth.info/pdf_docs/SCNGuide_5thEd.pdf

Omay, A. B., C. W. Rice, L. D. Maddux, and W. B. Gordon. 1997. Changes in soil microbial and chemical properties under long-term crop rotation and fertilization. *Soil Sci* 61:1672–1678.

Pedersen, P. and J. G. Lauer. 2003. Corn and soybean response to rotation sequence and tillage system. Pp. 35–41. In *Proc 15th Annual Integrated Crop Mgmt Conf*, Iowa State University, Ames, 3–4 December 2002.

Porter, P. M., J. G. Lauer, W. E. Lueschen, J. H. Ford, T. R. Hoverstad, E. S. Oplinger, and R. K. Crookston. 1997. Environment affects the corn and soybean rotation effect. *Agron J* 89:441–448.

Randall, G. W., and J. A. Vetsch. 2005b. Nitrate losses in subsurface drainage from a soybean–corn rotation as affected by fall and spring application of nitrogen and nitrapyrin. *J Environ Qual* 34:590–597.

Randall, G. W., J. A. Vetsch, and J. R. Huffman. 2003. Nitrate losses in subsurface drainage from a soybean–corn rotation as affected by time of nitrogen application and use of nitrapyrin. *J Environ Qual* 32:1764–1772.

Randall, G. W., D. R. Huggins, M. P. Russelle, D. J. Fuchs, W. W. Nelson, and J. L. Anderson. 1997. Nitrate losses through subsurface tile drainage in conservation reserve program, alfalfa, and row crop systems. *J Environ Qual* 26:1240–1247.

Rathke, G. W., B. J. Wienhold, W. W. Wilhelm, and W. Diepenbrock. 2007. Tillage and rotation effect on corn–soybean energy balances in eastern Nebraska. *Soil Tillage Res* 97:60–70.

Roder, W., S. C. Mason, M. D. Clegg, and K. R. Kniep. 1989. Yield-soil water relationships in sorghum-soybean cropping systems with different fertilizer regimes. *Agron J* 81:470–475.

Staggenborg, S. A., K. C. Dhuyvetter, and W. B. Gordon. 2008. Grain sorghum and corn comparisons: Yield, economic, and environmental responses. *Agron J* 100:1600–1604.

Stanger, T. F., J. G. Lauer, and J. P. Chavas. 2008. The profitability and risk of long-term cropping systems featuring different rotations and nitrogen rates. *Agron J* 100:105–113.

Swink, S. N., Q. M. Ketterings, and W. J. Cox. 2007. Nitrogen fertilizer replacement value of soybean for corn. *Crop Mgmt* 5 Oct, http://www.plantmanagementnetwork.org/sub/cm/review/2007/replace/replace.pdf (online only; limited access)

Triplett, G. B. and S. M. Dabney. 1999. Soil erosion and soybean production. Pp. 19–39. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008b. Acreage. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-30-2008.pdf

Varvel, G. E. 1995. Precipitation use efficiency of soybean and grain sorghum in monoculture and rotation. *Soil Sci Soc Am J* 59:527–531.

Varvel, G. E. 2000. Crop rotation and nitrogen effects on normalized grain yields in a long-term study. *Agron J* 92:938–941.

Varvel, G. E. and W. W. Wilhelm. 2003. Soybean nitrogen contribution to corn and sorghum in western Corn Belt rotations. *Agron J* 95:1220–1225.

Varvel, G. E. and W. W. Wilhelm. 2008. Soil carbon levels in irrigated western Corn Belt rotations. *Agron J* 100:1180–1184.

Watson, S. 2003. Long-term tillage and rotation study: Ashland Bottoms. Kcare environmental news no. 22. June 25, Kansas State University, Manhattan, http://www.oznet.ksu.edu/ctec/newsletter/06_25_03.htm

Wiebold, B. and T. Belt. 2006. Effect of rotation on soybean and corn yield planted without tillage. University of Missouri Extension Service, Columbia, http://plantsci.missouri.edu/soyx/research/2006/notill_rotation2006.pdf

Wilhelm, W. W. and C. S. Wortmann. 2004. Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. *Agron J* 96:425–432.

Wortmann, C. S., M. Mamo, and A. Dobermann. 2007. Nitrogen response of grain sorghum in rotation with soybean. *Agron J* 99:808–813.

Yamoah, C. F., M. D. Clegg, and C. A. Francis. 1998. Rotation effect on sorghum response to nitrogen fertilizer under different rainfall and temperature environments. *Ag Ecosys Environ* 68:233–243.

Zhu, Y., and R. H. Fox. 2003. Corn-soybean rotation effects on nitrate leaching. *Agron J* 95:1028–1033.

Soil Nutrient Management

Like all green plants, soybean requires 16 elements to complete the metabolic processes necessary for growth and reproduction (Table 2.10). Regardless of the system of production, lack of an adequate supply of any of these elements will decrease plant growth and potential yield, as well as result in soil nutrient depletion that decreases productivity. To minimize a decrease in soybean yield caused by a lack of any of these nutrients, or to avoid applying nutrients that have a low probability of economically increasing yield, producers should develop and use a nutrient management plan.

An effective nutrient management plan identifies the amount, source, time of application, and placement of nutrients needed to sustain economic viability of crops, while simultaneously protecting the environment. Plans should optimize the use of all sources of nutrients, including soil reserves, external inorganic nutrient additions, legume crops, and organic sources such as manure and industrial or municipal waste. The plan should ensure that the potential for plant nutrients to degrade water or soil quality is minimized.

Fertile soil supports vigorous plant growth that covers the soil surface early in the growing season. The increased soil cover will decrease soil moisture evaporation, decrease wind and water erosion, and maximize the amount of plant residue remaining after harvest to minimize erosion during the nongrowing season. Vigorously growing plants are more resistant to *biotic* and *abiotic* stresses, including diseases and insects (Funderburk, Rhoads, and Teare 1994; Parker et al. 1975; Rupe et al. 1993), weeds, and adverse weather conditions.

Nutrient Management Plan

Development of a nutrient management program begins with collecting soil samples from a production unit or field, followed by a soil test. Sampling protocol is important to ensure accuracy of results and proper application of test recommendations to the unit. Because most fields are variable in topography, slope, and soil series, nutrient levels will vary considerably within a field. Samples must be collected in a systematic manner across a field, or within variable units within a field.

Sampling protocols from various institutions are available (A & L Great Lakes 2005; Crouse and McCarty 2006; Ferguson and Hergert 2000; MCES 2006; Rains and Thomas 2001; Reetz 2008; Rehm et al. 2001), and the protocol for the appropriate environment should be followed to ensure accurate test results. Precisely marking the location of each sample will allow nutrient application using *variable rate technology* (VRT), which may be more economical (Bullock et al. 1994).

Soil pH and Liming

Maintaining soil pH in the range of 6.0 to 7.0 will enhance availability of inherent and fertilizer nutrients; reduce availability of toxic elements, particularly aluminum and manganese; and enhance microbial activity (Hoeft et al. 2000). Phosphorus (P) availability decreases in acid soils due to the formation of insoluble aluminum phosphate compounds. At pH levels greater than 7.4, P availability decreases due to the formation of insoluble calcium phosphates.

Micronutrient availability, with the exception of molybdenum, increases as soil pH decreases. Molybdenum availability increases in soils with a pH greater than 7. Soils with a pH of less than 5 may have manganese concentrations at levels toxic to plants.

Increased microbial activity associated with maintaining pH in the optimum range results in increased *oxidation of organic matter* and, consequently, in increased release of nutrients from the organic matter. Increased microbial activity also will increase nitrogen (N) availability for soybean by increasing the activity of rhizobia bacteria that are responsible for *symbiotic nitrogen fixation*.

Nitrogen

Properly nodulated soybean grown at the proper soil pH will fix about two-thirds of the N contained in the harvested crop (Hoeft 2002). Weber (1966) found that the amount of dinitrogen (N_2) fixation varied depending on soil N, soil water, or both, and ranged from 1 to 74% of the total N uptake. Using ^{15}N isotope, Deibert, Bijeriego, and Olson (1979) observed that when no fertilizer N was applied, N_2 fixation accounted for 66% of the total N in the plant at harvest. When fertilizer N was applied at planting at the rate of 120 lb/acre, however, N_2 fixation dropped to 31%, with fertilizer N accounting for 28% and the soil for 40% of the total N in the plant at harvest. Thus, costly fertilizer N apparently supplants rather than supplements the cost-free N provided by symbiotic nitrogen fixation in soybean.

Soybean grain yield response to applied fertilizer N has varied across experimental trials. Results

Table 2.10. The sixteen elements required for plant growth

Element	Chemical Form Absorbed by Plants	Primary Source of Element
	Elements Not Considered in a Fertility Program	
Carbon	CO_2	Air and Water
Hydrogen	H_2O	Air and Water
Oxygen	CO_2, H_2O	Air and Water
	Major or Primary Nutrients	
Nitrogen	NH_4^+, NO_3^-	Soil
Phosphorus	HPO_4^{-2}, $H_2PO_4^{-1}$	Soil
Potassium	K^+	Soil
	Secondary Nutrients	
Calcium	Ca^{++}	Soil
Magnesium	Mg^{++}	Soil
Sulfur	SO_4^{-2}, SO_2	Sulfate absorbed from soil; Sulfur dioxide absorbed from air
	Micronutrients	
Boron	H_3BO_3	Soil
Chlorine	Cl^-	Soil
Copper	Cu^{+2}	Soil
Iron	Fe^{+3}, Fe^{+2}	Soil
Manganese	Mn^{+2}	Soil
Molybdenum	MoO_4^{-2}	Soil
Zinc	Zn^{+2}	Soil

from the majority of studies, however, showed no yield increase from applied fertilizer N when plants were properly nodulated and soil moisture conditions were optimum for production (Deibert, Bijeriego, and Olson 1979; Heatherly and Elmore 2004; Heatherly, Spurlock, and Reddy 2003; Scharf and Wiebold 2003; Schmitt et al. 2001; Weber 1966; Welch et al. 1973). This was true even with continuous soybean (Table 2.11) and with high rates of fertilizer N (Table 2.12).

When soybean was grown under drought conditions, in acid subsoil conditions, in soils having low residual N, in a high-yield environment, or in late and/or doublecrop plantings, yield increases resulting from additions of fertilizer N have been measured (Bhangoo and Albritton 1976; Ham et al. 1975; Heatherly and Elmore 2004; Lyons and Early 1952; Ray, Heatherly, and Fritschi 2006; Taylor et al. 2005; Wesley et al. 1998). These yield responses to fertilizer N, however, usually are not economical.

Table 2.11. Yield of continuous soybean with rates of added nitrogen (Welch et al. 1973)

Nitrogen	Soybean Yield
lb/acre	bu/acre
0	37
40	36
120	37

Application of fertilizer N decreases the weight, number, and size of *nodules* (Weber 1966) and consequently the symbiotic activity of rhizobia (i.e., it reduces N_2 fixation). Attempts to overcome this negative effect by applying fertilizer N after nodule formation, using an ammonium form of N, or using an

Table 2.12. Soybean yield as affected by high rates of nitrogen (Welch et al. 1973)

Nitrogen			Soybean Yield		
Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
	lb/acre			bu/acre	
0	0	0	54	53	40
40	200	200	54	57	41
80	400	400	56	57	45
120	800	800	53	55	42
160	1,600	1,600	55	34	36

organic source of N have been unsuccessful (Barker and Sawyer 2005; Bhangoo and Albritton 1976; Ham et al. 1975; Welch et al. 1973).

Phosphorus

Phosphorus deficiency in soybean is not common, but does occur in some soybean-growing regions of the United States. The soil P level necessary for optimum soybean yield is in the same range as that for optimum corn yield (Dodd and Mallarino 2005). Soil P levels should be maintained at or slightly above that optimum range to minimize the potential for yield loss from P deficiency. An accurate soil test is required to identify soil P levels and determine their adequacy for optimum soybean performance.

Soybean removes approximately 0.85 pound of phosphate (P_2O_5) for each bushel of seed harvested. On most fields, at least this removal amount should be applied to maintain adequate P fertility. Because P application is not needed every year, it is most economical to apply an ammoniated material ahead of the corn crop in a biennial soybean-corn rotation. This practice results in using the cheapest source of N for the corn crop and will cut applications and associated costs in half. Nonorganic growers can select from straight P materials such as triple superphosphate or from liquid or dry formulations of ammoniated phosphates, whereas organic growers must rely on rock phosphate or manures.

Potassium

Soybean removes approximately 1.2 pounds of potash (K_2O) per bushel of seed produced. Continued removal without replacement will lower the soil supply to a level that will not support optimum yield. Soil test levels may change considerably from one sampling time to the next. Thus, soil potassium (K) should be monitored over time, and variable test values should be used with caution.

There are several materials available to supply K to the soil. Unless sulfur and/or magnesium are needed, however, potassium chloride is the most economical form. Potassium chloride can be applied in the fall or spring preceding the soybean crop, except on sandy soils. Producers of certified organic soybean are limited to the use of potassium sulfate (K_2SO_4) or manures to supply K.

Secondary Nutrients

Calcium, magnesium, and sulfur comprise the secondary nutrient group. Documented deficiencies of these three nutrients are few. Calcium deficiency is unlikely if soil pH is maintained above 5.5. Small yield increases have been observed with a foliar application of magnesium in a Missouri study (Reinbott and Blevins 1995). Neither the magnitude nor the consistency of response, however, has been great enough to encourage producers to consider making the application. Even though soybean is a high-protein crop and removes a significant amount of sulfur from soil, documented response to sulfur fertilizer is almost nonexistent. The primary source of sulfur from the soil is oxidation of organic matter.

Micronutrients

Micronutrient deficiencies and toxicities are the exception rather than the rule in the soybean-producing areas of the United States. In most instances, simply maintaining a proper soil pH prevents most micronutrient problems (Heatherly and Elmore 2004). For example, high soil pH (> 7.4) is the primary factor that causes iron deficiency. Manganese can be either toxic (pH < 5) or deficient (pH > 7.4), depending on soil pH. Molybdenum deficiency occurs on very acid soils and becomes more available at higher pH levels.

Some reports have associated glyphosate applications to soybean with the immobilization of manganese in the plant (Huber et al. 2004), as well as an association of glyphosate-resistant (GR) varieties with reduced uptake of manganese (Gordon 2007). But research that would substantiate or characterize these interactions has failed to consistently demonstrate the relationship of glyphosate applications to soybean or use of GR varieties with inadequate manganese nutrition (Bernards, Perim, and Schleufer 2008; Binford et al. 2004; Bott et al. 2008). Occurrences of manganese deficiency in GR soybean are isolated and inconsistent and seem to be specific to environmental conditions, variety, glyphosate dose, and soil nutrient availability. This condition is not considered a threat to the sustainability of using GR varieties.

Fertilizer Placement and Application

Unless soils are very low in P or K, broadcast application of these fertilizer nutrients is acceptable (Buah, Polito, and Killorn 2000; Ham and Caldwell 1978; Ham et al. 1975; Yin and Vyn 2002). Borges and Mallarino (2000) observed a small yield increase with *banded* vs. *broadcast* K under no-till conditions, but they suggested that the increase would seldom offset the increased application cost associated with banding. In *ridge tillage* systems, deep banding (6-8 inches deep) of P and K tended to result in higher yield than broadcast application (Borges and Mallarino 2003).

Foliar application of nutrients to soybean is an effective application technique for micronutrients, but has not been cost-effective for application of the primary nutrients (Haq and Mallarino 2000; Nelson, Motavalli, and Nathan 2005). The exception to this finding may occur in situations in which climatic and soil conditions decrease nutrient uptake from the soil (Nelson, Motavalli, and Nathan 2005).

Variable Rate Technology for Fertilizer Application

The concept of variable rate application of nutrients dates back more than 80 years when farmers used grid soil sampling to determine where lime applications were needed. The benefits of this practice were both economical (lowered input cost) and physical (less labor), because lime often was spread with an end-gate spreader fed by individuals using shovels. With the development in the latter part of the twentieth century of computerized fertilizer applicators connected to global positioning systems, ease of fertilizer application on an as-needed basis using VRT became a reality (Wollenhaupt, Wolkowski, and Clayton 1994).

With VRT equipment, fertilizer rates can be varied across fields according to map-based instructions. Bullock and colleagues (1994) suggested that cost could be lowered using VRT by eliminating overapplication on areas that did not need fertilization, and that yield could be increased on those areas where fertilizer might be under-applied when using a uniform rate of application across a field. Others have suggested that water quality can be improved by VRT because no fertilizer would be applied to areas of a field testing above-optimum for crops (Mulla 1993; Sawyer 1994). In the midsouthern United States, VRT application of fertilizer nutrients combined with a no-till system resulted in only very small soybean yield increases, but significantly increased profits and decreased K and N loss (Intarapapong, Hite, and Hudson 2003).

Although the advantages listed here are theoretically possible, the economics of the system will depend on the variability of nutrient levels across fields. Bermudez and Mallarino (2007) suggested that the failure of VRT to provide a yield advantage compared with fixed rate application in 13 site-year studies may have been due to greater variability across the field than could be detected by the utilized sampling scheme. That idea was supported by a study that demonstrated that variability in soil test results found in intensive sampling of 23 Ontario fields would require those fields to be sampled at a scale less than 100 feet apart (Lauzon et al. 2005). A statistical procedure has been developed that will allow decision makers to use a low-density sampling program to determine the feasibility of using high-density sampling for VRT application on individual fields (Schmidt, Taylor, and Milliken 2002). Even though VRT application may not result in a yield increase on some fields, using the system may result in the use of less fertilizer and, at the same time, may decrease the inherent variability of nutrients. Such results will probably decrease the potential for environmental degradation from P runoff.

Environmental Impact of Fertilizer Nutrients

Degradation of the environment can result from nutrient deficiencies and/or excesses. If deficiencies occur, vegetative canopy development in the spring will be slower and the amount of plant residue left after harvest will be less. Both conditions will increase soil erosion potential. The long-term impact will be decreased productivity of the land and increased contamination of surface water supplies with sediment. Because many of these waters are used for human consumption, recreation, irrigation, and transportation, the impact on the economy could be substantial. Lessening of productivity on prime farm land by erosion will force a shift to increased row crop production on more marginal lands that often are more prone to erosion.

Nitrogen and P are the two nutrients most associated with contamination of surface water. In some areas of the United States, groundwater supplies also have been contaminated with N. Best Management Practices (BMPs) have been developed to minimize the potential for environmental contamination by fertilizer nutrients. The BMPs for N fertilization of a grain crop following soybean are listed here.

- Apply supplemental N, whether in organic or inorganic form, at the proper rate. Using more than the recommended rate increases the probability for environmental contamination.
- Apply N at the proper time based on the crop to be grown and soil type. Do not fall-apply N on sandy soils, or on soils where the risk of N loss in the spring is high.
- If N fertilizer is applied in the fall, delay the application until the soil temperature has fallen below 50°F.
- Use a *nitrification inhibitor* with fall applications of N fertilizers on soils having medium or higher potential for N loss.
- Do not fall- or winter-apply urea-containing fertilizers.
- Use the proper application technique for the material being applied. Inject or incorporate urea-containing fertilizers and inject or incorporate organic sources of N, especially manure. Injection of manure will minimize N loss to the atmosphere through volatilization and water contamination through runoff.
- Credit the N from a previous soybean crop and from organic additives such as manure when determining the amount of N fertilizer to apply to a grain crop following soybean.

The BMPs for P fertilization are the following:

- Use recent soil test results to determine the proper amount to apply for optimum crop production. Where possible, use VRT to apply the proper rate on a site-specific basis.
- Do not apply P fertilizer to frozen soils if the slope is greater than 5%.
- Incorporate or inject P whenever possible. Runoff is the primary source of P contamination of water sources. If the P fertilizer is applied below the soil surface, loss through runoff will not occur unless erosion is severe enough to remove soil down to the level where the P is placed.
- Use practices that minimize erosion because P loss is correlated closely to the amount of soil loss.

Section Summary

Producers should maintain soil pH in the range of 6.0 to 7.0 to enhance availability of inherent and added fertilizer nutrients, decrease availability of toxic elements, and enhance microbial activity. This practice will lead to sustainable production in the long term.

Nitrogen fertilization of soybean is an unnecessary expense on nonproblem soils. Adding N fertilizers to soybean delays or impedes nodulation and decreases N_2 fixation, and thus is not cost-effective. Nitrogen fertilization of soybean is not conducive to economical and environmental sustainability of any soybean production system.

Soil tests provide the best opportunity to measure nutrient deficiencies accurately and prevent overfertilization that may result in environmental contamination. Variable Rate Technology should be used to apply P on a site-specific basis to increase profits and decrease nutrient loss. Maintaining a proper pH will prevent most micronutrient deficiencies and toxicities that could limit crop productivity.

Glossary

Abiotic. Environmental factors such as drought, wind, hail, or excess moisture that impact the growth of living organisms.

Banded. Fertilizer placed below and to the side of the seed at planting.

Biotic. Biological factors that affect other living organisms.

Broadcast. Fertilizer spread on the soil surface.

Micronutrient. An essential nutrient that is needed in small quantities.

Nitrification inhibitors. Chemical compounds added to nitrogen fertilizer for the purpose of reducing the rate of conversion of ammonium form of fertilizer to nitrate form.

Nodules. Small organelles on the soybean root surface that contain the rhizobium bacteria.

Oxidation of organic matter. Breakdown of organic matter by microbial activity.

Ridge tillage. Soil is mounded up (a ridge is built) in the fall of the year and the crop is then planted on top of this shallow ridge.

Symbiotic nitrogen fixation. The conversion of N_2 from the atmosphere to inorganic nitrogen to a form that plants can use; the conversion is done by microorganisms that live in nodules on the roots of soybean plants.

Variable rate technology. Using computerized fertilizer applications connected to global positioning systems to apply fertilizers at varying rates to specific areas of a field.

Literature Cited

A&L Great Lakes Laboratories, Inc. 2005. Sample preparation—foundation of quality. Ft. Wayne, Indiana, http://www.algreatlakes.com/pdf/newsletters/05_spring.pdf

Barker, D. W. and J. E. Sawyer. 2005. Nitrogen application to soybean at early reproductive development. *Agron J* 97:615–619.

Bermudez, M. and A. P. Mallarino. 2007. Impacts of variable-rate phosphorus fertilization based on dense grid sampling on soil-test phosphorus and grain yield of corn and soybean. *Agron J* 99:822–832.

Bernards, M. L., L. Perim, and I. L. Schleufer. 2008. Glyphosate-resistant and conventional soybean response to foliar manganese fertilizer. *Proc North Cent Weed Sci Soc* 63:186, http://www.ncwss.org/

Bhangoo, M. S. and D. J. Albritton. 1976. Nodulating and non-nodulating Lee soybean isolines response to applied nitrogen. *Agron J* 68:643–645.

Binford, G. D., B. K. Hearn, M. A. Isaacs, D. J. Hansen, and R. W. Taylor. 2004. Foliar fertilization of roundup ready soybeans. *Crop Mgmt* 24 Nov, http://www.plantmanagementnetwork.org/pub/cm/research/2004/rr/ (Online only, limited access)

Borges, R. and A. Mallarino. 2000. Grain yield, early growth, and nutrient uptake of no-till soybean as affected by phosphorus and potassium placement. *Agron J* 92:380–388.

Borges, R. and A. Mallarino. 2003. Broadcast and deep-band placement of phosphorus and potassium for soybean managed with ridge tillage. *Soil Sci Soc Am J* 67:1920–1927.

Bott, S., T. Tesfamariam, H. Candan, I. Cakmak, V. Romheld, and G. Neumann. 2008. Glyphosate-induced impairment of plant growth and micronutrient status in glyphosate-resistant soybean. *Plant Soil* 312:185–194.

Buah, S. J., T. A. Polito, and R. Killorn. 2000. No-tillage soybean response to banded and broadcast and direct and residual fertilizer phosphorus and potassium applications. *Agron J* 92: 657–662.

Bullock, D. G., R. G. Hoeft, P. Dorman, T. Macy, and R. N. Olson. 1994. Nutrient management with intensive soil sampling and differential fertilizer spreading. *Better Crops with Plant Food* 78:10–12.

Crouse, K. and W. McCarty. 2006. Soil testing for the farmer. Information sheet 346. Mississippi State University Extension, http://msucares.com/pubs/infosheets/is0346.pdf

Deibert, E. J., M. Bijeriego, and R. A. Olson. 1979. Utilization of 15N fertilizer by nodulating and non-nodulating soybean isolines. *Agron J* 71:717–723.

Dodd, J. R. and A. P. Mallarino. 2005. Soil-test phosphorus and crop grain yield responses to long-term phosphorus fertilization for corn-soybean rotations. *Soil Sci Soc Am J* 69:1118–1128.

Ferguson, R. B. and G. W. Hergert. 2000. Soil sampling for precision agriculture. EC 00-154. University of Nebraska Cooperative Extension Service, Lincoln, http://ianrpubs.unl.edu/fieldcrops/ec154.pdf

Funderburk, J. E., F. M. Rhoads, and I. D. Teare. 1994. Modifying soil nutrient level affects soybean insect predators. *Agron J* 86:581–585.

Gordon, B. 2007. Manganese nutrition of glyphosate-resistant and conventional soybeans. *Better Crops with Plant Food* 4:12–13.

Ham, G. E. and A. C. Caldwell. 1978. Fertilizer placement effects on soybean seed yield, N_2 fixation, and ^{33}P uptake. Agron J 70:779-783.

Ham, G. E., I. E. Liener, S. D. Evans, R. D. Frazier, and W. W. Nelson. 1975. Yield and composition of soybean seed as affected by N and S fertilization. *Agron J* 67:293–297.

Haq, M. U. and A. P. Mallarino. 2000. Soybean yield and nutrient composition as affected by early season foliar fertilization. *Agron J* 92:16–24.

Heatherly, L. G. and R. W. Elmore. 2004. Managing inputs for peak production. Pp. 451–536. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*. Agronomy Monograph, 3rd ed. American Society of Agronomy, Madison, Wisconsin.

Heatherly, L. G., S. R. Spurlock, and K. N. Reddy. 2003. Weed management and early-season nitrogen for conventional and glyphosate-resistant soybean grown with and without irrigation. *Agron J* 95:446–453.

Hoeft, R. G. 2002. Soil testing and fertility. Pp. 91–131. In I*llinois Agronomy Handbook*, 23rd ed. University of Illinois Extension Service, Champaign.

Hoeft, R. G., E. D. Nafziger, R. R. Johnson, and S. R. Aldrich. 2000. *Modern Corn and Soybean Production*. 1st ed. MCSP Publications. Savoy, Illinois.

Huber, D. M., J. D. Leuck, W. C. Smith, and E. P. Christmas. 2004. Induced manganese deficiency in GM soybeans. In R. G. Hoeft (ed.) *Proc 34th North Cent. Extension-Industry Soil Fert Conf* 20:80–83. Potash & Phosphate Inst., Brookings, South Dakota.

Intarapapong, W., D. Hite, and D. Hudson. 2003. Economic and environmental impacts of variable-rate fertilizer application in Mississippi. Bull. #1129. Mississippi Agricultural & Forestry Experiment Station, Mississippi State University, http://msucares.com/pubs/bulletins/b1129.pdf

Lauzon, J. D., I. P. O'Halloran, D. J. Fallow, A. P. von Bertoldi, and D. Aspinall. 2005. Spatial variability of soil test phosphorus, potassium and pH of Ontario soils. *Agron J* 97:524–532.

Lyons, J. C. and F. B. Early. 1952. The effect of ammonium nitrate applications to field soils on nodulation, seed yield, and nitrogen and oil content of the seed of soybeans. *Soil Sci Soc Am J* 16: 259–263.

Maryland Cooperative Extension Service (MCES). 2006. Soil sampling procedures for nutrient management. College Park, http://anmp.umd.edu/Advisors/Soil_Sampling_Advisors.pdf

Mulla, D. J. 1993. Mapping and managing spatial patterns in soil fertility and crop yield. Pp. 15–26. In P. C. Robert, R. H. Rust, and W. E. Larson (eds.). *Proc of Soil Specific Crop Management: A Workshop on Research and Development Issues*. Minneapolis, Minnesota. ASA, CSSA, SSSA, Madison, Wisconsin, 14-16 April 1992.

Nelson, K. A., P. P. Motavalli, and M. Nathan. 2005. Response of no-till soybean [*Glycine max* (L.) Merr.] to timing of preplant and foliar potassium applications in a claypan soil. *Agron J* 97:832–838.

Parker, M. B., N. A. Minton, O. L. Brooks, and C. E. Perry. 1975. Soybean yields and lance nematode populations as affected by subsoiling, fertility, and nematicide treatments. *Agron J* 67:663–666.

Rains, G. C. and D. L. Thomas. 2001. Soil-sampling issues for precision management of crop production. Bull. #1208. University of Georgia Cooperative Extension Service, Athens, http://pubs.caes.uga.edu/caespubs/pubs/PDF/B1208.pdf

Ray, J. D., L. G. Heatherly, and F. B. Fritschi. 2006. Influence of large amounts of nitrogen on nonirrigated and irrigated soybean. *Crop Sci* 46:52–60.

Reetz, H. 2008. Agrifacts: New ideas and reminders on soil sampling, http://www.back-to-basics.net/agrifacts/pdf/b2b13.pdf (online only)

Rehm, G. W., A. Mallarino, K. Reid, D. Franzen, and J. Lamb. 2001. Soil sampling for variable rate fertilizer and lime application. SB-7647. University of Minnesota Extension, St. Paul, http://www.extension.umn.edu/distribution/cropsystems/DC7647.html

Reinbott, T. M. and D. G. Blevins. 1995. Response of soybean to foliar-applied boron and magnesium and soil-applied boron. *J Plant Nutrition* 18:179–200.

Rupe, J. C., W. E. Sabbe, R. T. Robbins, and E. E. Gbur, Jr. 1993. Soil and plant factors associated with sudden death syndrome of soybean. *J Prod Agric* 6:218–221.

Sawyer, J. E. 1994. Concepts of variable rate technology with considerations for fertilizer application. *J Prod Agric* 7:195-201.

Scharf, P. C. and W. J. Wiebold. 2003. Soybean yield responds minimally to nitrogen applications in Missouri. 17 Nov, http://www.plantmanagementnetwork.org/pub/cm/research/2003/soy/ (online only; limited access)

Schmidt, J. P., R. K. Taylor, and G. A. Milliken. 2002. Evaluating the potential for site-specific phosphorus application without high-density soil sampling. *Soil Sci Soc Am J* 66:276–283.

Schmitt, M. A., J. A. Lamb, G. W. Randall, J. H. Orf, and G. W. Rehm. 2001. In-season fertilizer nitrogen applications for soybean in Minnesota. *Agron J* 93:983–988.

Taylor, R. S., D. B. Weaver, C. W. Wood, and E. van Santen. 2005. Nitrogen application increases yield and early dry matter accumulation in late-planted soybean. *Crop Sci* 45:854–858.

Weber, C. R. 1966. Nodulating and nonnodulating soybean isolines: ii. Response to applied nitrogen and modified soil conditions. *Agron J* 58:46–49.

Welch, L. F., L. V. Boone, C. G. Chambliss, A. T. Christiansen, D. L. Mulvaney, M. G. Oldham, and J. W. Pendleton. 1973. Soybean yields with direct and residual nitrogen fertilization. *Agron J* 65:547–550.

Wesley, T. L., R. E. Lamond, V. L. Martin, and S. R. Duncan. 1998. Effects of late-season nitrogen fertilizer on irrigated soybean yield and composition. *J Prod Agric* 11:331–336.

Wollenhaupt, N. C., R. P. Wolkowski, and M. K. Clayton. 1994. Mapping soil test phosphorus and potassium for variable-rate fertilizer application. *J Prod Agric* 7:441–448.

Yin, X. and T. J. Vyn. 2002. Soybean responses to potassium placement and tillage alternatives following no-till. *Agron J* 94:1367–1374.

Pests and Weeds

Pests—*diseases*, nematodes, and insects—and weeds must be managed in all soybean production systems to limit their negative effect on yield and product quality. Management of pests and weeds involves both environmental and economical considerations; management measures often interact with nontarget areas or the surrounding environment and add to the cost of production.

Integrated pest management (*IPM*) is the scientific approach advocated to manage weeds, *plant pathogens*, and insect pests while minimizing the use of agrichemicals. The IPM approach involves using Best Management Practices to do the following:

- avoid a pest problem (e.g., choose disease- or nematode-resistant varieties, shift planting date to avoid a particular pest),
- determine that there truly is a problem (setting an action threshold for curative action),
- identify the causal agent or organism on a site-by-site basis (scouting sites with different potential for pest outbreaks), and
- select control measures that target the specific problem.

Integrated pest management combines *biological, chemical*, and *cultural control* tactics to make pest and weed management economical, environmentally sound, and socially acceptable (Buhler, Liebman, and Obrycki 2000; Kogan 1998). The IPM paradigm is valid for all cropping systems. The specific tactics used on a given site or in a particular region depend on local and regional socioeconomics and environmental conditions; however, the choices are made within an IPM framework.

Producers in the United States use IPM tactics to manage soybean pests. For example, many soybean varieties contain resistance to numerous pests. Early plantings in the midsouthern United States have successfully avoided outbreaks of Asian soybean rust (ASR, caused by *Phakopsora pachyrhizi*) and late-season foliage-feeding insects, thus lowering the potential need for synthetic pesticide applications. The sentinel plot network for detecting ASR has worked effectively to forewarn growers of the appearance of this virulent pathogen. Transgenic glyphosate-resistant (GR) varieties allow use of the environmentally friendly (Cerdeira and Duke 2006), *nonselective herbicide* glyphosate for weed management. Row spacing and canopy structure also are used effectively to manage weeds. Rotation with grain crops is used to control some nematode species.

Pathogens, insects, and weeds cause pervasive and extensive management challenges in U.S. soybean. Currently, management of these pests and weeds in U.S. soybean is possible through IPM and constantly developing technology. This section and following sections of this report address major issues regarding the sustainability of U.S. soybean production in the face of ever-changing pest and weed problems.

Diseases and Nematodes

Pests are significant contributors to soybean yield losses in the United States. The soybean pathogen spectrum is different between the northern and southern United States. In the northern region, losses attributed to pathogens averaged approximately 294 million bushels from 1999 to 2005 (Wrather and Koenning 2006; Wrather, Koenning, and Anderson 2003). During this period, the primary losses throughout most of the region were due to soybean cyst nematode (SCN), followed by root and seedling diseases, Sclerotinia stem rot, and stem canker. Yield losses to foliar, seed, and virus diseases also were substantial, but comprised only a combined 6% of the total losses.

In the southern region, primary causes of yield loss from 1999 to 2005 were SCN and root-knot nematodes. These causes were followed by foliar, stem, and root diseases. Overall, the average annual loss to plant diseases and nematodes was approximately 51.4 million bushels. The first reported losses (485 thousand bushels) due to soybean rust were reported in 2005 (Wrather and Koenning 2006).

Insects

Background information on insects and mites that damage U.S. soybean has been compiled (Higley and Boethel 1994). Additional information about these pests can be found in the soybean profiles available from the National Information System for Regional IPM Centers (NIS–RIPMC 2008). Boethel (2004) published information that summarizes practices for the integrated management of soybean insects.

Soybean can tolerate injury by arthropods and compensate for that injury to a much greater extent than most other crops (Higley and Boethel 1994). This is particularly true for defoliation, which—during the early growth stages of soybean—rarely decreases yield or requires control of damaging insect pests. Insects that directly consume flowers, pods, and seeds or that defoliate during reproductive development can be much more damaging and often require monitoring for treatable levels of infestation. The most damaging defoliators are velvetbean caterpillar (*Anticarsia gemmatalis* L.), soybean looper (*Pseudoplusia includens* Walker), green cloverworm (*Plathypena scabra* F.), Mexican bean beetle (*Epilachna varivestis* Mulsant), and bean leaf beetle (*Ceratoma triflurcata* Forster). The most damaging pod feeders are southern green stink bug (*Nezara viridula* L.), green stink bug (*Aerosternum hilare* Say), corn earworm (*Helicoverpa zea* Boddie), and bean leaf beetle (Boethel 2004; Gianessi 2009).

In general, insect pressure is greatest on soybean grown in the southern United States, where 6 to 12 insects are problematic enough to cause significant damage to soybean in some environments. The most damaging defoliating insects in this region are velvetbean caterpillar, soybean looper, and bean leaf beetle; the most damaging pod feeders are corn earworm and southern green stink bug (Boethel 2004; Gianessi 2009).

In the Midwest, most insect pests are attacked by natural enemies or biological control agents (Gianessi 2009). The most effective of these are beneficial insect predators, mainly ladybird beetles (*Harmonia axyridis*) and lacewings (family *Chrysopidae*). Few arthropods other than the soybean aphid (*Aphis glycines*) cause consistent problems. Bean leaf beetle and two-spotted spider mites (*Tetranychus urticae* Koch) also are considered serious arthropod pests on a sporadic basis. A biotype of the western corn rootworm has evolved egg laying outside of cornfields, and this new behavior (lack of fidelity to corn) diminishes the corn–soybean rotation as a viable stategy for controlling this pest (Boethel 2004).

The soybean aphid was first observed in the United States in 2000 (Hartman et al. 2001). This invasive species from Asia invaded Wisconsin and Illinois and has spread throughout most U.S. soybean regions except the Southeast. The soybean aphid has a complex life cycle with as many as 18 generations annually. The aphid spends the winter on buckthorn (*Rhamnus*) plants as eggs. They pass through a series of wingless and winged generations on soybean during the summer. Aphid populations have the potential to increase 10-fold every week and can grow very quickly to thousands of aphids per soybean plant in the summer (Onstad 2001). Winged aphids can be spread across large geographic areas by winds during the summer. This insect pest problem has become serious enough in the Midwest to warrant breeding for host-plant resistance. Several genes have been identified for the control of aphids and the ability of these genes to control different aphid biotypes currently is being assessed (Hill, Li, and Hartman 2004a, b, c; Kang, Rouf Mian, and Hammond 2008; Mensah, DiFonzo, and Wang 2008; Mensah et al. 2005; Rouf Mian, Hammond, and St. Martin 2008). These discoveries will be useful for developing varieties with aphid resistence. Insecticides for effective management of soybean aphids are available (University of Minnesota 2008).

The combined efforts of soybean entomology professionals, input suppliers, and growers will continue to sustain insect management in U.S. soybean. Most stakeholders in soybean production support and continue to improve IPM by integrating economic thresholds for chemical control with biological control and decisions concerning landscape design. Thus, even with periodic invasions of new insect pests or evolution of old ones, protection of soybean against insects likely is sustainable because of the integration of control tactics and the development of new IPM strategies.

Weeds

The pervasive nature of weeds provides a constant challenge for global soybean producers. Weeds have been credited with the ability to cause more potential soybean production losses than either insects or diseases (Gibson, Johnson, and Hillger 2005; Oerke 2006). In fact, weeds have been estimated to cause a potential 37% in production losses globally. The realized losses from weeds can be reduced to 7.5% with the implementation of modern weed management strategies (Oerke 2006).

In 1974, the four most problematic weed species in southern U.S. agronomic crops were johnsongrass (*Sorghum halepense*), common cocklebur (*Xanthium strumarium* L.), fall panicum (*Panicum dichotomiflorum* Michx.), and nutsedges (*Cyperus* spp.), in order of rank (Webster and Coble 1997). From 1971 to 1995, sicklepod (*Senna obtusifolia* [L.] Irwin and Barneby) and bermudagrass (*Cynodon dactylon* [L.] Pers.) developed into more problematic species while johnsongrass, crabgrass spp. (*Digitaria* spp.), and common cocklebur became less problematic (Webster and Coble 1997). More recent surveys of U.S. agronomic crop producers suggest that pigweed species (*Amaranthus* spp.), morningglory species (*Ipomoea* spp.), johnsongrass, ragweed species (*Ambrosia* spp.), foxtail species (*Setaria* spp.), and velvetleaf are among the most problematic weeds (Gibson, Johnson, and Hillger 2005; Kruger et al. 2009). The citing by producers of some weeds as more problematic, however, does not directly suggest that the weeds occur at a high frequency or that the majority of growers have these specific weeds under management (Gibson, Johnson, and Hillger 2005).

The dynamics of weed populations, as well as how the weed spectrum will change in species composition and abundance in response to soybean production practices and weed management techniques, creates a moving target for management. This movement necessitates a continually adaptive management strategy to provide for sustainable weed management in soybean (Dekker 1997; Derksen et al. 2002). This practice is, in effect, a continuation of past weed management strategies in soybean in which a continual infusion of new practices and technologies resulted in long-term success during the past century.

For maximal effectiveness, weed management systems should be developed at a regional level to accommodate the diversity in weed species, environmental factors, and production systems within a given geographic or climatic region (Gibson, Johnson, and Hillger 2005). Weed science professionals have long worked together across state boundaries to address weed management on a regional basis. This approach has resulted in a constant upgrading and adoption of new and/or innovative strategies to address evolving weed management issues.

Section Summary

Pests—diseases, nematodes, and insects—and weeds cause pervasive and extensive management challenges in all U.S. soybean production systems, and they must be managed to limit their negative effect on yield and product quality. Measures to manage pests and weeds often interact with nontarget areas or the surrounding environment and add to the cost of production.

Presently, IPM is used to manage soybean pests. This system includes using BMPs to avoid a pest problem, monitoring to determine that there is a problem, identifying the causal agent or organism, and selecting control measures that target the problem. Integrated pest management combines biological, chemical, and cultural control tactics to make pest management economical, environmentally sound, socially acceptable, and sustainable.

In the northern United States, annual losses attributed to diseases and nematodes (mainly SCN) averaged approximately 294 million bushels from 1999 to 2005. In the southern United States, primary causes of an estimated 51.4 million bushels in annual yield losses from 1999 to 2005 were SCN and root-knot nematode. In general, insect pressure is greatest on soybean grown in the southern United States, where 6 to 12 insects are problematic enough to cause significant damage to soybean in some environments. In the Midwest, most insect pests are attacked by natural enemies or biological control agents. Few arthropods other than the soybean aphid cause consistent problems.

Weeds have been credited with the ability to cause more potential soybean production losses than either pathogens or insects. The dynamics of weed populations, as well as changes in species composition and abundance in response to soybean production practices and weed management techniques, necessitates a continual adaptive management strategy to provide for sustainable weed management. This practice is, in effect, a continuation of past weed management strategies in soybean in which a continual infusion of new practices and technologies resulted in long-term success during the past century.

Glossary

Biological control. Pest management that protects, augments, or releases organisms that are natural enemies of the pest.

Chemical control. Pest management that uses a chemical toxin or repellent.

Cultural control. Pest management that uses tillage, sanitation, harvesting, and other techniques to alter the pest's environment. This method also includes practices that enhance plant productivity to overcome the effects of pest injury.

Disease. Plant injury from biotic stress resulting from infection of plants by fungi, oomycetes, bacteria, or viruses.

Integrated pest management (IPM). The ecologically based decision support system for managing weeds, plant pathogens, and insect pests while minimizing use of agrichemicals. IPM combines complementary and compatible biological, chemical, and cultural control tactics to make pest management economical, environmentally sound, and socially acceptable.

Nonselective herbicide. An herbicide that is generally toxic to all plants treated. Some selective herbicides may become nonselective if used at very high rates.

Plant pathogen. Refers to fungi, oomycetes, nematodes, bacteria, or viruses that infect plants and cause injury.

Literature Cited

Boethel, D. J. 2004. Integrated management of soybean insects. Pp. 853–881. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*, 3rd ed. Agronomy Monograph 16. American Society of Agronomy, Madison, Wisconsin.

Buhler, D. D., M. Liebman, and J. J. Obrycki. 2000. Theoretical and practical challenges to an IPM approach to weed management. *Weed Sci* 48:274–280.

Cerdeira, A. L., and S. O. Duke. 2006. The current status and environmental impact of glyphosate-resistant crops: A review. *J Environ Qual* 35:1633–1658.

Dekker, J. 1997. Weed diversity and weed management. *Weed Sci* 45:357–363.

Derksen, D. A., R. L. Anderson, R. E. Blackshaw, and F. Maxwell. 2002. Weed dynamics and management strategies for cropping systems in the northern Great Plains. *Agron J* 94:174–185.

Gianessi, L. 2009. The benefits of insecticide use: Soybeans. CropLife Foundation, Washington, D.C., http://www.croplifefoundation.org

Gibson, K. D., W. G. Johnson, and D. E. Hillger. 2005. Farmer perceptions of problematic corn and soybean weeds in Indiana. *Weed Technol* 19:1065–1070.

Hartman, G. L., L. L. Domier, L. M. Wax, C. G. Helm, D. W. Onstad, J. T. Shaw, L. F. Solter, D. J. Voegtlin, C. J. D'Arcy, M. E. Gray, K. L. Steffey, S. A. Isard, and P. L. Orwick. 2001. Occurrence and distribution of *Aphis glycines* on soybeans in Illinois in 2000 and its potential control. *Plant Health Prog 5* Feb, http://www.plantmanagementnetwork.org/pub/php/brief/aphisglycines/ (online only; limited access)

Higley, L. G. and D. J. Boethel. 1994. *Handbook of Soybean Insect Pests*. Entomological Society of America, Lanham, Maryland.

Hill, C. B., Y. Li, and G. L. Hartman. 2004a. Resistance to the soybean aphid in soybean germplasm. *Crop Sci* 44:98–106.

Hill, C. B., Y. Li, and G. L. Hartman. 2004b. A single dominant gene for resistance to the soybean aphid in the soybean cultivar Dowling. *Crop Sci* 44:1601–1605.

Hill, C. B., Y. Li, and G. L. Hartman. 2004c. Soybean aphid resistance in soybean Jackson is controlled by a single dominant gene. *Crop Sci* 44:1606–1608.

Kang, S-T., M. A. Rouf Mian, and R. B. Hammond. 2008. Soybean aphid resistance in PI 243540 is controlled by a single dominant gene. *Crop Sci* 48:1744–1748.

Kogan, M. 1998. Integrated pest management: Historical perspectives and contemporary developments. *Ann Rev Entomol* 43:243–270.

Kruger, G. R., W. G. Johnson, S. C. Weller, M. D. K. Owen, D. R. Shaw, J. W. Wilcut, D. L. Jordan, R. G. Wilson, M. L. Bernards, and B. G. Young. 2009. U.S. grower views on problematic weeds and changes in weed pressure in GR corn, cotton, and soybean cropping systems. *Weed Technol* (in press).

Mensah, C., C. DiFonzo, and D. Wang. 2008. Inheritance of soybean aphid resistance in PI 567541B and PI 567598B. *Crop Sci* 48:1759–1763.

Mensah, C., C. DiFonzo, R. L. Nelson, and D. Wang. 2005. Resistance to soybean aphid in early maturing soybean germplasm. *Crop Sci* 45:2228–2233.

National Information System–Regional Integrated Pest Management Centers (NIS–RIPMC). 2008. NIS–RIPMC, Washington, D.C. and Raleigh, North Carolina, http://www.ipmcenters.org/cropprofiles/

Oerke, E. C. 2006. Crop losses to pests. *J Agri Sci* 144:31–43.

Onstad, D. W. 2001. Biology of Asian soybean aphid. Publ. 31. *Proc 31st Soybean Seed Res Conf*. Dec. 5–7, Chicago, Illinois. American Seed Trade Association, Alexandria, Virginia.

Rouf Mian, M.A., R. B. Hammond, and S. K. St. Martin. 2008. New plant introductions with resistance to the soybean aphid. *Crop Sci* 48:1055–1061.

University of Minnesota Extension. 2008. Soybean aphid. In *Minnesota Soybean Production*. St. Paul, http://www.soybeans.umn.edu/crop/insects/aphid/aphid.htm

Webster, T. M. and H. D. Coble. 1997. Changes in the weed species composition of the southern United States: 1974 to 1995. *Weed Technol* 11:308–317.

Wrather, J. A. and S. R. Koenning. 2006. Estimates of disease effects on soybean yields in the United States 2003-2005. *J Nematol* 38:173–180.

Wrather, J. A., S. R. Koenning, and T. R. Anderson. 2003. Effect of diseases on soybean yields in the United States and Ontario (1999-2002). *Plant Health Prog* 4 March, http://www.plantmanagementnetwork.org/pub/php/review/2003/soybean/ (online only; limited access)

Drought and Irrigation

The adverse effects of water-deficit stress (drought) and the beneficial effects of irrigation on soybean production are well documented (Heatherly and Ray 2007). Drought is the most damaging abiotic stress to soybean grown in the United States. In the midsouthern United States and Southeast, moderate to severe drought stress to soybean occurs annually. In the Midwest, drought stress can severely reduce yields in years such as 2003 when it occurs on a region-wide scale. Drought-reduced yields are a threat to sustainability of all soybean production systems. Properly applied irrigation will alleviate the effects of drought stress to soybean; however, prohibitive cost and/or lack of an available water source often preclude irrigation as an option for alleviating drought stress in soybean.

Sinclair and Ludlow (1986) divided the response of plants to soil water deficits into three distinct stages.

- Stage I occurs when soil water is sufficient to allow maximum transpiration.
- Stage II begins when water uptake from the soil is less than that needed for optimum transpiration. At this point, water loss from the plant matches water uptake from the soil.
- Stage III occurs when stomatal conductance and the rate of water uptake from the soil are minimal.

Most major plant processes that contribute to crop yield are inhibited by soil drying beginning in late Stage I or in early Stage II (Serraj and Sinclair 2002). Crop plants in Stage III are fighting for survival; soybean production in these environs is not sustainable without supplemental water.

Alleviating Drought Stress Effects

As stated by Egli (2008), a challenge for the future of soybean production in the United States is to develop and apply technology to increase yields in high-stress, low-yield environments such as drought-prone production areas. Development of management practices for avoiding some of the effects of drought stress as well as development of varieties with traits that will impart at least partial drought tolerance would bring improvements in this area. Three recent technological advances provide an opportunity to do this.

The first advance is the development and increased use of the Early Soybean Production System (ESPS) in the midsouthern United States. This system is based on replacing the previous pattern of May and June planting of late-maturing varieties (Maturity Group [MG] V-VIII) with the new paradigm of earlier planting of early-maturing varieties (MG II-V) (Boquet 1998; Heatherly 1999b, 2005a; Heatherly and Elmore 2004; Heatherly and Spurlock 1999). Using this system allows soybean to avoid a large portion of the drought period that occurs in the region because drought-sensitive reproductive stages occur earlier in the growing season (Heatherly 2005b) and to avoid the increasingly higher temperatures and moisture deficits that occur in July, August, and September. Increased use of the ESPS system in Arkansas, Louisiana, and Mississippi is associated with average yields increasing from a range of 24.4 to 27.4 bu/acre in the three states during 1989 to1993 to a range of 33.4 to 35.7 bu/acre during 2001 to 2005 (Heatherly 2005c). Use of the ESPS also lowers production risks (Boquet 1998) and thus enhances sustainability of soybean production in the region. Details of the ESPS have been outlined by Heatherly (1999b) and Heatherly and Bowers (1998).

The second advance is the identification of soybean *plant introductions* (*PI*) that are slow wilting (Bliss 2008; SEFP 2009). These PIs have been used to develop advanced breeding lines that carry the slow-wilting trait, and these lines have been evaluated in the U.S. Department of Agriculture (USDA) Uniform tests for 4 years. The slow-wilting lines yield 4 to 8 bu/acre more than conventional varieties under drought conditions. These drought-resistant lines seem best suited for lower-yielding, drought-prone environments. Some of this germplasm will be released in 2009. It will be available as breeding stock for the development of varieties that can better withstand drought, thus improving sustainability of soybean production in U.S. areas with limited water.

The third advance is the release of two breeding lines (R01-416F and R01-581F) that maintain a higher rate of N_2 fixation during drought periods (Chen et al. 2007; Sinclair et al. 2007). Soybean N_2 fixation begins to respond negatively to soil drying earlier in Stage I than other plant processes including transpiration, photosynthesis, and biomass accumulation (Heatherly and Ray 2007). This greater sensitivity of N_2 fixation to soil drying may reduce grain yield capability by as much as 18% (Purcell and King 1996). The two breeding lines offer genetic potential for reducing this yield loss in soybean during late Stage I/early Stage II drought stress. Seed of these lines are available for research purposes and variety development. Newly developed varieties that possess this enhanced N_2 fixation trait in drought environs will contribute to yield stability and sustainability in drought-prone regions.

Irrigation to Remedy Drought Stress

In each of the three previously designated regions of U.S. soybean production (Chapter 1, p. 5), irrigation is used to some extent. In 2002 and 2007, 8% (5.46 million acres) and 7.5% (5.24 million acres) of U.S. soybean were irrigated, respectively (USDA–NASS 2009). The majority of the irrigated soybean acreage is in the western Corn Belt and the midsouthern United States (USDA–NASS 2008a) where summer weather patterns result in drought stress that makes dryland production risky over the long term. Where irrigation is used, the ideal goal is to provide supplemental water to achieve maximum seed yield by maintaining soil water at a level to hold the crop in Stage I.

Irrigated soybean systems are the most productive in the United States (Egli 2008; Heatherly 1999c; Heatherly and Ray 2007). Irrigation is the most important factor in sustaining a doublecropping system in the midsouthern United States (Wesley 1999). In drought-prone areas where irrigation is widely used and properly managed, it is the single most important factor for sustaining consistently profitable yields (Heatherly and Elmore 2004; Heatherly and Ray 2007).

Water for future irrigation will become less available if current sources are depleted below recoverable levels. If water for irrigation becomes limited or restricted, resulting limited irrigation will support only small yield increases that may not be sufficient to ensure profitability. Alternatively, some irrigated soybean acreage will revert to dryland production where yield levels likely will not be profitable (Heatherly and Elmore 2004; Heatherly and Ray 2007) even when using newly developed varieties with the drought-avoiding traits described here.

Sustainability of the present level of U.S. soybean irrigation depends on maintaining irrigation water supplies. Water resources are being monitored and regulated increasingly by local and regional water management districts to ensure adequate supplies for future irrigation. Such regulatory bodies usually are chartered by state governments and currently provide the only reasonable governance of the judicious use of water for irrigation in a particular district or region. This governance could improve irrigation water use efficiency, promote water conservation in those areas that are dependent on irrigation for sustained profitability, and ensure that water resources needed for irrigation continue to be available. These regulatory bodies also have programs to address such environmental concerns as groundwater quality, protection of endangered species, irrigation runoff, soil nitrate levels, and stream/river flows together with monitoring/regulating irrigation water use (see website URLs on p. 36 for representative districts and their functions/programs).

Section Summary

Drought is the most damaging abiotic stress to soybean. Even mild water stress can cause decreases in seed yield by reducing growth and development and lowering the rate of N_2 fixation. The challenge for future soybean production is to develop technology to increase yields in drought-prone production areas.

Three recent advances in soybean production management and breeding provide an opportunity to mitigate some of the effects of drought. The first is the development of the ESPS for the midsouthern United States. This new paradigm uses early planting of earlier-maturing varieties to avoid the most drought-prone period of the growing season. The second advance is the release of two breeding lines that maintain a higher rate of N_2 fixation during drought periods. The third is the identification of two soybean PIs that are slow wilting. These two PIs have been used to develop breeding lines that carry the slow-wilting trait. These developments offer management options and genetic potential that can be used to reduce yield loss in soybean as a result of the effects of mild to moderate drought stress.

Irrigated soybean systems are the most productive in the United States; they provide consistent and sustainable soybean production in the long term in regions that receive too little or too erratic rainfall to ensure stable yields without irrigation. Sustainability of irrigation as a viable input is dependent on maintaining adequate ground and surface water resources in those regions. Local and regional water management districts are seeking to maintain adequate resources on an increasing scale. These regulatory bodies likely will provide the only reasonable governance to ensure adequate water supplies for future soybean irrigation and address environmental concerns such as groundwater quality, protection of endangered species, irrigation runoff, soil nitrate levels, and stream/river flows that may be affected by irrigation.

Glossary

Plant introduction. Germplasm brought to the United States from other parts of the world to provide new genes for potential improvement of crop productivity.

Literature Cited

Bliss, R. M. 2008. Drought-hardy soybean lines show their stamina. *Agric Res Magazine* 56(10):14–15, http://www.ars.usda.gov/is/AR/archive/nov08/soybean1108.htm

Boquet, D. J. 1998. Yield and risk utilizing short-season soybean production in the midsouthern USA. *Crop Sci* 38:1004–1011.

Chen, P., C. H. Sneller, L. C. Purcell, T. R. Sinclair, C. A King, and T. Ishibashi. 2007. Registration of soybean germplasm lines R01-416F and R01-581F for improved yield and nitrogen fixation under drought stress. *J Plant Registration* 1:166–167.

Egli, D. B. 2008. Soybean yield trends from 1972 to 2003 in midwestern USA. *Field Crops Res* 106:53–59.

Heatherly, L. G. 1999b. Early soybean production system (ESPS). Pp. 103–118. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Heatherly, L. G. 1999c. Soybean irrigation. Pp. 119–141. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Heatherly, L. G. 2005a. Midsouthern USA soybean yield affected by maturity group and planting date. *Crop Management* 18 April, http://www.plantmanagementnetwork.org/cm/ (Online only, limited access)

Heatherly, L. G. 2005b. Soybean development in the midsouthern USA related to date of planting and maturity classification. *Crop Management* 21 April, http://www.plantmanagementnetwork.org/cm/ (Online only, limited access)

Heatherly, L. G. 2005c. Mid-south soybean yield trends up. *Delta Farm Press* 62(50):12.

Heatherly, L. G., and G. R. Bowers (eds.). 1998. *Early Soybean Production System Handbook*. USB-6009-091998-11000. United Soybean Board, St. Louis, Missouri.

Heatherly, L. G. and R. W. Elmore. 2004. Managing inputs for peak production. Pp. 451–536. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*, 3rd ed. Agronomy Monograph 16. American Society of Agronomy, Madison, Wisconsin.

Heatherly, L. G. and J. D. Ray. 2007. Soybean and corn. Pp. 477–533. In R. J. Lascano and R. E. Sojka (eds.). *Irrigation of Agricultural Crops*, 2nd ed. Agronomy Monograph 30. American Society of Agronomy, Madison, Wisconsin.

Heatherly, L. G., and S. R. Spurlock. 1999. Yield and economics of traditional and early soybean production system (ESPS) seedings in the midsouthern USA. *Field Crops Res* 63:35–45.

Purcell, L. C., and C. A. King. 1996. Drought and nitrogen source effects on nitrogen nutrition, seed growth, and yield in soybean. *J Plant Nutr* 19:949–966.

Serraj, R., and T. R. Sinclair. 2002. Osmolyte accumulation: Can it really help increase crop yield under drought conditions? *Plant, Cell, Environ*. 25:333–341.

Sinclair, T. R., and M. M. Ludlow. 1986. Influence of soil water supply on the plant water balance of four tropical grain legumes. *Aust J Plant Phys* 13:329–341.

Sinclair, T. R., L. C. Purcell, C. A. King, C. H. Sneller, P. Chen, and V. Vadez. 2007. Drought tolerance and yield increase of soybean resulting from improved symbiotic N_2 fixation. *Field Crops Res* 101:68–71.

Southeast Farm Press (SEFP). 2009. Researchers identify drought-hardy soybeans. Feb. 3, http://southeastfarmpress.com/soybeans/soybean-research-0203/index.html

U.S. Department of Agriculture–National Agriculture Statistics Service (USDA–NASS). 2008a. Quick stats: Agricultural statistics data base. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/QuickStats/

U.S. Department of Agriculture–National Agriculture Statistics Service (USDA–NASS). 2009. Census of Agricultural Quick Stats. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/index.asp.

Wesley, R. A. 1999. Doublecropping wheat and soybeans. Pp. 143–156. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

URLs for websites of water management districts in agricultural regions of the United States

Central Platte Natural Resources District http://www.cpnrd.org/

Groundwater Management Districts Association http://www.gmdausa.org/index.htm

Ground Water Management Districts/Agencies in California http://www.agwa.org/gwm_dists.html

Kansas Ground Water Management Districts http://www.kgs.ku.edu/Hydro/gmd.html

Middle Republican Natural Resources District http://www.nrdnet.org/news-events/news_pdfs/MRNRD_010207.pdf

State of Colorado, Colorado Ground Water Commission, Designated Basins and Ground Water Management Districts http://water.state.co.us/cgwc/DB-GWMgmtDist.htm

Yazoo Mississippi Delta Joint Water Management District http://www.ymd.org/

3 Soybean Production Systems in the United States: Conventional System (Nontransgenic Varieties)

Breeding and Variety Development/Availability

Soybean varieties have been developed using conventional breeding techniques since about 1930. These varieties have allowed a progressive improvement in soybean culture through improved resistance to pests and increased efficiency of plant processes. Currently, less than 8% of the U.S. soybean acreage is devoted to conventional varieties. Most public and private sector soybean breeding programs are now using transgenic varieties as parent material for future variety development.

Conventional breeding strategies have been very successful in improving soybean productivity and quality. There are numerous methods that can be used to develop soybean varieties, but the single seed descent procedure is the one most widely used today to develop conventional varieties (Brim 1966, 1973; Fehr 1987a, b). In the past decade or so, genetic improvement in soybean has included both conventional and molecular-based strategies (Orf, Diers, and Boerma 2004). As the private sector moves to include multiple transgenic events or different transgenic events in the same variety, some private programs are contemplating doing their basic genetic improvement using conventional breeding techniques and then backcrossing the transgenic trait(s) into the lines for eventual release as a variety (Fehr 1987b).

It is likely that most public soybean breeding programs will continue to emphasize conventional breeding rather than using transgenic materials. These trends suggest that conventional soybean varieties will continue to be developed, but the availability of seed will depend on the demand from domestic and international markets that specifically seek seed from conventional varieties and/or the ability for conventional varieties to keep pace with transgenic varieties in terms of yield and economic value. If this demand continues, conventional varieties for use in conventional and organic systems should continue to be available in limited quantity.

Three recent occurrences have combined to increase producer interest in reverting to a soybean production system that uses conventional varieties (Bennett 2009): the higher price of glyphosate-resistant (GR) seed, the cost of glyphosate, and concern about GR weeds. There are limitations and conditions, however, that may prevent this reversion on a large scale.

1. Availability and amount of seed of conventional nontransgenic varieties is very limited as of this writing. Thus, only a small acreage of these varieties can be planted in the foreseeable future.
2. Planting non-GR varieties in a GR landscape poses a threat of misapplied herbicide and drift damage to non-GR varieties.
3. If producers revert to planting non-GR varieties and using nonglyphosate herbicides, ability to correctly identify weed species and determine weed size will be imperative to obtain maximum effective weed control. Timing of application of nonglyphosate herbicides to weeds generally is more critical than it is for glyphosate.
4. Using conventional non-GR varieties may entail reverting to a wide-row system to allow row cultivation and postdirected spraying, which will involve investing in a different set of equipment.
5. Using GR varieties will allow the application of nonglyphosate herbicides, and this will nullify many of the negatives associated with using conventional non-GR varieties in a GR landscape.

Disease/Nematode Management

Diseases

Many of the diseases causing soybean yield losses are readily managed by using varieties with high levels of resistance or by applying cultural and chemical controls (Table 3.1). Thus, a portion of the yield losses that may have occurred in production environments would have been prevented if available controls had been used. For example, frogeye leaf spot (caused by *Cercospora sojina* Hara) reached very high levels on 500,000 acres of a particular variety in Ohio during 2006, which resulted in a 35% decrease in yield. This variety had never been evaluated for resistance to this

Table 3.1. Major pathogens that affect soybean in the northern and southern United States and indication of soybean resistance. Listed management and/or control measures are for environments with known infestations of listed pathogen. Where varietal resistance is available, using a resistant variety is an assumed management measure and is not listed as such (adapted from Heatherly and Elmore [2004])

Pathogen			
Common Name	Causal Organism(s)	Varietal Resistance	Management/Control Measures
Anthracnose	*Colletotrichum truncatum* (Schw.) Andrus & W.D. Moore	No	North—occurrence rare; South—plant disease-free, treated seed[a]; apply foliar fungicide during reproductive development; clean till; rotate with non-legume crops
Asian soybean rust	*Phakopsora pachyrhizi*	In development	North—monitor incidence in southern United States; apply foliar fungicides when risk is high; South—plant early to avoid infection; apply foliar fungicide based on occurrence in sentinel plots
Brown spot	*Septoria glycines* Hemmi	Yes	North—clean till; fungicides rarely economical; South—occurrence rare
Brown stem rot	*Phialophora gregata*	Yes (Rbs genes)	North—clean till; rotate with corn, small grains, or forage legumes; South—same as north plus plant late
Cercospora leaf blight, purple seed stain	*Cercospora kikuchii* (T. Matsu. & Tomoyasu) Gardner	Yes	North—occurrence rare; South—plant disease-free seed; plant late; apply foliar fungicide during reproductive development; rotate with non-legume crop
Charcoal rot	*Macrophomina phaseolina* (Tassi) Goid	No	North—plant *tolerant* varieties (genetic resistance identified but not yet in varieties); rotate out of soybean; avoid excessive seeding rates; minimize plant stresses; South—same as north
Frogeye leaf spot	*Cercospora sojina* Hara	Yes (Rcs3 gene)	North—plant disease-free seed; clean till; apply foliar fungicide during reproductive development; South—same as north
Fusarium root rot and seedling blight	*Fusarium solani*, *F. oxysporum*, and *F. graminearum*	Not well characterized	North—Plant high-quality, treated seed[a]; optimize drainage; South—same as north; plant late; clean till
Phytophthora root and stem rot	*Phytophthora sojae*	Yes (Rps and partial resistance)	North—use high rates of seed treatment[a]; maintain good surface drainage; South—same as north
Pod and stem blight, Phomopsis seed decay	*Diaporthe phaseolorum* (Cke. & Ell.) Sacc. f. sp. *sojae* (Lehman) Wehm., *Phomopsis sojae* Lehman, and *Phomopsis longicolla* Hobbs	Yes	North—plant disease-free, treated seed[a]; apply foliar fungicide during reproductive development; harvest promptly at maturity; South—same as north
Pythium seed decay	*Pythium* spp.	Not well characterized	North—plant treated seed[a]; maintain optimum surface drainage; South—same as north
Rhizoctonia foliar (aerial) blight	*Rhizoctonia solani* anastomosis group (AG) 1	No	North—occurrence rare; South—plant tolerant varieties; apply foliar fungicide during reproductive development; avoid excessive irrigation
Sclerotinia stem rot	*Sclerotinia sclerotiorum*	Yes	North—plant treated seed[a]; plant sclerotia-free seed; rotate; apply foliar fungicides to high-value soybean during reproductive development; South—occurrence rare
Soybean cyst nematode	*Heterodera glycines*	Yes	North—monitor SCN populations to determine problem; rotate sources of resistance and with non-host crop; South—same as north
Stem canker	*Diaporthe phaseolorum* var. *meridionalis* (south) and var. *caulivora* (north)	Yes	North—plant disease-free seed; rotate; clean till; South—same as north
Root knot and reniform nematodes	*Meloidogyne* spp., *Rotylenchulus reniformis*	Yes	North—occurrence rare; South—rotate
Sudden death syndrome	*Fusarium virguliforme*	Yes	North—control SCN; rotate; clean till; South—same as north; plant early

[a]See Table 3.2 for proper fungicide.

Table 3.2. Seed-treatment fungicide combinations (contact + systemic) available for broad-spectrum control of soybean seed and seedling diseases, and organisms controlled or suppressed by each fungicide product as stated on its label or in extension publications (Sources: product labels; Coker et al. [2008]; Giesler and Ziems [2008]; Pedersen [2007]; Wrather, Sweets, and Wiebold [2008])

Trade Name	Ingredients	Pathogens Controlled or Suppressed
ApronMaxx RTA and Warden RTA	Mefenoxam, Fludioxonil	Phytophthora, Pythium, Fusarium, Rhizoctonia, Phomopsis
Bean Guard/Allegiance	Metalaxyl, Captan, Carboxin	Pythium, Phytophthora, Fusarium, Rhizoctonia, Phomopsis
Catapult XL	Mefenoxam, Chloroneb	Phytophthora, Pythium, Rhizoctonia
Prevail	Metalaxyl, Carboxin, PCNB	Pythium, Rhizoctonia, Phomopsis
Protector-L-Allegiance	Metalaxyl, Thiram	Pythium, Rhizoctonia, Phomopsis
Soygard	Metalaxyl, Azoxystrobin	Pythium, Rhizoctonia, Phomopsis, Fusarium
Stiletto	Metalaxyl, Carboxin, Thiram	Pythium, Fusarium, Rhizoctonia, Phomopsis, Phytophthora

Cautions: Check product label for compatibility with *B. japonicum* inoculant, and do not feed or sell treated seeds that are not planted.

disease although the variety was widely sold under several brand names. Selecting a variety with known resistance to the pathogen might have prevented these 2006 losses.

As indicated in Table 3.1, many common pathogens that affect soybean may be managed by using resistant varieties. Arguably, *varietal resistance* is the most widely used and effective management tool for soybean diseases and has contributed to the trend of yield increases in U.S. soybean production. Most varieties have resistance to multiple pathogens; however, as the soybean base germplasm diversifies and the seed industry changes, chances increase that a variety will not be exposed to a specific pathogen during its time of development. This circumstance increases the importance of selecting varieties with known resistance to a particular pathogen that may be prominent in a specific production environment.

The few fungicides labeled for soybean before 2005 were used primarily as seed treatments (e.g., to protect against fungal attack to planted seed); conversely, few were labeled for foliar applications. Many of the earlier seed treatments were contact fungicides and were not active on several soil- and seed-borne fungi that were problematic for soybean stand establishment. Recently, new systemic fungicides have been developed and labeled as a seed treatment for soybean (Table 3.2). The availability of myriad compounds that are a combination of contact and systemic fungicide treatments and their low cost (<$3.50/acre) allow for the economical control of most prominent disease pathogens that were and are problematic for soybean stand establishment. Currently, several strobilurin compounds are in the process of acquiring registration as seed treatments in the United States. The combinations of active ingredients in seed treatments will be critical because each fungicide is effective only against a limited number of pathogens (Broders et al. 2007).

For foliar disease control before 2002, thiophanate methyl and azoxystrobin were the only two labeled fungicides. They were applied to <1% of U.S. soybean acres in 2001 (USDA–NASS 2002a), primarily to manage aerial blight, frogeye leaf spot, and *Diaporthe* stem canker in the southern production regions (Schneider et al. 2008). Dramatic changes have occurred since 2002, primarily due to the arrival of Asian soybean rust (ASR) (caused by *Phakopsora pachyrhizi*). This foliar pathogen has caused both substantial yield losses and increased production costs in every country where it has become established. Yield losses in the United States were projected to be between 10 and 50% depending on the timing of infection and the amount of inoculum that could build up each season. To prepare for these losses, additional strobilurin-type compounds were labeled and numerous triazole-type compounds were given Environmental Protection Agency (EPA) Section 18 (emergency exemption) labels (Table 3.3). As a result, foliar fungicides were applied to 4% of U.S. soybean acres in 2006, a 4.3-fold increase (484,000 vs. 108,000 lb) above 2002 applications, with strobilurins comprising approximately two-thirds of the applied amount (USDA–NASS 2003, 2007). Mueller (2008) summarized the current status of these fungicides and other features including bee toxicity.

Presently, U.S. yield losses directly attributable to ASR are small. These losses were limited to Georgia and Alabama in 2005 when the incidence of rust increased very early in the production season, and to

Table 3.3. Fungicides labeled (EPA section 3 [full label] and section 18 [emergency exemption]) for use on soybean for management of soybean rust

Trade Name	Manufacturer	Chemical Group	Spray Interval (Days)	Preharvest Interval
Headline®2.09EC	BASF Corporation	Strobilurin	7–21	21
Quadris®2.08EC	Syngenta Crop Protection, Inc.	Strobilurin	21	14
Alto®100SL	Syngenta Crop Protection, Inc.	Triazole	14–21	30
Punch™	DuPont	Triazole	14–21	30
Topguard™125SC	Cheminova	Triazole	21	21
Caramba™	BASF Corporation	Triazole	10–21	30
Laredo™25EC	Dow AgroSciences	Triazole	14–21	28
Laredo™25EW	Dow AgroSciences	Triazole	14–21	28
Tilt®250EC	Syngenta Crop Protection	Triazole	14	<R5
PropiMax™3.6EC	Dow AgroSciences	Triazole	14	<R5
Bumper®41.8EC	Makhteshim_Agari	Triazole	14	<R5
Domark®230ME	Valent USA	Triazole	15–21	<R5
Folicur®3.6F	Bayer Crop Science	Triazole	10–21	30
Orius™3.6F	Makhteshim_Agari	Triazole	10–21	30
Uppercut™	DuPont	Triazole	10–21	30
Quadris®Xtra	Syngenta Crop Protection	Triazole and strobilurin	21	14
Headline®Caramba™ CoPack	BASF Corporation	Triazole and strobilurin	10–21	21
Stratego®250EC	Bayer Crop Science	Triazole and strobilurin	10–21	<R5
Quilt™1.67SC	Syngenta Crop Protection	Triazole and strobilurin	14–21	<R5
Headline®SBR	BASF Corporation	Triazole and strobilurin	10–21	21

Texas and Missouri in 2007 when rust increased in Texas and slowly made its way north to impact a few fields late in the season. By contrast, in 2006 and 2008 soybean rust did not impact yield; this result is thought to be due to the low amount of rust that was able to overwinter as well as the unfavorable environmental conditions for inoculum build-up in the spring. Simply stated, since the arrival of ASR in the United States in late 2004, environmental conditions have not been favorable for ASR development and dissemination; thus, it has not been a problematic pathogen in soybean production. A continuation of the sentinel plot system (Giesler, Kemerait, and Sconyers 2008) is the surest way to minimize production risk from ASR in the United States.

Although environmental impacts of fungicides are not as predominant as those for other pesticides, there are secondary impacts attributable to their application. In several instances where foliar fungicides were applied to fields, insect pests increased to damaging levels. Fungicides applied to soybean put all *entomopathogenic* fungi at risk (Ragsdale, Koch, and Grau 2008). In both Minnesota and Wisconsin, foliar fungicides decreased the level of disease on aphids and mites, respectively (Ragsdale, Koch, and Grau 2008). In addition, both strobilurin and triazole-based fungicides have single mode-of-action and thus are subject to development of fungicide resistance by fungal pathogens. The risk is high for the strobilurins (QoI inhibitor) and medium for triazoles (Demethylation inhibitor) (Bradley 2008). There are currently 29 plant pathogens that have resistance to the strobilurins (FRAC 2008), but none of them infect soybean at this time. Judicious use of strobilurin compounds to manage soybean diseases should help prolong their effectiveness against soybean pathogens.

Soybean Cyst Nematode

Soybean cyst nematode (SCN) is the most damaging pest to soybean in the United States (Niblack et al. 2008). It is found in a greater number of fields each year. Recent surveys showed an increase in the total number of counties in North America that have fields with SCN (Niblack and Tylka 2008) (Fig. 3.1). The biggest challenge facing producers is that SCN impacts yield with no or few visible aboveground symptoms (Niblack 2005). Producers must take soil samples for nematode analysis to determine the presence and type of the pathogen (Morrison 2009).

Soybean cyst nematode currently is managed effectively through a combination of planting resistant varieties and rotating with nonhost crops such as alfalfa (*Medicago sativa* L.), corn, and wheat (Chen 2007; Heatherly and Elmore 2004; Niblack and Tylka 2008). Chemical control is neither effective nor economical.

More than 90% of the varieties with SCN resistance available today are derived from one primary genetic source of resistance, PI 88788. This development has led to adaptation (formerly called race shift) of some SCN populations in some regions, which is a concern for future SCN management across the north central United States (Faghihi et al. 2008; Hershman, Heinz, and Kennedy 2008; Mitchum et al. 2007; Niblack 2005). Approximately 80% of the SCN populations collected from 45 locations in Missouri could reproduce on PI 88788 (Mitchum et al. 2007). In addition, SCN populations were able to reproduce on PI 548402 (Peking), PI 548316 (Cloud), and PI 209332. This action can be offset by using other sources such as PI 90763, 437654, PI 89772, or PI 438489B for resistance in Missouri (Mitchum et al. 2007). A similar trend was reported in Illinois, where populations that could reproduce on PI 88788 increased from 30% in 1991 to more than 60% in 2005 (Niblack et al. 2008). In Illinois, most populations have not adapted to PI 548402 (Peking) or PI 437654 sources of resistance. Presently, rotating alternative sources of resistance will slow SCN's adaptation to resistance and preserve the utility of using resistant varieties to sustain soybean production in the presence of SCN for a longer period (Morrison 2009; Niblack et al. 2008).

The future of managing SCN will depend on intro-

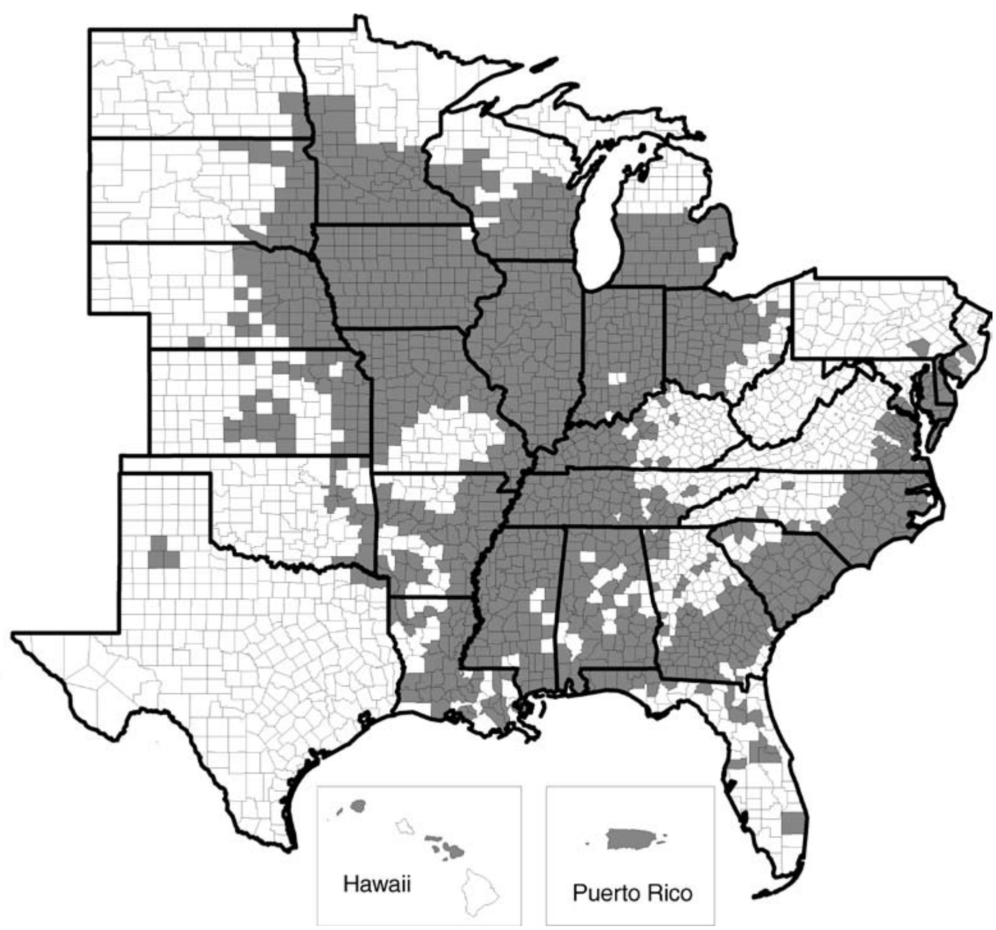

Figure 3.1. Soybean cyst nematode distribution in the United States (Niblack and Tylka 2008).

gressing novel genes for resistance to SCN into soybean varieties and exploring new types of resistance (partial resistance or tolerance) (Shannon, Arelli, and Young 2004). For long-term sustainability of SCN management, more genes for resistance need to be incorporated into the public germplasm pool. To accomplish this effectively, the genes as well as tightly linked markers to these genes need to be identified. Greenhouse techniques for screening populations are well defined, and these screenings can be conducted year-round (Shannon, Arelli, and Young 2004). With the current rapid pace of development of new and improved soybean varieties that have new proprietary traits, it is most important that these novel genes be mapped expeditiously. For these types of traits, the process requires large populations in the advanced stages (F6 or F7) to be effective. Marker-assisted selection has been used successfully for incorporating resistance to SCN into new varieties (Shannon, Arelli, and Young 2004).

Tolerance is being introduced into SCN resistance management. This concept describes a situation in which yields are the same for a particular variety when planted in locations with or without SCN pressure (Shannon, Arelli, and Young 2004). Recent releases of varieties with resistance to PI88788 were compared with releases made before 1997 in six locations in Iowa (De Bruin and Pedersen 2008). Modern SCN varieties had greater yields under the same SCN pressure as older varieties. How the yield differences compare without SCN pressure remains to be determined, but the result does demonstrate that significant progress in decreasing the yield impact of SCN has been made through conventional breeding methods.

Section Summary

The most effective and widely deployed management strategy for soybean pathogens is host-plant resistance. Numerous sources of resistance to common soybean pathogens have been identified, but only a few of these new genes have been incorporated into commercial varieties. In addition to identifying sources of resistance, it is now important to identify both the number of genes and molecular markers for those new genes to expedite the development of varieties with resistance to multiple pathogens. In addition, more screening of varieties in disease nurseries is needed before their release in this new era of rapid variety development.

For diseases caused by fungi where host resistance has not been identified or is difficult to incorporate, there are now many fungicides labeled for use on soybean. This fact provides many advantages for the near future, especially regarding management of soybean rust. These fungicides must be applied in an integrated management approach to mitigate development of resistance in rust populations and to avoid secondary environmental impacts.

Soybean cyst nematode is the most damaging pest to soybean in the United States; SCN is managed effectively through a combination of planting resistant varieties, rotating varieties with alternative sources of resistance, and rotating with nonhost crops. Chemical control is neither effective nor economical. Managing SCN effectively in the future depends on exploring/incorporating new types of resistance into high-yielding varieties.

Insect Management

Because integrated pest management (IPM) has been promoted and used in soybean production, significant cost savings and limited environmental impacts have occurred. Three approaches have been developed and delivered to growers during the past few decades: (1) host plant resistance through plant breeding; (2) biological control using predators, parasitoids, and entomopathogens; and (3) landscape design.

The breeding of soybean varieties resistant to arthropod pests has a long history and is still a valuable effort (Dadson et al. 2007; Li et al. 2007; Sinclair, Kogan, and McGlannery 1997; Wada, Endo, and Takahashi 2006). Soybean germplasm provides the genes needed to improve resistance to *herbivory*, and this genetic material is available to breeders and geneticists. High-yielding varieties with resistance to insects, however, have not been developed for the United States (Gianessi 2009).

Soybean growers perform a variety of activities in conventional systems that promote IPM (Table 3.4). Some growers plant their fields in areas to avoid pest infestations. Most growers scout their fields for insect pests to determine if/when curative measures are needed. A small fraction of growers use, or at least maintain, biological control. In fact, biological control of soybean insects can contribute the most to IPM and sustainability because few insects vector diseases and cosmetic damage to soybean is not an issue.

Native predators and entomopathogens clearly have played key roles in regulating some insect pests (Kogan and Turnipseed 1987; Pitre 1983). Exotic predators and parasitoids also can be important natural enemies. For example, in the Midwest, exotic

Table 3.4. Percentage of U.S. soybean growers performing various insect pest management activities in 2006 (USDA–NASS 2007)

Activity	Percentage
Scouted for arthropods	72
Chose pest resistant variety	50
Planted at site to avoid pests	13
Maintained beneficial insect habitat	4
Used biological pesticides	2
Used biological control	1

ladybird beetles can control soybean aphid populations (Costamagna and Landis 2007). Unfortunately, exotic biological control agents, including these two beetles, can sometimes harm nontarget insects and become pests themselves (Bigler, Babendreier, and Kuhlmann 2006; Follett and Duan 2000; Onstad and McManus 1996).

Landscape design is the third major approach to nonchemical control of soybean arthropods. Kogan and Turnipseed (1987) stated that soybean planting and maturation play a major role in determining damage caused by an insect pest. The cropping system is designed by picking a variety, selecting a planting time, and choosing a location to plant the soybean crop. As Table 3.4 indicates, growers can plant the crop at a site to avoid insect pests or to be near sources of natural enemies of the pests. The farm landscape can be designed to include habitat that is managed or left alone to maintain natural enemies. Landis and colleagues (2008) found that the influence of agricultural landscape on biological control of soybean aphid can be economically important for soybean IPM. Trap crops can be planted in the landscape as part of the design. The landscape design is the foundation on which subsequent control tactics are adjusted in response to observations of insect pests.

Because defoliation during early vegetative soybean stages rarely causes yield loss, scientists have proposed planting early-maturing varieties as early in the year as possible to avoid defoliation by the more abundant and damaging late-season defoliators (Heatherly and Bowers 1998). To test this approach in southern states, Baur and colleagues (2000) compared a conventional soybean production system (varieties in Maturity Group [MG] V–VII planted in May) with an early soybean production system (ESPS) (varieties in MG IV and V planted in April). Early plantings of MGs IV and V allow them to escape damage from late-season defoliators because plants reach maturity before migratory defoliating insect pests build to damaging population peaks late in the growing season. Like other researchers, (Boyd et al. [1997], McPherson and Bondari [1991], McPherson, Russin, and Harville [1996]), and McPherson et al. [1998]), Baur and colleagues (2000) demonstrated the value of early-planted, early-maturing varieties for avoiding defoliators that occur late in the growing season. But they discovered that the ESPS was inhabited by larger populations of southern green stink bug, three-cornered alfalfa hopper (*Spissistilus festinus*), and early-season predators. And they observed an early peak of bean leaf beetle adults in the ESPS.

The adoption of the ESPS will present new challenges in the management of insect pests. Stink bugs and possibly bean leaf beetle may require more intense management (Baur et al. 2000). Furthermore, the complex interactions of insect pests and natural enemies across landscapes planted using the ESPS and at conventional times remain to be investigated. If both systems are planted in close proximity, will they improve, worsen, or balance out management problems as pest populations migrate, grow, and decline? Thus, it is not clear which production system or combination of systems has the potential for greater environmental impact from an insect management standpoint. Presently, there are no indications that insect management is more problematic with the increase in early planting in the southern United States. What is known is that required management of late-season defoliating herbivores is lessened, and this result subsequently reduces pesticide applications for their control.

Published data on insecticide use in U.S. soybean for 2006 are based on more than 3,000 reports from farms in 19 states (USDA–NASS 2007); Alabama, Florida, Georgia, and South Carolina were not included in the survey. Synthetic insecticides were used on 16% of soybean acreage in reporting states. Typically, when insecticides were used, only one application was made per year. The most commonly applied chemicals in 2006 were lambda-cyhalothrin, chlorpyrifos, and esfenvalerate, which were used on 6%, 5%, and 3% of the acreage, respectively. Esfenvalerate and lambda-cyhalothrin were applied at low rates of active ingredient per acre, so the total amounts of these two toxins applied in 2006 were relatively low (USDA–NASS 2007). But much greater amounts of chlorpyrifos (0.454 lb active ingredient [a.i.] per acre; 1.7 million lb) and acephate (0.720 lb a.i. per acre; 546,000 lb) were applied to soybean throughout the United States. Louisiana accounted for the majority of acephate use in 2006: 412,000 lb

Table 3.5. Acute toxicity of two common classes of insecticides used in soybean (EXTOXNET 2008)

	Acute Toxicity to:			
Chemical	Humans	Birds	Aquatic Organisms	Beneficial Insects
		Organophosphates		
Acephate	Medium	Medium	Low	High
Methyl parathion	High	High	Medium–high	High
Chlorpyrifos	Medium	Medium	High	High
		Pyrethroids		
Esfenvalerate	Low–medium	Low	High	High
Lambda-cyhalothrin	Medium–high	Low	High	High

on 42% of its 870,000 acres of soybean. Acephate is commonly used against stink bugs, including brown stink bug (*Euschistus servus*), and the three-cornered alfalfa hopper in Louisiana, according to the 2003 Crop Profile (NIS–RIPMC 2008). Two Midwest states accounted for almost 75% of the chlorpyrifos use in 2006: North Dakota applied 434,000 lb of chlorpyrifos on 27% of its 3.9 million soybean acres, and Minnesota applied 832,000 lb on 23% of its 7.4 million soybean acres (USDA–NASS 2007). This chemical is used to treat soybean aphid and/or two-spotted spider mite. The latter can reach damaging populations under hot, dry conditions in the Midwest. Clearly, pest outbreaks in small regions can influence insecticide use significantly.

Insecticides available for use on soybean have a wide range of toxicities for humans and wildlife. The Extension Toxicology Network (EXTOXNET 2008) provides toxicological information about many insecticides (Table 3.5). Toxicity of a product for humans is particularly important for farmers and their employees. Acute toxicity to nontarget organisms determines some of the environmental impacts of the chemicals. Methyl parathion is moderately toxic to fish but highly toxic to aquatic invertebrates (Table 3.5). Esfenvalerate has low dermal and inhalation toxicity for humans but moderate oral toxicity. The toxicity of lambda-cyhalothrin depends greatly on the formulation of the commercial product. Not shown in Table 3.5 are the chronic and indirect effects of chemical use on humans and wildlife. It is noted that the EPA extensively reviews all pesticides before approving them for use, and pesticides are labeled for use by producers only after they have passed this review process. This administrative process and the earlier-cited low usage of insecticides on soybean results in a low risk of exposure for humans and the environment.

According to the Arthropod Pesticide Resistance Database (APRD) (Whalon et al. 2008), the soybean looper has evolved resistance in 20 recorded cases. The corn earworm has evolved resistance in 30 cases, but not necessarily only in soybean. Both species have evolved resistance to 12 different insecticides with varied modes of action. The population dynamics and genetics of both species in a landscape of cotton, soybean, and other crops may contribute to their resistance (Boethel et al. 1992; Thomas and Boethel 1994). In comparison, the velvetbean caterpillar has only one case of resistance recorded in the APRD. Insecticide resistance can decrease sustainability and increase environmental impacts by eliminating options for control or by increasing the required intensity of control.

If some of the chemicals listed in Table 3.5 are restricted or banned in the future, other chemicals and other tactics are available to replace them. Pike and colleagues (1995) performed an analysis of insecticide use on soybean in 1992 and determined that the benefits or costs of substitution would depend on the chemical and the insect species targeted. With regard to future sustainability, if one of these chemicals is used every year in every soybean crop, this may be an indication of one of two scenarios. First, soybean growers may be facing a serious threat from a new, invasive insect pest, and biocontrol and plant breeding have not responded quickly enough to safeguard the crops. It is expected that integrated approaches eventually will replace simple reliance on chemical control. Second, the continuous use of chemical insecticides on every soybean crop year after year may be an indication that soybean production is not sustainable in that region. Resistance by insects to the insecticides resulting from their continual extensive use eventually will make soybean production difficult.

Section Summary

Integrated pest management has been promoted and used for insect management in soybean in the United States and has resulted in significant cost savings and limited environmental impact. Natural enemies provide considerable control of insect pests in most years and regions. Scouting of fields to determine insect pressure is used widely and effectively to avoid unwarranted applications of control measures. When damaging insect outbreaks occur, chemical insecticides are available and are used to provide consistent, effective control. In the midsouthern United States, early planting is used to avoid damaging late-season defoliators. Host-plant resistance through plant breeding is available, but high-yielding insect-resistant varieties have not been developed. This may change, however, with the recent discoveries of soybean aphid-resistant genes in soybean germplasm that should result in the development of aphid-resistant varieties. Synthetic insecticides are used on a low percentage of U.S. soybean acres, and there is a low risk of human and environmental exposure to insecticides applied to soybean.

Resistance to insecticides in some insect species that infest soybean is documented. The fact that the same insecticides may be applied to all crops in a multicrop landscape may contribute to this selection for resistance. If some insecticides become limited in their effectiveness in the future, other chemicals and tactics are available to replace them. As with any pesticide, rotation of insecticide chemistries that offer similar control will retard selection for resistance.

Weed Management

The primary *weed control* tactics used in conventional integrated weed management programs include prevention of occurrence, cultural practices, mechanical forces, biological control agents, and chemicals (Monaco, Weller, and Ashton 2002; Ross and Lembi 2009).

Preventative Practices

The goal of preventative practices in soybean production systems is to stop the transfer of weed seeds or vegetative propagules to noninvaded fields (Monaco, Weller, and Ashton 2002). This action entails cleaning equipment or crop seed before transport to prevent the introduction of weed seed or organic matter to a field that does not contain a particular weed or weeds. Unfortunately, these methods do not receive significant consideration by weed management practitioners and are thus largely ineffective. This circumstance has resulted in humans being the primary dispersers of weeds (Ross and Lembi 2009). The lack of producer implementation of stringent preventative methods for weed management likely has not differed between conventional and GR soybean production systems.

Cultural Practices

Primary cultural practices that are easily implemented to provide a positive impact on weed management in soybean are narrower row spacings (generally less than 10 inches) and higher plant populations (generally greater than 200,000 per acre) (Harder, Sprague, and Renner 2007; Hock et al. 2006). The combination of these two factors will provide more rapid canopy closure that theoretically will be a major deterrent to weed germination and growth (Harder, Sprague, and Renner 2007).

Two factors gradually have increased the economic burden for growers: (1) the variable seed placement (both depth and spacing) with narrow-row drill equipment and (2) the high cost associated with using high seeding rates of increasingly more expensive seed. Thus, a recent trend has been to use soybean planters instead of drills to ensure more effective seed placement and allow lower seeding rates in rows that are between 15 and 30 inches wide. This alteration in seeding practices has resulted in a net decrease in the level of cultural weed management (Arce, Pedersen, and Hartzler 2009; Harder, Sprague, and Renner 2007). A likely result is an increase in the use of tillage and/or chemicals to manage weeds.

Mechanical Practices

Mechanical approaches for attaining weed control in soybean can be achieved with any physical means of weed removal or growth suppression. These options include hand-weeding, mowing, mulches, heat, and tillage (Ross and Lembi 2009). The predominant mechanical weed control method used in conventional soybean is tillage, which often is done before planting and may be more for seedbed preparation than for controlling emerged weeds. This before-planting tillage may be accomplished with a primary or secondary tillage tool, and often is followed by another secondary tillage operation (see Chapter 2, p. 9). The extent of tillage depends on the previous crop and its resulting plant residue, as well as on soil conditions.

After soybean planting, fields also may receive tillage operations that include rotary hoeing and/or row cultivation. Postplant tillage will not be as conducive to soil loss as preplant tillage because it is limited to between-row areas. In addition, the fuel consumption and subsequent fuel costs for rotary hoeing and row cultivation are at least 50 and 75% lower, respectively, than for a field cultivator operation (Table 2.2). Postemergence row cultivation requires a wide row spacing (generally >22 inches), which disallows some of the cultural weed management benefits provided by narrower rows.

Replacing a tillage operation with an *herbicide* application will decrease fuel consumption by up to 1.5 gallons per acre and perhaps retain 25 to 70% of crop residue when compared with a field cultivator (Table 2.2). Furthermore, no-till production may reduce soil erosion losses by 90% compared with conventional tillage (Table 2.6). It is estimated that no-till soybean production is used on nearly 40% of the full-season soybean acreage in the United States (CTIC 2007). Large soybean-producing states such as Illinois use no-till for soybean on slightly more than 50% of the acreage, or 5.2 million acres (CTIC 2006). Tillage used on the remaining acreage may be primarily for seedbed preparation, which contributes to weed management in varying degrees.

Biological Control Practices

Biological methods for weed control are the most efficacious in perennial wildlands with the target weeds being alien, invasive weed species (Ross and Lembi 2009). Thus, their use for weed management in soybean is an uncommon occurrence.

Chemical Control Practices

The use of herbicides had the greatest impact on weed management in soybean during the past century (Carpenter et al. 2002; Ross and Lembi 2009). Weed management in soybean has evolved along with the discovery and commercialization of new herbicide compounds since the late 1940s (Ennis 1958). Herbicides were gradually incorporated into weed management strategies along with common cultural and mechanical practices (Peters et al. 1961). The most effective herbicides were typically soil *residual herbicides* that were applied before crop and weed emergence.

The sought-after advantages of soybean herbicides include the following:

- more effective and complete weed management;
- improved control of perennial weed species compared with mechanical methods;
- increased soybean grain yields;
- less reliance on tillage resulting in decreased soil erosion;
- a lower requirement for labor, equipment, and fuel compared with tillage or hand-weeding;
- and, perhaps, greater simplicity in the overall strategy to manage weeds (Gianessi and Reigner 2007).

Before the widespread use of herbicides occurred after the 1950s, crop yields were limited by weeds. The labor required for cultivation or hand-weeding ranged from 20 to 41 man-hours per acre in some agronomic crops (Ennis 1958). By the early 1990s, the ease of weed management had improved markedly beyond that of the previous four decades. But the integration of sequential herbicide applications with cultivation was still necessary for obtaining control of certain problematic species long enough during the growing season to prevent soybean yield loss (Newsom and Shaw 1994; Reynolds et al. 1995).

One of the earliest herbicides used in soybean was pentachlorophenol (PCP) applied at 20 lb per acre. It provided significant control of pigweeds (*Amaranthus* spp.) and crabgrass (*Digitaria* spp.), with a subsequent improvement in soybean yield (Peters, Klingman, and Larson 1959). The PCP, however, was used in combination with row cultivation or a rotary hoe and still did not decrease weed populations consistently to a level that prevented some decrease in soybean yield. Chloramben represents the first major herbicide to be adopted by soybean producers, with greater than 30% of the soybean acres treated in the late 1960s to early 1970s in Illinois (Pike, McGlamery, and Knake 1991). Chloramben provided broad spectrum control of grass and broadleaf weed species when applied as a preemergence banded application over the crop row (Pike, McGlamery, and Knake 1991). This practice, in conjunction with between-row cultivation, provided effective weed management without incurring excessive herbicide costs.

Progressive improvements in weed management occurred with the discovery and adoption of herbicides such as trifluralin, metribuzin, and alachlor from the mid-1960s to the mid-1980s (Pike, McGlamery, and Knake 1991). The development of highly active herbicides in the late 1980s provided further advancement in weed control efforts while being applied at relatively low doses (ounces/acre), which resulted in a reduction in the environmental load due to weed management (Ross and Lembi 2009).

The adoption of herbicide use grew rapidly so that 95 to 98% of the U.S. soybean acreage received an herbicide application from the 1990s to 2005 (Carpenter et al. 2002; USDA–NASS 2008d). As herbicides progressively became a greater component of soybean weed management, yield loss due to weeds was lowered from 17% in the 1950s (USDA–ARS 1965) to 7% in the 1990s (Bridges 1992). Some of the early herbicides such as trifluralin that were developed and used on soybean in the 1950s and 1960s are still valuable today (USDA–NASS 2008d; Table 3.6).

Herbicides used for weed management in conventional soybean can be classified by several criteria, including mode of action, selectivity, translocation in the plant, and degree of soil and/or foliar activity. The potential negative aspects associated with herbicide applications are off-target toxicity to humans and desirable flora and fauna in local ecosystems; potential to injure crop(s); and the evolution of herbicide-resistant weeds that affects the sustainability of weed management through the continued use of a particular herbicide. An overview of herbicide behavior in soils (Carpenter et al. 2002) and detailed information on the toxicity, *soil persistence*, water solubility, and terminal degradation pathways for specific herbicide active ingredients are available (Senseman 2007).

The combination of soil persistence and water solubility has led to the detection of some soybean herbicides in groundwater. A survey of municipal wells in Iowa frequently confirmed the presence of alachlor, metolachlor, and metribuzin or their metabolites (Kolpin, Thurman, and Linhart 1998). These herbicides are sometimes applied at soybean planting for residual weed control; some also are registered for use in corn. Ultimately, favorable traits for an herbicide would be short soil persistence, adsorption by soil particles, a moderate to low level of water solubility, and a very low toxicity to fauna.

All herbicides used for weed management in soybean have some degree of soil persistence (Table 3.6). The soil persistence in many instances, however, is a result of some herbicides being readily adsorbed (bound) to the soil particles and not being released for degradation (Franz, Mao, and Sikorski 1997; Monaco, Weller, and Ashton 2002). For instance, glyphosate will not provide residual control of weed species that emerge after the herbicide has been applied, yet the herbicide has an average half-life of 47 days in the soil (EXTOXNET 2008) (Table 3.6). This is longer than the 21-day half-life of the herbicide alachlor, which only has herbicidal activity through uptake from the soil (Senseman 2007; Table 3.6).

Weed *resistance to herbicides* used in soybean was first documented in the 1970s (Heap 2008), and the selection of herbicide-resistant weed species intensified into the early 1990s. The speed of weed selection for resistance to the newly developed herbicide group known as the acetolactate synthase (ALS)-inhibiting herbicides was unprecedented (Horak and Peterson 1995). Common waterhemp (*Amaranthus rudis*) that was resistant to the ALS-inhibiting herbicides was first confirmed in Illinois in 1993 and has been estimated to infest more than two million acres (Heap 2008), which has essentially removed these herbicides from being considered as options to aid in waterhemp management. Arguably, this development slowed the progressive enhancements in weed management afforded by typical new herbicide discoveries, and perhaps also slowed the adoption of no-till systems that require robust chemical weed control. Even with the early development of ALS-resistant weeds, these herbicides have proved useful for control of a wide spectrum of weed species and have a very favorable environmental profile due to low mammalian toxicity, limited movement in soils, and extremely low application rates (Senseman 2007).

In 1996, a total of 27 different herbicide active ingredients representing 9 different herbicide modes of action were used in soybean (USDA–NASS 2008d; Table 3.6). The method of use and specific herbicide active ingredients has remained relatively unchanged for weed management in conventional soybean during the past decade, with no new herbicide modes of action discovered or introduced.

The most common approach to weed management in conventional soybean has been to control weeds before planting with tillage or a burndown application of glyphosate and/or 2,4-D. Glyphosate and 2,4-D applied in the fall has been used since the 1970s for management of perennial weed species. Spring applications have been used to control perennials, winter annuals, and early-emerging summer annual weed species. As stated previously, the use of no-till systems and effective burndown herbicides has enabled growers to lower equipment and fuel costs while providing a soil surface that is less conducive to soil erosion.

A soil residual herbicide such as chlorimuron, cloransulam, metolachlor, metribuzin, pendimethalin, trifluralin, or sulfentrazone often has been applied in combination with a burndown herbicide or at the time

Table 3.6. Major herbicides used in U.S. soybean production in 1996, 2001, and 2006 (Heap 2008; Senseman 2007; USDA–NASS 2008b)

Herbicide Group/Mode of Action	Representative Herbicide	Area Applied (Rank) 1996	2001	2006	Soil Persistence, Half-life
		%			days
ACCase Inhibitors/Inhibition of acetyl CoA carboxylase (ACCase)	Clethodim	7	4	3 (T-4)	3
	Fenoxaprop	4	3	<1	9
	Fluazifop, P, butyl	7	3	1	15
	Quizalofop, ethyl	7	nd	nd	60
	Sethoxydim	9 (T-10)	1	<1	5
ALS Inhibitors/Inhibition of acetolactate synthase ALS (acetohydroxyacid synthase AHAS)	Chlorimuron, ethyl	14 (6)	5 (T-5)	4 (3)	40
	Cloransulam	nd	5 (T-5)	1	14–33
	Flumetsulam	2	<1	<1	30–90
	Imazamox	nd	5 (T-5)	<1	20–30
	Imazaquin	15 (5)	2	1	60
	Imazethapyr	43 (1)	9 (3)	3 (T-4)	60–90
	Thifensulfuron	10 (9)	2	1	12
	Tribenuron	nd	nd	1	10
Photosystem-I-electron diversion	Paraquat	1	nd	1	1000
Carotenoid Biosynthesis Inhibitor/ Bleaching: Inhibition of carotenoid biosythensis at the phytoene desaturase step (PDS)	Clomazone	3	<1	nd	24
Glycines/Inhibition of EPSP synthase	Glyphosate	25 (3)	73 (1)	92 (1)	47
Mitosis Inhibitors/Inhibition of mitosis/ microtubule polymerization inhibitor	Acetamide	nd	<1	<1	nd
	Alachlor	5	<1	<1	21
	Pendimethalin	27 (2)	10 (2)	3 (T-4)	44
	Metolachlor	5	<1	1	90–150
	Trifluralin	22 (4)	7 (T-4)	2 (T-5)	45
Photosystem II Inhibitors/Inhibition of photosynthesis at photosystem II	Bentazon	11 (8)	1	<1	20
	Linuron	1	nd	nd	60
	Metribuzin	9 (T-10)	2	2 (T-5)	30–60
PPO Inhibitors/Inhibition of protoporphyrinogen oxidase (PPO)	Acifluorfen	nd	3	<1	14–60
	Carfentrazone	nd	nd	<1	0.1
	Flumiclorac, pentyl	2	<1	1	<1–6
	Fomesafen	5	7 (T-4)	2 (T-5)	100
	Lactofen	8	1	<1	3
	Sulfentrazone	nd	5 (T-5)	1	121–302
Synthetic Auxins/Synthetic Auxin	2,4-D	13 (7)	4	10 (2)	10
	2,4-DB	<1	nd	nd	5–10

Abbreviations: nd = no data; T = tie for ranking.

of planting as a preemergence application (Table 3.6). These soil residual herbicides typically are applied at rates to promote the longest possible period of weed control. They seldom, however, control problematic weed species long enough to be considered acceptable as a stand-alone control by most growers (Reynolds et al. 1995). Control of broadleaf weed species with the residual herbicides has been the greatest priority because there are several postemergence herbicides that provide effective, economical control of grass weed species (Vidrine, Reynolds, and Blouin 1995). The use of soil residual herbicides is more common in conventional soybean than in GR soybean because the herbicides available for postemergence use with conventional varieties are not as effective as glyphosate. Also, the cost for residual herbicides typically is more than for glyphosate, and this fact often limits their use in a glyphosate-based system.

Herbicides that can be applied for postemergence weed control in conventional soybean originate from three different modes of action. Postemergence herbicides that inhibit the acetyl CoA carboxylase

(ACCase) enzyme will control only grass weed species and are referred to collectively as graminicides (e.g., sethoxydim, clethodim, fluazifop, fenoxaprop, quizalofop; Table 3.6). Herbicides that inhibit the protoporphyrinogen oxidase (PPO) enzyme or the ALS enzyme comprise the only two valuable herbicide groups for postemergence control of broadleaf weed species. The most commonly used of these postemergence herbicides are chlorimuron, imazethapyr, and fomesafen (Table 3.6). The only significant herbicide introductions since the mid-1990s have been cloransulam and sulfentrazone, which are ALS- and PPO-inhibitors, respectively.

The limited availability of unique herbicide modes of action for postemergence control of broadleaf species in conventional soybean is a formidable challenge for growers who do not use cultivation because herbicide resistance to these two modes of action is prevalent. Ninety-seven weed biotypes that are resistant to the ALS-inhibiting herbicides, and three that are resistant to the PPO-inhibiting herbicides, have been identified (Heap 2008). Furthermore, common waterhemp and common ragweed have resistance to both of these modes of action, and they have been cited as being the most problematic for growers (Gibson, Johnson, and Hillger 2005; Kruger et al. 2009). Thus, weed management in conventional soybean may require row cultivation because it may not be possible to get season-long control of weeds using residual herbicides applied at planting or to control herbicide-resistant broadleaf weed populations with postemergence herbicides.

The effectiveness of weed management in conventional soybean continues to decline with the heavy reliance on chemical weed management and the spreading problem of herbicide-resistant weed populations. This decline may require growers to consider implementing more frequent tillage operations to counteract the decrease in herbicide effectiveness. This action will necessarily require that row spacing be increased to 30 inches or greater to allow for row cultivation and could subsequently contribute to increased soil erosion. In reality, a dramatic increase in postemergence tillage for today's conventional soybean production would not be feasible because of larger farm sizes and greater labor constraints compared with previous decades. Furthermore, the future loss of some older herbicide chemistries may be forthcoming because herbicides such as metolachlor, alachlor, and metribuzin have been found in municipal water supplies due to excessive movement in soils (Kolpin, Thurman, and Linhart 1998). All three of these herbicides can be used in corn as well as soybean production, and this fact may trigger at least some governmental regulation to limit amounts of each that can be applied to a site during a given period of time. In response to environmental concerns, growers have implemented effective Best Management Practices for mitigating pesticide movement into water supplies (Maringanti et al. 2008).

The effort to discover new herbicide modes of action for control of problematic weed species in conventional soybean is well justified, but it has not been a key target for herbicide manufacturers because conventional soybean varieties or those developed through nontransgenic means comprise less than 8% of U.S. soybean acreage (USDA–NASS 2008b). Interestingly, the most frequent action taken by conventional soybean growers when faced with weed populations they cannot easily manage has been to move to GR-soybean varieties.

Section Summary

Sustainability of weed management in a conventional or nontransgenic soybean production system apparently will be limited by several factors. First, few new herbicide chemistries that will control problem weeds or address weed resistance concerns are forthcoming. Second, available chemistries may disappear because of environmental concerns and lack of market to sustain their production. Several companies that manufacture off-patent herbicides that can be used in conventional soybean have created premixed herbicide product combinations to provide greater value to the grower and justify the continuation of sales for a specific herbicide active ingredient. Third, few nontransgenic varieties are being developed and released by seed companies because grower demand has been for GR soybean. In fact, future soybean breeding efforts probably will use transgenic, herbicide-resistant parents to develop new varieties. Finally, reverting to postemergent tillage to facilitate weed management in conventional soybean is not likely to occur because of erosion concerns, labor constraints, and farm size.

Glossary

Entomopathogen. A microbe that harms an insect when the microbe invades its body.

Herbicide. A chemical substance or cultured biological organism used to kill or suppress the growth of plants.

Herbivory. The consumption of plant tissues by an animal such as an insect.

Residual herbicide. An herbicide that persists in the soil and injures or kills germinating weed seedlings for a relatively short period of time after application.

Resistance to herbicides. The inherited ability of a plant population to survive and reproduce following repeated exposure to a dose of herbicide normally lethal to the wild type. Resistance also may be induced by such techniques as genetic engineering or selection of variants produced by tissue culture or mutagenesis (HRAC 2005).

Soil persistence. Refers to the length of time that an herbicide applied to or in soil remains effective; to some degree phytotoxic to some species (HRAC 2005).

Tolerant. The inherent ability of a plant to survive and reproduce after herbicide treatment. This implies that there was no selection or genetic manipulation to make the plant tolerant; it is naturally tolerant.

Varietal resistance. Resistance of a particular variety to injury caused by herbicides, pathogens, or insects. Resistance to the same pest is expressed at different levels among different varieties.

Weed control. The process of reducing weed growth and/or infestation to an acceptable level.

Literature Cited

Arce, G. D., P. Pedersen, and R. G. Hartzler. 2009. Soybean seeding rate effects on weed management. *Weed Technol* (in press).

Baur, M. E., D. J. Boethel, M. L. Boyd, G. R. Bowers, M. O. Way, L. G. Heatherly, J. Rabb, and L. Ashlock. 2000. Arthropod populations in early soybean production systems in the Mid-South. *Environ Entomol* 29:312–328.

Bennett, D. 2009. More conventional soybean acres? *Delta Farm Press* 66(6):33, http://deltafarmpress.com/soybeans/conventional-acres-0210/

Bigler, F., D. Babendreier, and U. Kuhlmann (eds.). 2006. *Environmental Impact of Invertebrates for Biological Control of Arthropods: Methods and Risk Assessment*. CABI Publishing, Switzerland.

Boethel, D. J., J. S. Mink, A. T. Wier, J. D. Thomas, B. R. Leonard, and F. Gallardo. 1992. Management of insecticide resistant soybean loopers (*Pseudoplusia includens*) in the southern United States. Pp. 66–67. In L. G. Copping, M. B. Green, and R. T. Rees (eds.). *Pest Management in Soybean*. Elsevier, Essex, England.

Boyd, M. L., D. J. Boethel, B. R. Leonard, R. J. Habetz, L. P. Brown, and W. B. Hallmack. 1997. Seasonal abundance of arthropod populations on selected soybean varieties grown in early season production systems in Louisiana. *La Agric Exp Stn Bull* 860. Louisiana State University, Baton Rouge.

Bradley, C. A. 2008. Fungicide resistance management in soybean. Pp. 57–60. In A. E. Dorrance, M. A. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Bridges, D. C. 1992. *Crop Losses Due to Weeds in the United States-1992*. Weed Science Society of America, Champaign, Illinois.

Brim, C. A. 1966. A modified pedigree method of selection in soybeans. *Crop Sci* 6:220.

Brim, C. A. 1973. Quantitative genetics and breeding. Pp. 155–186. In B. E. Caldwell (ed.). *Soybeans: Improvement, Production and Uses*. American Society of Agronomy, Madison, Wisconsin.

Broders, K. D., P. E. Lipps, P. A. Paul, and A. E. Dorrance. 2007. Characterization of Pythium spp. associated with corn and soybean seed and seedling disease in Ohio. *Plant Dis* 91(6):727–735.

Carpenter, J., A. Felsot, T. Goode, M. Hammig, D. Onstad, and S. Sankula. 2002. *Comparative Environmental Impacts of Biotechnology-derived and Traditional Soybean, Corn, and Cotton Crops*. Council for Agricultural Science and Technology, Ames, Iowa.

Chen, S. 2007. Tillage and crop sequence effects on *Heterodera glycines* and soybean yields. *Agron J* 99:797–807.

Coker, C., J. Rupe, S. Monfort, and T. Kirkpatrick. 2008. Arkansas plant disease control products guide: Soybean seed treatments. MP 154. University of Arkansas Extension Service, Little Rock, http://www.uaex.edu/other_areas/publications/pdf/mp154/soybseedtreat.pdf

Conservation Technology Information Center (CTIC). 2006. Crop Residue Management Survey, http://www.conservationinformation.org/pdf/2006CRMSurveyHiRes.pdf

Conservation Technology Information Center (CTIC). 2007. Crop Residue Management Survey. 2007 Amendment to the National Crop Residue Management Survey Summary, http://www.conservationinformation.org/pdf/National_Summary_2007_Amendment.pdf

Costamagna, A. C. and D. A. Landis. 2007. Quantifying predation on soybean aphid through direct field observations. *Biol Ctrl* 42:16–24.

Dadson, R. B., I. Javaid, F. M. Hashem, and J. M. Joshi. 2007. Antibiosis in soybean breeding lines for the management of corn earworm for sustainable soybean production. *J Sustain Ag* 30:137–146.

De Bruin, J. L. and P. Pedersen. 2008. Response of old and new soybean varieties to *Heterodera glycines* Ichinohe. *Agron J* 100:1347–1353.

Ennis, W. B., Jr. 1958. The challenges of modern weed control. *Weeds* 6:363–369.

Extension Toxicology Network (EXTOXNET). 2008. Pesticide Information Profiles. Oregon State University, Corvallis, http://extoxnet.orst.edu/pips/ghindex.html

Faghihi, J., V. Ferris, P. Donald, G. Noel, and T. Welacky. 2008. Changes in resistance of PI88788 to field populations of soybean cyst nematode (SCN). *Proc 4th National Soybean Cyst Nematode Conference*, Tampa, Florida, 6–7 March.

Fehr, W. R. 1987a. Breeding methods for variety development. Pp. 249–293. In J. R. Wilcox (ed.). *Soybeans: Improvement, Production and Uses*. 2nd ed. Agron. Monogr. 16. ASA, CSSA, WSSA, Madison, Wisconsin.

Fehr, W. R. 1987b. *Principles of Variety Development: Theory and Technique.* McMillan Publishing Co., New York.

Follett, P. A. and J. J. Duan. 2000. *Nontarget Effects of Biological Control*. Kluwer Academic Publishers, Boston, Massachusetts.

Franz, J. E., M. K. Mao, and J. A. Sikorski. 1997. *Glyphosate-A Unique Global Herbicide*. American Chemical Society, Washington, D.C.

Fungicide Resistance Action Committee (FRAC). 2008. List of pathogens with field resistance towards QoI fungicides. Fungicide Resistance Action Committee (FRAC), CropLife International, Brussels, Belgium, http://www.frac.info/frac/meeting/2008/Pathogens_with_field-resistance_towards_2008.pdf

Gianessi, L. 2009. The benefits of insecticide use: Soybeans. CropLife Foundation, Washington, D.C., http://www.croplifefoundation.org

Gianessi, L. P. and N. P. Reigner. 2007. The value of herbicides in U.S. crop production. *Weed Technol* 21:559–566.

Gibson, K. D., W. G. Johnson, and D. E. Hillger. 2005. Farmer perceptions of problematic corn and soybean weeds in Indiana. *Weed Technol* 19:1065–1070.

Giesler, L. J. and A. D. Ziems. 2008. Seed treatment fungicides for soybeans. G1852. University of Nebraska-Lincoln Extension, http://www.ianrpubs.unl.edu/epublic/live/g1852/build/g1852.pdf

Giesler, L., R. Kemerait, and L. Sconyers. 2008. The sentinel plot system: Monitoring movement of an invasive pathogen. Pp. 35–38. In A. E. Dorrance, M. A. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Harder, D. B., C. L. Sprague, and K. A. Renner. 2007. Effect of soybean row width and population on weeds, crop yield, and economic return. *Weed Technol* 21:744–752.

Heap, I. 2008. *International Survey of Herbicide Resistant Weeds.* WeedScience.org, http://www.weedscience.org/In.asp

Heatherly, L. G. and G. R. Bowers (eds.). 1998. *Early Soybean Production System Handbook*. USB 6009-09 1998-11000. United Soybean Board, St. Louis, Missouri.

Heatherly, L. G. and R. W. Elmore. 2004. Managing inputs for peak production. Pp. 451–536. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*. 3rd ed. Agronomy Monograph 16. American Society of Agronomy, Madison, Wisconsin.

Herbicide Resistance Action Committee (HRAC). 2005. Glossary. Herbicide Resistance Action Committee (HRAC). CropLife International, Brussels Belgium, http://www.hracglobal.com/Glossary/tabid/369/default.aspx

Hershman, D. E., R. D. Heinz, and B. S. Kennedy. 2008. Soybean cyst nematode, *Heterodera glycines*, populations adapting to resistant soybean varieties in Kentucky. *Plant Dis* 92:1475–1476.

Hock, S. M., S. Z. Knezevic, A. R. Martin, and J. L. Lindquist. 2006. Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. *Weed Sci* 54:38–46.

Horak, M. J. and D. E. Peterson. 1995. Biotypes of Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) are resistant to imazethapyr and thifensulfuron. *Weed Technol* 9:192–195.

Kogan, M. and S. G. Turnipseed. 1987. Ecology and management of soybean arthropods. *Ann Rev Entomol* 32:507–538.

Kolpin, D. W., E. M. Thurman, and S. M. Linhart. 1998. The environmental occurrence of herbicides: The importance of degradates in ground water. *Arch Environ Contam Toxicol* 35:385–390.

Kruger, G. R., W. G. Johnson, S. C. Weller, M. D. K. Owen, D. R. Shaw, J. W. Wilcut, D. L. Jordan, R. G. Wilson, M. L. Bernards, and B. G. Young. 2009. U.S. grower views on problematic weeds and changes in weed pressure in glyphosate-resistant corn, cotton, and soybean cropping systems. *Weed Technol* (in press).

Landis, D. A., M. M. Gardiner, W.v.d. Werf, and S. M. Swinton. 2008. Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. *Proc Nat Acad Sci* 105:20552–20557.

Li, Y., C. B. Hill, S. R. Carlson, B. W. Diers, and G. L. Hartman. 2007. Soybean aphid resistance genes in the soybean varieties Dowling and Jackson map to linkage group M. *Molec Plant Breed* 19:25–34.

Maringanti, C., I. Chaubey, M. Arabi, and B. Engel. 2008. A multi-objective optimization tool for selection and placement of BMP's for pesticide control. *Hydrol Earth Syst Sci Discuss* 5:1821–1862, www.hydrol-earth-syst-sci-discuss.net/5/1821/2008/

McPherson, R. M. and K. Bondari. 1991. Influence of planting date and row width on abundance of velvetbean caterpillars (*Lepidoptera: Noctuidae*) and southern green stink bugs (*Heteroptera: Pentatomidae*) in soybean. *J Econ Entomol* 84:311–316.

McPherson, R. M., J. S. Russin, and B. G. Harville. 1996. Impact of early season soybean production on pest management in the southern region. *Proc Fourth Ann Southern Soybean Conf,* Memphis, Tennessee, 7–9 February. United Soybean Board, St. Louis, Missouri.

McPherson, R. M., R. C. Layton, W. J. McLaurin, and W. A. Mills. 1998. Influence of irrigation and maturity group on the seasonal abundance of soybean arthropods. *J Entomol Sci* 33:378–392.

Mitchum, M. G., J. A. Wrather, R. D. Heinz, J. G. Shannon, and G. Danekas. 2007. Variability in distribution and virulence phenotypes of *Heterodera glycines* in Missouri during 2005. *Plant Dis* 91:1473–1476.

Monaco, T. J., S. C. Weller, and F. M. Ashton. 2002. *Weed Science: Principles and Practices.* John Wiley and Sons, New York.

Morrison, L. 2009. Know your nematode numbers. *Corn Soybean Digest* 69(1):26–28.

Mueller, D. 2008. Fungicides for soybean rust. Pp. 107–110. In A. E. Dorrance, M. D. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

National Information System–Regional Integrated Pest management Centers (NIS–RIPMC). 2008. NIS– RIPMC, Washington, D.C. and Raleigh, North Carolina, http://www.ipmcenters.org/cropprofiles/

Newsom, L. J. and D. R. Shaw. 1994. Influence of cultivation timing on weed control in soybean (*Glycine max*) with AC 263,222. *Weed Technol* 8:760–765.

Niblack, T. L. 2005. Soybean cyst nematode management reconsidered. *Plant Dis* 89:1020–1026.

Niblack, T. L. and G. L. Tylka (eds.). 2008. *Soybean Cyst Nematode Management Guide*, 5th ed. North Central Soybean Research Program, Urbandale, Iowa, http://www.planthealth.info/pdf_docs/SCNGuide_5thEd.pdf

Niblack, T. L., A. L. Colgrove, K. Colgrove, and J. P. Bond. 2008. Shift in virulence of soybean cyst nematode is associated with use of resistance from PI 88788. *Plant Health Prog* 18 January, http://www.plantmanagementnetwork.org/sub/php/research/2008/virulence/ (online only; limited access)

Onstad, D. W. and M. L. McManus. 1996. Risks of host-range expansion by insect-parasitic biocontrol agents. *BioSci* 46:430–435.

Orf, J. H., B. W. Diers, and H. R. Boerma. 2004. Genetic improvement: Conventional and molecular-based strategies. Pp.

417–450. In H. R. Boerma and J. E. Specht (eds.). *Soybeans: Improvement, Production and Uses*. 3rd ed. Agronomy Monograph 16. ASA, CSSA, WSSA, Madison, Wisconsin.

Pedersen, P. 2007. Fungicide seed treatments. Iowa State University Extension, Ames, http://extension.agron.iastate.edu/soybean/seedfungtmt.html

Peters, E. J., D. L. Klingman, and R. E. Larson. 1959. Rotary hoeing in combination with herbicides and other cultivations for weed control in soybeans. *Weeds* 7:449–458.

Peters, E. J., F. S. Davis, D. L. Klingman, and R. E. Larson. 1961. Interrelations of cultivations, herbicides and methods of application for weed control in soybeans. *Weeds* 9:639–645.

Pike, D. R., M. D. McGlamery, and E. L. Knake. 1991. A case study of herbicide use. *Weed Technol* 5:639–646.

Pike, D. R., K. L. Steffey, M. E. Gray, H. W. Kirby, D. I. Edwards, and R. H. Hornbaker. 1995. *Biologic and Economic Assessment of Pesticide Use on Corn and Soybeans*. National Agricultural Pesticide Impact Assessment Program Report No. 1-CA-95. USDA, Washington, D.C. 132 pp.

Pitre, H. N. 1983. *Natural Enemies of Arthropod Pests in Soybean*. South Coop Ser Bull 285. Southern Association of Agricultural Experiment Station Directors, Raleigh, North Carolina.

Ragsdale, D., K. Koch, and C. R. Grau. 2008. Secondary effects of fungicides. Pp. 83–85. In A. E. Dorrance, M. A. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Reynolds, D. B., D. L. Jordan, P. R. Vidrine, and J. L. Griffin. 1995. Broadleaf weed control with trifluralin plus flumetsulam in soybean (*Glycine max*). *Weed Technol* 9:446–451.

Ross, M. A. and C. A. Lembi. 2009. *Applied Weed Science*. 3rd ed. Pearson Prentice Hall, Upper Saddle River, New Jersey.

Schneider, R., E. Sikora, B. Padgett, and G. Sciumbato. 2008. Managing late-season soybean diseases and soybean rust: A southern perspective. Pp. 72–77. In A. E. Dorrance, M. A. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Senseman, S. A. 2007. *Herbicide Handbook*. 9th ed. Weed Science Society of America, Lawrence, Kansas.

Shannon, J. G., P. R. Arelli, and L. D. Young. 2004. Breeding for resistance and tolerance. Pp. 157–180. In D. P. Schmitt, J. A. Wrather, and R. D. Riggs (eds.). *Biology and Management of Soybean Cyst Nematode*. 2nd ed. University of Missouri–Delta Center, Portageville.

Sinclair, J. B., M. Kogan, and M. D. McGlannery. 1997. Guidelines for the integrated pest management of soybean pests. National Soybean Research Laboratory Publication 2. University of Illinois, Urbana–Champaign.

Thomas, J. D. and D. J. Boethel. 1994. Synergism of insecticides in tests with resistant soybean looper larvae (*Lepidoptera:Noctuidae*) in the laboratory and field. *J Econ Entomol* 87:1416–1422.

U.S. Department of Agriculture–Agricultural Research Service (USDA–ARS). 1965. Losses in Agriculture. Agricultural Handbook 291. USDA–ARS, Washington, D.C.

U.S. Department of Agriculture–National Agriculture Statistics Service (USDA–NASS). 2002a. Agricultural Chemical Usage 2001 Field Crops Summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC//2000s/2002/AgriChemUsFC-08-07-2002.pdf

U.S. Department of Agriculture–National Agriculture Statistics Service (USDA–NASS). 2003. Agricultural Chemical Usage 2002 Field Crops Summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC//2000s/2003/AgriChemUsFC-05-14-2003.pdf

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2007. Agricultural Chemical Usage 2006: Field Crops Summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC//2000s/2007/AgricChemUsFC-05-16-2007_revision.pdf

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008b. Acreage. http://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-30-2008.pdf

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008d. Agricultural Chemical Usage-Field Crops. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1560

Vidrine, P. R., D. B. Reynolds, and D. C. Blouin. 1995. Grass control in soybean (Glycine max) with graminicides applied alone and in mixtures. *Weed Technol* 9:68–72.

Wada, T., N. Endo, and M. Takahashi. 2006. Reducing seed damage by soybean bugs by growing small-seeded soybeans and delaying sowing time. *Crop Protect* 25:726–731.

Whalon, M. E., D. Mota-Sanchez, R. M. Hollingsworth, and L. Duynslager. 2008. Arthropod Pesticide Resistance Database. Michigan State University Extension, East Lansing, http://www.pesticideresistance.org/

Wrather, J. A., L. E. Sweets, and W. J. Wiebold. 2008. Soybean disease management. Publ. G0442. University of Missouri Agricultural Experiment Station, Columbia, http://aes.missouri.edu/delta/muguide/g4452.stm

4 Soybean Production Systems in the United States: Transgenic Variety System

Variety Development and Availability

A transgenic soybean production system is one that uses transgenic or genetically modified organism (GMO) varieties. Transgenic soybean varieties are a result of genetic transformation (using recombinant deoxyribonucleic acid [DNA]) of soybean by adding a gene or genes from another species plus the other necessary regulatory sequences to the soybean genome (Parrott and Clemente 2004). The purpose is to use genes from other species to design plants with specific characteristics. The current trend is toward increased development and use of transgenic soybean varieties in the United States. Most private sector soybean breeding programs (and some public sector programs) are now using transgenic varieties as parent material for future variety development.

Transgenic soybean was first introduced in the mid-1990s when glyphosate-resistant (GR) varieties became available. In 2008, transgenic varieties (exclusively herbicide tolerant) were grown on 92% of U.S. soybean acreage (USDA–NASS 2008b). Varieties with glyphosate resistance trace back to line 40-3-2 (developed by Monsanto Company, St. Louis, Missouri), a line that is resistant to high levels of glyphosate, the active ingredient in the herbicide Roundup. Varieties containing this event are called "Roundup Ready" (Monsanto Company). Roundup Ready varieties have been developed by backcrossing the Roundup resistant "gene" into a conventional breeding line or variety, by crossing a susceptible line with a resistant line, or by crossing two resistant lines and selecting segregants with a high level of resistance and then following conventional breeding procedures (Fehr 1987b; Parrott and Clemente 2004).

Beginning in 2009, there will be additional transgenic varieties available that carry a different Roundup resistant "event" known as "Roundup Ready 2 Yield" (Monsanto Company) or that carry a "gene" for resistance to glufosinate, the active ingredient in commercial herbicide products known as Liberty or Ignite. The latter varieties are known as "Liberty Link" (Bayer Company, Germany). It is expected that the Roundup Ready 2 Yield product will rapidly replace the first generation Roundup Ready soybean varieties. These new transgenic, herbicide-resistant soybean products have gained acceptance in international markets (Table 4.1) and will be commercially available for limited planting in 2009. In future years, varieties with other transgenic events may become available as regulatory approvals are obtained. As noted in the comments on conventional varieties, at least some breeding programs will develop lines in the future using conventional techniques followed by backcrossing the transgene into the lines to give transgenic varieties. Other breeding programs will develop transgenic varieties as noted here for Roundup Ready varieties.

Disease/Nematode Management

Presently, there are no transgenic disease management traits in soybean. But molecular approaches that inhibit this parasitic process through molecular genetic techniques may be forthcoming (Fuller, Lilley, and Urwin 2008). For example, through the course of infection, soybean cyst nematode (SCN) females establish feeding sites in plant roots, and this action induces dramatic changes in the plant root cells nearest to the female and those cells immediately surrounding this region. Numerous proteins have been identified, and their functionality in SCN feeding site establishment currently is being tested in model plant systems and soybean (Davis et al. 2008). The discovery of ribonucleic acid (RNA) interference (RNAi) technology involves the process in which the host expresses genes that regulate many plant cellular functions. In addition, some host RNAs may interfere with the parasitic process; thus, this could be a new strategy to develop resistant varieties that interfere with the feeding process of SCN (Hewezi et al. 2008). The first experiments in which specific RNAis are being evaluated for their effect on SCN feeding and reproduction are in progress (Sindhu et al. 2009).

Table 4.1. Country approval status (A = approved) of transgenic soybean as of October 2008 (ASA 2008; Bomer-Lauritsen, S. 2008. Personal communication)

	Roundup Ready		Roundup Ready 2 Yield		Liberty Link	
Country	Food	Feed	Food	Feed	Food	Feed
Argentina	A	A				
Australia/New Zealand	A		A			
Canada	A	A	A	A	A	A
China	A	A	A	A		
European Union	A	A	A	A	A	A
Japan	A	A	A	A		
Korea	A					
Mexico	A		A			
South Africa	A	A				
Taiwan	A		A			
United States	A	A	A	A	A	A

New biotechnology strategies that exploit the plant's system of regulation currently are being investigated. How these new strategies will work and their effectiveness for the long term is unknown. These are the first of many studies that will take advantage of the plant's own regulatory system to improve its response to plant pathogens.

Insect Management

Transgenic insecticidal soybean based on *Bacillus thuringiensis* (*Bt*) endotoxins has been evaluated in the United States and found to be highly effective against some Lepidoptera that defoliate soybean (MacRae et al. 2005; Miklos et al. 2007; Walker et al. 2000). Experts generally agree, however, that the first generation of transgenic insecticidal soybean will be commercialized only in South America because of the much higher economic impact of controlling Lepidoptera insects there. In the United States, defoliating insect damage occurs primarily in the southern region, and the acreage there is not large enough to justify the high cost of obtaining regulatory approval. In addition, some moths infest soybean, corn, and cotton; thus, management of resistance by these insect pests to the transgenic crops expressing the same toxin genes from *Bt* will be complicated by any plantings of *Bt* soybean. Because some strains of *Bt* are known to kill beetles, and because new biotechnology using RNA interference also has been effective against Coleoptera (Baum et al. 2007; Onstad 2008), transgenic insecticidal soybean will not be limited biologically to the control of moths. A transgenic approach to controlling stink bugs would be very valuable for U.S. soybean growers.

Weed Management

History and Use of Transgenic Soybean

Glyphosate-resistant soybean allows for broadcast applications of glyphosate over the top of emerged soybean (Dill, CaJacob, and Padgette 2008). In 1995, when glyphosate was used primarily for preplant weed control, it was applied to 20% of the 51.84 million U.S. soybean acres and comprised approximately 11% of the 56.44 million pounds of herbicide applied (USDA–NASS 1996). In 2006 when most of the 72.88 million U.S. soybean acres were planted to GR varieties, glyphosate was applied to 98% of the acres and comprised approximately 89% of the 103.49 million pounds of herbicide applied (USDA–NASS 2007). The amount of nonglyphosate herbicides that include acifluorfen, alachlor, bentazon, imazethapyr, metribuzin, pendimethalin, metolachlor, and trifluralin applied to U.S soybean declined from 0.97 lb/acre in 1995 to 0.16 lb/acre in 2006, or an average 83.5% reduction.

The use of glyphosate dominates weed management in soybean, with no other single herbicide being applied on more than 10% of soybean acres. The second most common herbicide is 2,4-D (10% of soybean acres) that is applied preplant because it cannot be applied within 7 days of soybean planting or thereafter because of potential injury to soybean. No single herbicide used for postemergent weed management in soybean is used on more than 4% of soybean acres.

The adoption of GR soybean by producers resulted from the desire to realize a net decrease in the cost of weed control, tillage operations, and labor inputs (Dill 2005; Gianessi 2005; Reddy and Whiting 2000). Conventional weed management in soybean can provide similar levels of weed control, soybean grain yield, and economic returns compared with GR soybean (Nolte and Young 2002). But the simplicity of weed management in GR soybean and the perception by growers that weed pressures are lower as a result of using a glyphosate-based weed management system (Kruger et al. 2009) are intangibles that may be weighted by growers as much as the sum of all other factors. The simplicity of using a single, broad-spectrum herbicide such as glyphosate for control of multiple weed species with a large range in size is a significant consideration for growers.

Weed Management Factors Affected by Using Transgenic Soybean

All the tools for weed management in conventional soybean plus the addition of glyphosate following crop emergence are available to develop weed management systems in GR soybean. But the adoption of GR soybean has been characterized by a decrease in the number of herbicide active ingredients from 2.5 in 1994 to 1.6 in 2002 (Young 2006). Estimates from the early adoption of GR soybean through 2006 suggest that up to 75% of soybean production acreage annually receives only glyphosate for weed management (Dill, CaJacob, and Padgette 2008; Young 2006). Not only did glyphosate provide greater control of typical weed species than conventional soybean weed management strategies, it also enabled control of weeds that evolved resistance to conventional soybean herbicides (Nolte and Young 2002). Thus, growers were able to achieve unprecedented weed control with a single herbicide and had little incentive to incorporate additional weed control tactics that included tillage.

Conventional tillage in GR soybean was estimated in the range of 30 to 35% from 2002 to 2006 compared with 45 to 50% in conventional soybean during the same period (Dill, CaJacob, and Padgette 2008). The decrease in tillage used with GR soybean has been credited with mitigating soil erosion, as well as decreasing fuel consumption by substituting the herbicide for tillage (Gianessi and Reigner 2006). Glyphosate replaces herbicides that have a 3.4 to 16.8 times greater toxicity rating according to a chronic risk indicator based on the Environmental Protection Agency (EPA) reference dose for humans (USDA–ERS 2005a). Cerdeira and Duke (2006) concluded from a literature review that the presence of glyphosate in soil, water, and air poses a minimal environmental risk compared with alternative herbicides. The decrease in tillage, the replacement of less environmentally friendly herbicides used in conventional soybean, and control of all previous herbicide-resistant weed species are positive sustainability attributes associated with the use of GR soybean.

Transgenic Soybean and Weed Resistance

The sole reliance on glyphosate for weed management in GR soybean is in direct conflict with recommendations to prevent the evolution of herbicide-resistant weed species (Boerboom and Owen 2006; Radosevich, Ghersa, and Comstock 1992). Ironically, the performance of glyphosate in GR soybean has been so robust and its exclusive use so easy to manage that weeds are starting to develop resistance to glyphosate, thus effectively limiting the effectiveness of glyphosate with GR soybean as a stand-alone weed management system.

In 1996, the first GR weed was reported in the United States in a California population of rigid ryegrass (*Lolium rigidum*) (Heap 2008; Table 4.2). The first GR weed species to evolve in a soybean production site did not occur until 2000 in a population of horseweed (*Conyza canadensis*) (VanGessel 2001; Table 4.2). This occurrence also was the first instance of a broadleaf weed evolving resistance to glyphosate. Within a 3-year period of using only glyphosate in no-till GR soybean, the selection of GR horseweed biotypes occurred.

Glyphosate use in the United States spanned the previous 25 years before the year 2000, and glyphosate was considered a low-risk herbicide for developing weed resistance. But the increasingly intensive use of glyphosate in GR soybean and other GR crops and the lack of use of other weed management tactics such as tillage and herbicide active ingredients with alternative modes of action are credited for the selection of glyphosate resistance in several weed species. Since 2000, the selection of GR weeds has become more common as many U.S. growers continue to use a limited strategy for weed management in soybean compared with the previous half-century in which growers were obligated to implement a diverse set of control tactics to achieve effective weed management. The five GR weed species reported most recently all have devel-

Table 4.2. Reports of glyphosate-resistant weeds in the United States (Heap 2008)

Weed	Year First Reported	U.S. Location of Resistant Populations
Rigid ryegrass	1996	California
Horseweed (marestail)	2000	17 States
Italian ryegrass	2001	Oregon, Mississippi
Hairy fleabane	2003	California
Giant ragweed	2004	Ohio, Arkansas, Indiana, Kansas, Minnesota, Tennessee
Common ragweed	2004	Arkansas, Missouri, Kansas
Common waterhemp	2005	Missouri, Illinois, Kansas, Minnesota
Palmer amaranth	2005	Georgia, North Carolina, Arkansas, Tennessee, Mississippi
Johnsongrass	2005	Arkansas

oped in GR cropping systems with a heavy reliance on glyphosate (Table 4.2). It is important to note that no research to date has demonstrated clearly that GR giant ragweed, common ragweed, common waterhemp, and palmer amaranth populations did not evolve independently within each reporting state.

The dynamic evolution and spread of GR weeds precludes an exact measure of the affected soybean acreage in the United States. At least 5 million acres have been estimated (Heap 2008), however, and this figure does not account for the number of acres where a shift toward glyphosate-tolerant species (e.g., common lambsquarters, morningglory spp., and wild buckwheat) has reduced the efficacy, simplicity, and potential profitability of GR soybean production. The soybean production area impacted by a weed shift to glyphosate-tolerant species may be greater than areas with populations of GR resistant weeds because weed shifts occur at a high enough frequency to develop in small-plot research (Wilson et al. 2007).

Shifts in weed populations in response to herbicides, whether herbicide-resistant or just inherently less sensitive to the herbicide, are certainly not foreign to weed management. The entire production system for the crop and the integration of other weed control measures taken by growers also should be considered as the driving forces to create weed shifts (Owen 2008). But the historic trend of developing new weed management technologies, especially novel herbicide modes of action, has slowed substantially in recent years because of little market incentive for companies to discover new herbicides due to the near-monopoly of glyphosate use in GR soybean. The spread of GR weed species, the evolution of additional species with resistance, and the lack of new herbicide modes of action with inherent soybean tolerance could handicap weed management in the future.

Strategies for Weed Management in Transgenic Soybean

The most common strategy that results in generally effective weed management in GR soybean has been two applications of glyphosate after soybean emergence (Givens et al. 2009; Young 2006). This is generally the same or one less herbicide application event than is common in the conventional system. The application timing of glyphosate generally has been determined by a combination of weed height, weed density, and the potential for subsequent weed emergence after the application (Johnson, Gibson, and Conley 2007). Because the efficacy of glyphosate is maintained over a wide range of weed heights (VanGessel, Ayeni, and Majek 2000), its application timing has been significantly later than that of nonglyphosate herbicides for control of large weeds (Young 2006). Significant soybean yield reductions from early-season weed competition have been associated with these delayed postemergence applications of glyphosate (VanGessel, Ayeni, and Majek 2000; Knezevic, Evans, and Mainz 2003).

The integration of the application of other herbicides with glyphosate has been encouraged by weed specialists for several reasons:

- to improve the timing and duration of weed control to prevent soybean yield loss,
- to enhance control of some inherently glyphosate-tolerant weeds,
- to reduce the risk for developing GR weeds, and
- to control weeds that have already evolved

resistance to glyphosate (Boerboom and Owen 2006).

Applying soil residual and foliar-applied herbicides in combination with glyphosate has improved weed control compared with glyphosate applied alone (Eubank et al. 2008; Westhoven et al. 2008). Preplant applications of 2,4-D, dicamba, paraquat, glufosinate, alachlor, S-metolachlor, metribuzin, flumioxazin, and sulfentrazone have contributed to improved control of glyphosate-tolerant or -resistant weed populations (Eubank et al. 2008; Legleiter, Bradley, and Massey 2009; Westhoven et al. 2008). The diversity of the modes of action and herbicide activity (soil residual and/or foliar) has positive implications for management of weeds where glyphosate has suboptimal activity before soybean planting. In contrast, applying non-GR herbicides in combination with glyphosate for improved postemergence weed control has been inconsistent (Legleiter, Bradley, and Massey 2009). The presence of GR weeds and weeds that are resistant to the acetolactate synthase (ALS)- and protoporphyrinogen oxidase (PPO)-inhibiting postemergence herbicides used for broadleaf weed control (Legleiter, Bradley, and Massey 2009) creates a need for new technologies to maintain the sustainability of weed management in soybean.

The most rapid mechanism to alleviate weed management problems due to glyphosate ineffectiveness will be the adoption of new herbicide-resistant varieties. Glufosinate-resistant soybean (Liberty Link) will be grown on a limited acreage in the United States in 2009 (Allen and Fischer 2008; Liberty Link 2008). Glyphosate/ALS-resistant (GAT/HRA, Optimum GAT) soybean (Green 2007), dicamba-resistant soybean, and 2,4-D resistant (DHT) soybean (Simpson et al. 2008) are expected to be sold commercially in the United States in 2011, 2013, and 2014, respectively. Monsanto is developing a dicamba-tolerant soybean product that will be combined with its Roundup Ready 2 Yield product to provide growers the option to apply two different herbicide chemistries on the same variety to control weeds. Manufacturers of herbicide-resistant varieties also are recommending that pre-emergent herbicides with residual activity be used in combination with the transgenic varieties to reduce the likelihood that weeds will develop resistance to the herbicide to which the transgenic product provides resistance. This combining of present technologies and forthcoming new technologies should provide soybean producers the continuing ability to sustainably control GR weeds within their overall weed management programs that include glyphosate and GR varieties.

New herbicide modes of action with concurrent tolerance in soybean must be identified continually to ensure sustainable weed management. Weed management in soybean will still be possible, but on a more challenging scale because older herbicide compounds, tillage, and cover crops may have to be integrated into the development of effective weed control strategies in soybean due to the erosion of glyphosate activity (Owen 2008). This circumstance likely will increase both pesticide load to the environment and weed management costs. Thus, the evolution of GR weeds may decrease the positive environmental benefits from the use of glyphosate if increases in tillage and use of environmentally persistent herbicides again become a part of weed management strategy in soybean.

Ideally, growers will implement a diverse or integrated strategy to manage weeds in GR soybean before experiencing any dramatic decrease in glyphosate performance (Boerboom and Owen 2006; Owen 2008). This practice will enhance the sustainability of weed management in GR soybean and allow for greater flexibility in accommodating environmental stewardship.

To date, no major detriments to environmental quality have occurred due to the adoption of GR soybean (Cerdeira and Duke 2006; Owen 2008). There is the potential for low concentrations of glyphosate and its degradation product to appear in surface and groundwater supplies at infrequent intervals (Carpenter et al. 2002; Scribner et al. 2007). But, concentrations and losses of glyphosate from areas of application are lower than those of non-GR herbicides and thus result in glyphosate having a relatively favorable environmental profile (Carpenter et al. 2002). Application methods have been refined and adopted to reduce drift to off-target areas (Young et al. 2003) because some glyphosate formulations and widespread application of glyphosate can increase potential drift injury to off-target species (Mueller and Womac 1997). The agroecosystem has endured the greatest impact from using GR soybean because of the weed population dynamic change in response to repeated glyphosate applications. This impact on the agroecosystem primarily resides in agronomic sites and is not anticipated to influence the ecosystem outside of agricultural boundaries.

Chapter Summary

Presently, there are no transgenic disease management traits in soybean; however, molecular approaches that inhibit this parasitic process through molecular genetic techniques may be forthcoming. New biotechnology strategies that exploit the plant's system of regulation currently are being investigated. How these new strategies will work and their effectiveness for the long term are unknown.

Transgenic insecticidal soybean has been evaluated in the United States and found to be highly effective against some Lepidoptera defoliators. Experts generally agree, however, that the first generation of transgenic insecticidal soybean will be commercialized only in South America. In the United States, defoliating insect damage primarily occurs in the southern region, and the acreage there is not large enough to justify the high cost of obtaining regulatory approval.

The development of GR soybean has been considered the greatest step toward a sustainable weed management system because the use of glyphosate can displace tillage operations while not resulting in undue harm to the environment. Widespread use and reliance on glyphosate due to its effectiveness, simplicity, and cost-effectiveness, however, has stimulated a change in weed populations to species that are difficult to control or that have developed resistance to glyphosate. The problem is not that growers use glyphosate; rather, the problem is that growers have been reluctant to use other strategies that may or may not include glyphosate for weed management in GR soybean. Experts agree that this practice cannot continue and must change to using more diverse weed management strategies.

The future sustainability of transgenic soybean for weed management will rely on the availability of herbicides to which conventional soybean varieties are inherently tolerant as well as the commercialization of new transgenic soybean such as Liberty Link, Optimum GAT, dicamba resistance, and 2,4-D resistance. These new transgenic soybean, however, do not bring to market any new herbicide modes of action, and they all must be managed with a diverse mix of weed control strategies. In fact, glyphosate may be used in these systems because glyphosate resistance is a component of Optimum GAT, will be present in dicamba-resistant soybean, and likely will be incorporated into Liberty Link and 2,4-D resistant soybean in the future. Thus, when used properly with other herbicides and resistance mechanisms, glyphosate and GR soybean will continue to provide a large contribution toward the sustainability and environmental impact of soybean production in the United States.

Literature Cited

Allen, J. and J. Fischer. 2008. Development of Liberty Link soybean trait technology. *North Central Weed Science Society Proc* 63:87, http://www.ncwss.org/

American Soybean Association (ASA). 2008. ASA welcomes EU soybean import approval. *Southeast Farm Press*, December 5, http://southeastfarmpress.com/soybeans/soybean-exports-1205/

Baum, J. A., T. Boaert, W. Clinton, G. R. Heck, P. Feldmann, O. Hagan, S. Johnson, G. Plaetinck, T. Munyikwa, M. Pleau, T. Vaughn, and J. Roberts. 2007. Control of coleopteran insect pests through RNA interference. *Nat Biotech* 25:1322–1326.

Boerboom, C. and M. Owen. 2006. Facts about glyphosate-resistant weeds. Purdue Extension GWC-1. Purdue University Extension, West Lafayette, Indiana, http://www.ces.purdue.edu/extmedia/GWC/GWC-1.pdf

Carpenter, J., A. Felsot, T. Goode, M. Hammig, D. Onstad, and S. Sankula. 2002. *Comparative Environmental Impacts of Biotechnology-derived and Traditional Soybean, Corn, and Cotton Crops*. Council for Agricultural Science and Technology, Ames, Iowa.

Cerdeira, A. L. and S. O. Duke. 2006. The current status and environmental impact of glyphosate-resistant crops: A review. *J Environ Qual* 35:1633–1658.

Davis, E. L., R. S. Hussey, M. G. Mitchum, and T. J. Baum. 2008. Parasitism proteins in nematode-plant interactions. *Curr Opin Plant Biol* 11:360–366.

Dill, G. M. 2005. Glyphosate resistant crops: History, status, and future. *Pest Manag Sci* 61:219–224.

Dill, G. M., C. A. CaJacob, and S. R. Padgette. 2008. Glyphosate-resistant crops: Adoption, use and future considerations. *Pest Manage Sci* 64:326–331.

Eubank, T. W., D. H. Poston, V. K. Nandula, C. H. Koger, D. R. Shaw, and D. B. Reynolds. 2008. Glyphosate-resistant horseweed (*Conyza canadensis*) control using glyphosate-, paraquat-, and glufosinate-based herbicide programs. *Weed Technol* 22:16–21.

Fehr, W. R. 1987b. *Principles of Variety Development: Theory and Technique*. McMillan Publishing, New York.

Fuller, V. L., C. J. Lilley, and P. E. Urwin. 2008. Nematode resistance. *New Phytologist* 180:27–44.

Gianessi, L. 2005. Economic and herbicide use impacts of glyphosate-resistant crops. Pest Manag Sci 61:241-245.

Gianessi, L. P. and N. P. Reigner. 2006. The value of herbicides in U.S. crop production, 2005 update. CropLife Foundation, Washington, D.C., http://www.croplifefoundation.org/cpri_benefits_herbicides.htm

Givens, W. A., D. R. Shaw, W. G. Johnson, S. C. Weller, B. G. Young, R. G. Wilson, M. D. K. Owen, and D. Jordan. 2009. A grower survey of herbicide use patterns in glyphosate-resistant cropping systems. *Weed Technol* (in press).

Green, J. M. 2007. Review of glyphosate and ALS-inhibiting herbicide crop resistance and resistant weed management. *Weed Technol* 21:547–558.

Heap, I. 2008. *International Survey of Herbicide Resistant Weeds*. WeedScience.org, http://www.weedscience.org/In.asp

Hewezi, T., P. Howe, T. R. Maier, and T. J. Baum. 2008. Arabidopsis small RNAs and their targets during cyst nematode parasitism. *Molec Plant Microbe Interactions* 12:1622–1634.

Johnson, W. G., K. D. Gibson, and S. P. Conley. 2007. Does weed size matter? An Indiana grower perspective about weed control timing. *Weed Technol* 21:542–546.

Knezevic, S. Z., S. P. Evans, and M. Mainz. 2003. Row spacing influences the critical timing for weed removal in soybean (Glycine max). *Weed Technol* 17:666–673.

Kruger, G. R., W. G. Johnson, S. C. Weller, M. D. K. Owen, D. R. Shaw, J. W. Wilcut, D. L. Jordan, R. G. Wilson, M. L. Bernards, and B. G. Young. 2009. U.S. growers views on problematic weeds and changes in weed pressure in glyphosate-resistant corn, cotton, and soybean cropping systems. *Weed Technol* (in press).

Legleiter, T. R., K. W. Bradley, and R. E. Massey. 2009. Glyphosate-resistant waterhemp (*Amaranthus rudis*) control and economic returns with herbicide programs in soybean. *Weed Technol* (in press).

LibertyLink Soybeans. 2008. *Farm Industry News*, October 1. Penton Media, Inc., New York, http://farmindustrynews.com/seed/soybeans/1003_libertylink_soybeans/

MacRae, T. C., M. E. Baur, D. J. Boethel, B. J. Fitzpatrick, A.-G. Gao, J. C. Gamundi, L. A. Harrison, V. T. Kabuye, R. M. McPherson, J. A. Miklos, M. S. Paradise, A. S. Toedebusch, and A. Viegas. 2005. Laboratory and field evaluations of transgenic soybean exhibiting high-dose expression of a synthetic *Bacillus thuringiensis cry1A* gene for control of Lepidoptera. *J Econ Entomol* 98:577–587.

Miklos, J. A., M. F. Alibhai, S. A. Bledig, D. C. Connor-Ward, A-G. Gao, B. A. Holmes, K. H. Kolacz, V. T. Kabuye, T. C. MacRae, M. S. Paradise, A. S. Toedebusch, and L. A. Harrison. 2007. Characterization of soybean exhibiting high expression of a synthetic *Bacillus Thuringiensis cry1A* transgene that confers a high degree of resistance to lepidopteran pests. *Crop Sci* 47:148–157.

Mueller, T. C., and A. R. Womac. 1997. Effect of formulation and nozzle type on droplet size with isopropylamaine and trimesium salts of glyphosate. *Weed Technol* 11:639–643.

Nolte, S. A. and B. G. Young. 2002. Efficacy and economic return on investment for conventional and herbicide-resistant soybean (*Glycine max*). *Weed Technol* 16:388–395.

Onstad, D. W. 2008. *Insect Resistance Management: Biology, Economics and Prediction*. Academic Press, Burlington, Massachusetts.

Owen, M. D. K. 2008. Weed species shifts in glyphosate-resistant crops. *Pest Manage Sci* 64:377–387.

Parrott, W. A. and T. E. Clemente. 2004. Transgenic soybean. Pp. 265–302. In H. R. Boerma and J. E. Specht (eds.). *Soybeans: Improvement, Production and Uses*. 3rd ed. Agronomy Monographs 16. ASA, CSSA, WSSA, Madison, Wisconsin.

Radosevich, S. R., C. M. Ghersa, and G. Comstock. 1992. Concerns a weed scientist might have about herbicide tolerant crops. *Weed Technol* 6:635–639.

Reddy, K. N. and K. Whiting. 2000. Weed control and economic comparisons of glyphosate-resistant, sulfonylurea-tolerant, and conventional soybean (*Glycine max*) systems. *Weed Technol* 14:204–211.

Scribner, E. A., Battaglin, W. A., Gilliom, R. J., and Meyer, M. T. 2007. Concentrations of glyphosate, its degradation product, aminomethylphosphonic acid, and glufosinate in ground- and surface-water, rainfall, and soil samples collected in the United States, 2001–06. *Scientific Investigations Report 2007-5122*. U.S. Dept. of the Interior, U.S. Geological Survey, Reston, Virginia.

Simpson, D. M., T. R. Wright, R. S. Chambers, M. A. Peterson, C. Cui, A. E. Robinson, J. S. Richburg, D. C. Ruen, S. Ferguson, B. E. Maddy, and E. F. Schreder. 2008. DowAgroSciences herbicide tolerance traits in corn and soybean. *North Central Weed Science Society Proc* 63:85, http://www.ncwss.org/

Sindhu, A. S., T. R. Maier, M. G. Mitchum, R. S. Hussey, E. L. Davis, and T. J Baum. 2009. Effective and specific in planta RNAi in cyst nematodes: Expression interference of four parasitism genes reduces parasitic success. *J Expt Botany* 60:315–324.

U.S. Department of Agriculture–Economic Research Service (USDA–ERS). 2005a. Agricultural chemicals and production technology: Genetically engineered crops. USDA–ERS, Washington, D.C., http://www.ers.usda.gov/Briefing/AgChemicals/geneticengineered.htm

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 1996. Agricultural Chemical Usage 1995 Field Crops Summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1560

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2007. Agricultural Chemical Usage 2006 Field Crops Summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC//2000s/2007/AgricChemUsFC-05-16-2007_revision.pdf

U.S. Department of Agriculture–National Agricultural Service (USDA–NASS). 2008b. Acreage. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-30-2008.pdf

VanGessel, M. J. 2001. Glyphosate-resistant horseweed from Delaware. *Weed Sci* 49:703–705.

VanGessel, M. J., A. O. Ayeni, and B. A. Majek. 2000. Optimum glyphosate timing with or without residual herbicides in glyphosate-resistant soybean (*Glycine max*) under full-season conventional tillage. *Weed Technol* 14:140–149.

Walker, D. R., J. N. All, R. M. McPherson, H. R. Boerma, and W. A. Parrott. 2000. Field evaluation of soybean engineered with a synthetic *cry1Ac* transgene for resistance to corn earworm, soybean looper, velvetbean caterpillar (Lepidoptera: Noctuidae), and lesser cornstalk borer (Lepidoptera: Pyralidae). *J Econ Entomol* 93:613–622.

Westhoven, A. M., J. M. Stachler, M. M. Loux, and W. G. Johnson. 2008. Management of glyphosate-tolerant common lambsquarters (*Chenopodium album*) in glyphosate-resistant soybean. *Weed Technol* 22:628–634.

Wilson, R. G., S. D. Miller, P. Westra, A. R. Kniss, P. W. Stahlman, G. W. Wicks, and S. D. Kachman. 2007. Glyphosate-induced weed shifts in glyphosate-resistant corn or a rotation of glyphosate-resistant corn, sugarbeet, and spring wheat. *Weed Technol* 21:900–909.

Young, B. G. 2006. Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. *Weed Technol* 20:301–307.

Young, B. G., K. L. Schmoll, R. W. Steffen, and W. Moon. 2003. Survey of herbicide drift in Illinois. *Abst Weed Sci Soc Amer* 43:66–67.

5 Soybean Production Systems in the United States: Organic System

Organic agriculture is based on minimal use of off-farm inputs and on management practices that promote and enhance biodiversity, biological cycles, and soil biological activity. The principal guidelines for organic production are to use materials and practices that enhance the ecological balance of natural systems and that integrate the parts of the farming system into an ecological whole. Methods are used to minimize pollution of air, soil, and water. The primary goal of organic agriculture is to optimize the health and productivity of interdependent communities of soil life, plants, animals, and people. Practices and inputs such as crop rotation, cover crops and green manures, animal manures, rock minerals, and biological control of pests are used (Gold 2007b; Kuepper 2003).

It is possible to produce organic soybean without certification; however, to sell soybean in the United States as *certified organic*, the grower must be certified by a U.S. Department of Agriculture (USDA)-*accredited certification agency*. The first U.S. federal organic standards became effective on October 21, 2002 (USDA–AMS 2008). If food products carry the USDA Certified Organic label (seal), the soybean must be certified by agencies listed by the USDA (USDA–AMS 2008). Quoting the USDA–*Agricultural Marketing Service* (AMS) *National Organic Program*'s (NOP) overview, "The NOP develops, implements, and administers national production, handling, and labeling standards for organic agricultural products. The NOP also accredits certifying agents (foreign and domestic) who inspect organic production and handling operations to certify that they meet USDA standards" (USDA-AMS 2008). There are many requirements to meet to be certified organic; briefly, they include the following:

1. no synthetic fertilizers and pesticides, and no transgenic varieties for at least the previous 3 years;
2. an approved planned sequence of crops in each identified field;
3. use of organically produced seed; and
4. complete records of inputs and operations.

For a complete, current list of accepted compounds, products, and requirements, see the NOP website (USDA–AMS 2008).

Certified Organic Soybean Acreage

The latest information compiled by USDA on certified organic soybean acres in the United States is for 2005. Out of 72,142,000 acres of soybean that year (USDA–NASS 2008a), 122,217 acres were certified as organic, or 0.17% of the total (USDA–ERS 2005b). Minnesota, Iowa, and Michigan had almost half of the U.S. total (Table 5.1). Organic soybean acreage increased from fewer than 50,000 acres in 1995 to nearly 175,000 in 2001. Increased supply, along with competition from China, lowered prices for organic soybean, and acreage fell 27% in 2002 to approximately its current level (McBride and Greene 2008).

The market for organically grown soybean is likely to increase in the United States due to several factors:

- increased domestic and international demand for organic soybean products,
- increased interest in organic animal production and products (animals must be fed organically grown feed for the meat or other products such as milk and eggs to be certified organic), and
- increased need to supply producers growing organic soybean with the required *organic seed*.

This assumption, of course, is based on the premise that the premium paid for organic soybean will continue to be large enough to counteract the high cost of production and that yields of varieties used in organic soybean production will keep pace with the continuing increases in yields of transgenic varieties.

Organically grown soybean has a relatively large acreage in the United States compared with other organically grown crops because soybean has had a strong market and is perceived to be one of the most

Table 5.1. U.S. certified organic soybean acreage by state in 2005 (only states with certified acres are listed) (USDA–ERS 2005b)

State	Acreage
Arizona	676
Arkansas	4,420
California	16
Colorado	21
Connecticut	88
Delaware	10
Hawaii	9
Idaho	551
Illinois	6,505
Indiana	1,147
Iowa	15,570
Kansas	2,366
Kentucky	167
Maine	62
Maryland	522
Michigan	15,456
Minnesota	26,581
Missouri	7,640
Nebraska	6,953
New Jersey	59
New York	1,348
North Carolina	244
North Dakota	2,970
Ohio	8,330
Oklahoma	80
Pennsylvania	1,315
South Dakota	3,804
Tennessee	60
Texas	6,258
Virginia	155
West Virginia	281
Wisconsin	8,553

profitable (Karlen et al. 2004). Soybean fits well into the rotation system required for organic production because it is a legume and fixes nitrogen (N) for its own use and contributes N to following cereal crops.

Breeding and Variety Development/Availability

There has not been a specific effort by public or private breeders to develop varieties for organic production systems. Organic soybean producers use conventionally developed (nontransgenic) varieties from either public or private breeding programs. Breeders have done some research on traits such as competitiveness with weeds (Bussan et al. 1997; Jannink et al. 2000; Pester, Burnside, and Orf 1994) as well as the usual traits such as yield and pest/hazard (disease, nematode, insect, and abiotic stresses) resistance for organic production. But no soybean breeding effort has considered organic production exclusively. This circumstance is due in part to the myriad systems used for organic production. A study currently underway in Minnesota (Orf, J. 2008. Personal communication) addresses the question of whether or not a separate breeding program is needed for organic soybean production systems. Thus, for the present and foreseeable future (6 to 10 years are needed to develop a variety), organic producers will rely on conventionally developed, nontransgenic varieties.

Planting organically produced seed is required for certification, but there are some exceptions. Organic seed is required unless an equivalent organic variety is not commercially available. The certifying agent determines whether the operation's documentation of commercial availability is adequate to support the use of nonorganic seed. If organic seed of the particular variety is not commercially available, nonorganically produced, untreated seed (no pesticide seed treatment) may be used to produce an organic crop. If the seed variety is not commercially available in untreated form, nonorganically produced seed that has been treated with an allowed substance on the National List of Allowed and Prohibited Substances may be used to produce an organic crop. Without exception, however, organic seed is required for the production of edible sprouts (USDA–AMS 2008).

Varieties developed using conventional (nontransgenic) techniques are available from breeding programs in both the public and private sectors. Although most recently released varieties from the private sector are transgenic, nontransgenic seed varieties are available in limited quantities. Many public programs continue to develop nontransgenic breeding lines for potential variety release. In some areas there may be a lack of seed of specific varieties produced organically or conventionally, but in almost all instances, seed of an adapted nontransgenic variety is available. The authors anticipate (based on conversations with public and private breeders) that nontransgenic varieties will continue to be available for producers who desire to plant these materials.

Management Practices

McBride and Greene (2008) recently conducted a unique, extensive survey of Midwestern commercial soybean farmers to compare the economics and practices of conventional and organic soybean production. They found and/or concluded the following:

- organic soybean production is conducted on smaller farm operations than conventional production;
- significant labor requirements associated with organic soybean production make organic production less practical on larger farms due to the need to hire additional labor, whereas the labor requirements on smaller farms are often met by operator and other unpaid labor sources;
- organic soybean operations substitute field operations for chemicals and incur higher fuel, repair, and hired labor costs; and
- organic soybean producers have an average yield of 31 bu/acre compared with 47 bu/acre for conventional producers.

Organic soybean farmers have a plethora of management options to consider for optimizing production and profit (Table 5.2). It is important that these management practices be considered and assessed for inclusion in an organic soybean system to achieve yield levels greater than the average yield cited in this section. The practices discussed here are categorized similarly to those described in Chapters 2 and 3. But they are, in many instances, unique in their application in the organic system, and they are described in detail here as being specific to that system.

Table 5.2. Strategies for sustaining optimal organic soybean production and profit

Operation/Strategy	Rationale
Rotate crops	Required for certification; improves pest and weed control
Lengthen rotation	Improves pest and weed control
Use cover crops	Improves pest and weed control; improves/maintains soil quality and reduces erosion/runoff
Delay planting date	Aids in weed control by managing first weed flush; allows relative soybean seedling advantage
Increase seeding rate	Increases competitiveness with weeds; allows for tillage-reduced stands during post-emergence weed control operations
Food grade variety	Captures added value
Variety selection	Canopy type affects weed and pest control
Wide rows (>30 in.)	Allows row cultivation; can reduce white mold problem
Narrow rows (<30 in.)	Allows quicker canopy for weed control; preferable when planting into a cover crop or heavy mulch
Timely preplant tillage	Disk/rotary hoe to reduce weed seed population density and kill emerged weeds
Timely postemergence tillage	Rotary hoe/row cultivate in a timely manner for control of small weeds and to reduce weed escapes
Postemergence flame weeding	Reduces weed stand without tillage
Postemergence fallow field portions	Disk “trouble spots” to control weed “seed rain” and prevent subsequent weed problems
Hand-weed	Controls weed escapes and protects high-value crop
Apply approved fertilizers	Maintains proper soil fertility and protects certification
Diversify with livestock	Provides cheap and readily-available animal manure source
Apply livestock manure	Maintains soil fertility at low cost (assuming no purchase cost)
Apply approved substances	Because of added expense, use as a last resort to salvage a high-value crop
Bookkeeping	Facilitates inspection, aids in planning/altering rotations
Contract marketing	Establishes base price and stabilizes income

Tillage

One of the major criticisms of organic production is its heavy reliance on tillage. Tillage is required for eliminating perennial legumes before rotation to annual crops, for incorporating manure to avoid N volatilization losses, and for preparing a seedbed and controlling weeds (Teasdale, Coffman, and Mangum 2007). Some researchers have speculated that conventional no-till agriculture may provide superior soil improvement and potential environmental benefits compared with organic production practices because of the relatively intense tillage requirement of organic farming (Trewavas 2004). Teasdale, Coffman, and Mangum (2007) conducted a long-term experiment (9 years followed by a 3-year uniformity trial) to compare selected no-till grain cropping systems and a reduced-tillage organic system in the mid-Atlantic region. Their results suggest that the organic system can result in greater accumulation of organic matter in the soil; however, the organic system increased the risk of erosion and the commensurate loss of nutrients with the eroded soil (Green et al. 2005). Lack of adequate weed control was a major problem in the organic system as well (Cavigelli, Teasdale, and Conklin 2008).

Crop Rotation and Cover Crops Preceding Soybean

The choice of crop rotation sequence is fundamental and foundational. Skimping on rotation length and crop diversity in the rotation often will lead to increased problems with weeds, insects, diseases, and fertility.

The USDA–AMS–NOP defines crop rotation as "the practice of alternating the annual crops grown on a specific field in a planned pattern or sequence in successive crop years so that crops of the same species or family are not grown repeatedly without interruption on the same field. Perennial cropping systems use practices such as alley cropping, intercropping, and hedgerows to introduce biological diversity in lieu of crop rotation" (USDA–AMS 2008). Accredited certification agencies require proper record keeping of the planned sequence of crops in each identified field. The farmer is not required to adhere strictly to the planned sequences, and leeway is given in cases where changes to the planned sequences are justified. The NOP standards do not specify requirements for crop rotation length or what specific sequence of crops constitutes an acceptable crop rotation. The NOP standards leave further definition to the discretion of the accredited certification agencies, except to state that "the producer must implement a crop rotation including but not limited to sod, cover crops, green manure crops, and catch crops that provide the following functions that are applicable to the operation: (a) maintain or improve soil organic matter content, (b) provide for pest management in annual and perennial crops, (c) manage deficient or excess plant nutrients, and (d) provide erosion control" (USDA–AMS 2008).

The accredited certification agency determines that the producer is implementing a sound crop rotation. Typically, the crop rotation is assessed on a field-by-field basis. The standards do not state how frequently a crop such as soybean can occur in the rotation. Also, the standards do not state that a farmer must include cover crops or green manure crops in the rotation. There are valid reasons for the organic farmer to use appropriate crop rotations. Often, failure to pay close attention to the crop rotation used can result in future management problems related to soil fertility, weed and pest management, and/or crop performance.

The benefits and challenges of managing cover crops in the crop rotation with soybean have been well summarized (Clark 2007). Soybean has been planted successfully into a standing rye cover crop that was later mowed at anthesis (Porter et al. 2005) and rye that has been "roller-crimped" (Ashford and Reeves 2003). At the Rodale Institute, a roller has been designed that kills living crops by "crimping" their shoots. This roller can be placed on the front of the tractor with a three-point hitch; thus, planting can be accomplished in one pass. The cover crop is crimped and the mulch serves as a mat for weed control (Moyer, J. 2008. Personal communication). This system requires only one or two total trips across the field, and thus dramatically lowers costs. But the crimping operation must be done in a timely fashion to be effective; if the operation is not done at the proper cover crop stage to obtain an effective kill, the grower is left with an unacceptable environment for planting soybean because herbicides cannot be used to remedy the situation.

Fertility

After weed control, many organic farmers consider soil fertility the biggest challenge in organic production systems (Welsh 1999). Organic farmers generally rely on animal manures and legume cover crops to supply crops with N. Nitrogen is commonly the most limiting plant nutrient in organic production systems. Because soybean is a legume and does not require N as an input, it often is a favored crop to have in the rotation.

Rock phosphate, manure, or other organic sources of phosphorus (P) can be applied to maintain soil P level. Rock phosphate has a very low solubility, so rates of application will necessarily be high. Rock phosphate will be more effective on slightly acid soils than on soils with a pH of 7 or higher. Potassium sulfate and, if available, the potassium (K) from manure can be used as K sources. Most manures contain low amounts of K relative to P; therefore, using manure as the sole source of K will be coincidental with increases in soil P. A caveat for using manure or other organic materials as a P and K source is that manure contains N. As stated previously, added N may inhibit nodulation or nodule activity in soybean; thus, manure fertilizers should be applied a year in advance of growing a soybean crop.

Farms producing livestock and farms in proximity to livestock confinement operations have the advantage of access to animal manures. Manure from conventionally raised livestock can be used on certified organic land in accordance with the NOP standards (USDA–AMS 2008). A summary of sources for organic fertilizers and amendments has been compiled by Kuepper, Diver, and Sampson (2004).

Disease, Nematode, and Insect Management

For diseases other than Asian soybean rust (ASR), varietal resistance is arguably the best disease management option for organic soybean production. It is assumed that crop rotation and the intense tillage in organic systems also will control or manage some pathogens (Table 5.2). Certain pest management products are permitted under the NOP standards. Determination of whether specific products meet NOP rules has been entrusted primarily to the Organic Materials Review Institute (OMRI), an independent private agency. Manufacturers voluntarily submit products to OMRI for review. Those products deemed to be within the NOP guidelines are then allowed to display the OMRI-Listed Seal on their packaging and in marketing (OMRI 2008). Mahaffey and Cranshaw (2007) compiled a list of 25 generic categories thought to include products used in pest management.

Control of soybean cyst nematode (SCN) in an organic system probably presents the least problem. Where nematodes have become a problem, rotating to nonhost crops, integrating nematicidal cover crops into the crop rotation, and selecting SCN-resistant varieties have proved effective (Kuepper 2003). White mold (*Sclerotinia sclerotiorum*) can be a serious problem in organic soybean production, and variety selection is the foundation for most white mold management plans. Other management strategies include canopy management through row width alteration, delayed planting, crop rotation, reduced tillage, and the use of OMRI-approved biofungicides (Kuepper 2001).

Virtually all existing soybean varieties are susceptible to ASR; therefore, varietal resistance is not available as a management tool to combat ASR in organic systems. As described previously, numerous synthetic fungicides are effective in ASR management, but they are not acceptable in organic systems. Recent studies in Florida where ASR was present identified organic-approved copper fungicides that controlled ASR significantly better than products that did not contain copper. Organic-approved noncopper fungicides limited ASR, but not as effectively as the copper-containing materials (Gevens et al. 2008).

Organic soybean production is likely to rely on landscape design and integrated pest management (IPM) to manage insects and mites. Landscape design means that farmers may choose to plant the soybean field near natural and managed areas that can contribute natural enemies and trap crops to the soybean system (Zehnder et al. 2007). Design that eliminates alternative host plants from the farm also may decrease pest pressure from migrant pests leaving other crops during the growing season. Zehnder and colleagues (2007) state that organic cropping systems will take full advantage of crop rotations, conventional plant breeding, and biological control to integrate pest management. For example, traditional insecticidal applications of *Bacillus thuringiensis* can help control Lepidoptera in organic soybean. Impacts of permitted chemicals, predators, parasitoids, or *entomopathogens* on nontarget wildlife likely will be the same as those found (or more likely not found) in conventional systems using the same products and organisms. Delate and colleagues (2005) evaluated the efficacy of organically approved treatments to control bean leaf beetle (*Cerotoma trifurcata*), a vector of the seed-staining bean pod mottle virus (BPMV). They determined the treatments did not affect *C. trifurcata* populations. Despite this specific pest management challenge, the price premium for organic soybean favored their production relative to conventionally grown soybean (Delate et al. 2005).

Weed Management

Organic crop production occurs without the use of synthetic herbicides, which places greater reliance on cultural and mechanical weed management methods than in conventional and glyphosate-resistant (GR) systems. In fact, when organic producers are asked about their main production challenges, weed control is at or near the top of the list (Welsh 1999). Thus, successful weed management historically has been a major limitation to successful organic crop production. For example, weed seed present in soil can increase by a factor of four during the initial 3 years of organic crop production (Albrecht and Sommer 1998).

Because organic certification standards do not allow the use of herbicides (USDA–AMS 2008), other methods of weed control must be used. The most common practices include crop rotations, cover crops, mulching, cultivation, flame weeding, and hand-weeding (Kluchinski and Singer 2005; Nelson, Smoot, and Jones 2004). The least complex practices to implement in organic systems are tillage and/or hand-weeding. The frequency of tillage operations will vary from a no-till system (probably not sustainable in a long-term organic system [Teasdale, Coffman, and Mangum 2007]) to a tillage-intense schedule of three or more operations (Bond and Grundy 2001; Gianessi and Sankula 2003). In an Iowa study, a total of eight tillage operations were performed during the season for an organic soybean system (Delate 1999).

There is evidence that increased rotation length and complexity can decrease weed populations (Teasdale et al. 2004). Delayed planting to destroy one or two weed flushes with disking, rotary hoeing, or some other form of tillage is used by many organic farmers. (If this is done, the possible yield penalty for later planting must be considered [Bastidas et al. 2008; Robinson et al. 2009]). Once the crop has been planted, various weed control methods can be used. These methods include

- mechanical cultivation (Gunsolus 1990; Lovely, Weber and Staniforth 1958; Parish et al. 1990),
- flame weeding and crop rotation (Lampkin 1990; Weeds 2004),
- companion crops (Thelen, Mutch, and Martin 2004), and
- living cover crops (living mulch) and cover crop residues (Ateh and Doll 1996; De Bruin, Porter, and Jordan 2005; Liebl et al. 1992; Westgate, Singer, and Kohler 2005; Table 5.2).

In addition, variety selection can play an important role in weed control (Bussan et al. 1997; Jannink et al. 2000).

The extent of soil disturbance resulting from tillage will depend on the specific tillage used (e.g., rotary hoe, row cultivator, or tine harrow) and the frequency of use. The negative environmental aspects of increased fuel consumption, potentially greater soil erosion, and damage to soil structure resulting from tillage operations in organic systems may vary with the system used, but the preponderance of historical data indicates that the long-term effects of tillage are more negative than positive. This is especially true for soil erosion (see Chapter 2).

Kluchinski and Singer (2005) evaluated the contributions of narrow and wide rows (8-inch and 30-inch), mechanical weed control with a rotary hoe and row cultivator, cultivation frequency using one or both implements, and cultivation timing (early, late, or sequential) to weed control and grain yield. The narrow-row system decreased the time available for cultivation compared with wide rows. A rotary hoe was equally or less effective than a row cultivator for controlling weeds, but this result may be specific to a weed species or soil type. Weed control was similar regardless of the timing of application with both implements. They concluded that wide-row systems provide greater flexibility for weed control in an organic soybean system.

Hand-weeding is an essential component of some organic soybean systems, but the need for labor-intensive hand-weeding is variable and dependent on the effectiveness of other weed management tactics (Kluchinski and Singer 2005; Nelson, Smoot, and Jones 2004). Kluchinski and Singer (2005) documented that hand-weeding was a greater necessity for optimal weed control and soybean yield in narrow-row soybean where a rotary hoe was the primary tillage tool compared with wide-row soybean that allowed more effective row cultivation. This was probably because controlling weeds with a rotary hoe is more dependent on timing, soil condition, and weed size than is weed control with a row cultivator. This finding indicates that a wide-row production system will be more effective for weed management in organic soybean if hand labor is not available because of the effectiveness of using a row cultivator in a wide-row system.

Soybean may be one of the better-suited crops for organic production because the labor requirement may not be exorbitant. But availability and cost of labor for hand-weeding must be considered both before committing to an organic system that relies heavily on hand-labor and before deciding on the manageable size of an individual organic soybean operation. For example, extended periods of rain that result in muddy fields may preclude postplanting mechanical cultivation for weed control during some growing seasons and leave hand-weeding as the only alternative for timely weed control. For these situations, a ready source of workers for hand-weeding must be available, and this may not be the case.

Cover crops usually are a component of a rotation used in organic soybean production and can be a major contributor to managing weeds (Monaco, Weller, and Ashton 2002). Because herbicides will not be used to kill a cover crop before planting soybean in an organic system, tillage is usually used. A mechanical roller-crimper may be used in place of tillage to kill cover crops effectively in an organic system (Ashford and Reeves 2003; Kornecki, Raper, and Price 2004). This practice allows cover crop residues to remain on the soil surface to provide a physical barrier that limits weed emergence and, possibly, to release allelochemicals that suppress weed growth (Bond and Grundy 2001; Liebman and Davis 2000).

Natural herbicidal compounds have been used in some organic weed management systems. The majority of these compounds work best when applied to the foliage of young weeds (Burton et al. 2007). The chemistry may include vinegar (acetic acid), citric acid, certain fatty acids, clove oil, and thyme oil (Sullivan 2003). Vinegar applied as a 15% solution in 20 gallons of water carrier per acre decreased weed density within the soybean row (Mutch 2003). But vinegar was less effective in decreasing weed populations and resulted in less soybean yield than mechanical weed removal. Compared with low-dose, highly active synthetic herbicides that provide nearly complete weed control, the application of natural herbicides may require more labor-intensive methods such as spot spraying, or may require a high-volume spray carrier that provides thorough saturation of the weed foliage. These factors, plus the additional cost of natural herbicides compared with conventional herbicides (Burton et al. 2007), make chemical control in organic systems more complex and its contribution to the sustainability of an organic soybean system questionable. Regardless of the possible effectiveness of natural herbicides for managing weeds in an organic system, their use will require regulatory approval before they can be considered as a viable weed management option.

Chapter Summary

For the present and foreseeable future, organic producers will rely on conventionally developed, nontransgenic varieties. Varietal resistance is the best disease and nematode management option, whereas varietal resistance and crop rotation are effective measures for SCN management.

Organic soybean production will rely on tillage for cover crop management and weed control, and this practice may increase erosion potential from an organic system. Where tillage fails to maintain effective weed control, hand weeding will be necessary. Crop rotation and rotation sequence are fundamental in an organic system, and both practices are used to improve management of weeds, insects, diseases, nematodes, and fertility. An organic system will rely heavily on animal manures and legume cover crops as fertilizer sources. Most manures contain low levels of K relative to P; therefore, using manure as a sole source of K will result in increases in soil P.

Sustaining and/or increasing organic soybean production in the United States will depend on

- the capability of new organic producers to withstand the 3-year certification period with no premium income;
- continued availability of seed of organically grown, nontransgenic varieties;
- long-term management of weeds and pathogens using only organic methods;
- availability of hand labor for weeding;
- proximity to and availability of a cheap source of animal manure for fertilizer; and
- a strong market to ensure a price premium necessary for sustained profitability.

Glossary

Accredited certification agency. In the United States this term refers to an agency accredited by the National Organic Program that inspects organic production and handling operations to certify that the operations meet the USDA standards/regulations.

Agricultural Marketing Service (AMS). The branch within the USDA that administers the NOP.

Certified organic. In the United States this term refers to the USDA–AMS–NOP production, handling, and labeling standards for organic agricultural products.

Entomopathogen. A microbe that harms an insect when the microbe invades its body.

National Organic Program (NOP). The program within the USDA responsible for developing, implementing, and administering the U.S. Federal organic standards.

Organic seed. Nontransgenic seed that has been grown using production practices consistent with the USDA-NOP standards and has been certified by an accredited certification agency (this certification is not to be confused with "certified seed," which is a class of seed described in the Federal Seed Act).

Literature Cited

Albrecht, H. and H. Sommer. 1998. Development of the arable weed seed bank after the change from conventional to integrated and organic farming. *Aspects Appl Biol* 51:279–288.

Ashford, D. L. and D. W. Reeves. 2003. Use of a mechanical roller-crimper as an alternative kill method for cover crops. *Am J Alternative Ag* 18:37–45.

Ateh, C. M. and J. D. Doll. 1996. Spring planted winter rye (*Secale cereal*) as a living mulch to control weeds in soybean *(Glycine max)*. *Weed Technol* 10:347–353.

Bastidas, A. M., T. D. Setiyono, A. Dobermann. K. G. Cassman, R. W. Elmore, G. L. Graef, and J. E. Specht. 2008. Soybean sowing date: The vegetative, reproductive, and agronomic impacts. *Crop Sci* 48:727–740.

Bond, W. and A. C. Grundy. 2001. Non-chemical weed management in organic farming systems. *Weed Res* 41:383–405.

Burton, M., R. Weisz, A. York, and M. Hamilton. 2007. Organic field crop production and marketing in North Carolina: Weed management in organic grain. Center for Environmental Farming Systems, North Carolina State University Cooperative Extension, Raleigh, http://www.organicgrains.ncsu.edu/pestmanagement/organicweedmanagement.htm

Bussan, A. J., O. C. Burnside, J. H. Orf, E. A. Ristau, and K. J. Puettmann. 1997. Field evaluation of soybean (*Glycine max*) genotypes for weed competitiveness. *Weed Sci* 45:31–37.

Cavigelli, M. A., J. R. Teasdale, and A. E. Conklin. 2008. Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. *Agron J* 100:785–794.

Clark, A. (ed.). 2007. *Managing Cover Crops Profitably*. 3rd ed. Handbook Series Book 9. Sustainable Agriculture Research and Education (SARE), USDA–CSREES, Beltsville, Maryland, http://www.sare.org/publications/covercrops/covercrops.pdf

De Bruin, J. L., P. M. Porter, and N. R. Jordan. 2005. Use of a rye cover crop following corn in rotation with soybean in the upper-Midwest. *Agron J* 97:587–598.

Delate, K. 1999. The effect of tillage on organic soybean production following CRP land. Iowa State University Extension Service, Ames, http://extension.agron.iastate.edu/organicag/researchreports/mcnaycrp99.pdf

Delate, K., J. DeWitt, A. McKern, and R. Turnbull. 2005. Integrated approaches to organic pest management in the Midwestern USA: Case studies of three crops. *IPM in Organic Systems Symposium, XXII International Congress of Entomology*, Brisbane, Australia, 15-21 August, 2004, http://www.organic-research.com/Reviews.asp?action=display&openMenu=relatedItems&ReviewID=1172&Year=2005#

Gevens, A., D. Wright, A. Blount, R. Mizell, R. Sprenkel, C. Mackowiak, S. Olson, J. A. Smith, J. Marois, and L. Datnoff. 2008. Alternatives for organic soybean production. Pp. 81–82. In A. E. Dorrance, M. A. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Gianessi, L. and S. Sankula. 2003. The value of herbicides in U.S. crop production. CropLife Foundation, Washington, D.C., http://www.croplifefoundation.org

Gold, M. V. 2007b. Organic production/organic food: Information access tools. Alternative Farming Systems Information Center. U.S. Department of Agriculture–National Agricultural Library, Washington, D.C., http://www.nal.usda.gov/afsic/pubs/ofp/ofp.shtml

Green, S. V., M. A. Cavigelli, T. H. Dao, and D. C. Flanagan. 2005. Soil physical properties and aggregate-associated C, N, and P distributions in organic and conventional cropping systems. *Soil Sci* 170:822–831.

Gunsolus, J. L. 1990. Mechanical and cultural weed control in corn and soybeans. *Am J Altern Ag* 5:114–119.

Jannink, J. L., J. H. Orf, N. R. Jordon, and R. G. Shaw. 2000. Index selection for weed suppressive ability in soybean. *Crop Sci* 40:1087–1094.

Karlen, D. L., K. Delate, R. Turnbull, and J. Boes. 2004. Organic soybean production: Challenges and Perspectives of an Increasing Trend. Pp. 319–327. In *Proc World Soybean Research Conference VII*, Foz do Iguacu, Brazil.

Kluchinski, D. and J. W. Singer. 2005. Evaluation of weed control strategies in organic soybean production. *Crop Mgmt* 3 May, http://www.plantmanagementnetwork.org/pub/cm/research/2005/organic/ (online only; limited access)

Kornecki, T. S., R. L. Raper, and A. J. Price. 2004. Effectiveness of terminating cover crops using different roller implements. Pp. 336–345. In D. Jordan and D. Caldwell (eds.). *Proc 26th Annual Southern Conservation Tillage Conf for Sustainable Agriculture*, 7–9 June, Raleigh, North Carolina.

Kuepper, G. 2001. Organic control of white mold on soybeans. Pub. IP133. Appropriate Technology Transfer for Rural Areas–National Center for Appropriate Technology (ATTRA–NCAT), Fayetteville, Arkansas, http://attra.ncat.org/attra-pub/whitemold.html

Kuepper, G. 2003. Organic soybean production. Pub. CT120. Appropriate Technology Transfer for Rural Areas–National Center for Appropriate Technology (ATTRA–NCAT), Fayetteville, Arkansas, http://attra.ncat.org/new_pubs/attra-pub/organicsoy.html?id=DC

Kuepper, G., S. Diver, and J. Sampson. 2004. Sources of organic fertilizer amendments. Appropriate Technology Transfer for Rural Areas–National Center for Appropriate Technology (ATTRA–NCAT), Fayetteville, Arkansas, http://attra.ncat.org/attra-pub/orgfert.php

Lampkin, N. 1990. *Organic Farming*. Farming Press, Ipswich, United Kingdom.

Liebl, R. A., F. W. Simmons, L. M. Wax, and E. W. Stoller. 1992. Effect of rye (*Secale cereal*) mulch on weed control and soil moisture in soybean (*Glycine max*.). *Weed Tech* 6:838–846.

Liebman, M. and A. S. Davis. 2000. Integration of soil, crop and weed management in low-external-input farming systems. *Weed Res* 40:27–47.

Lovely, W. G., C. R. Weber, and D. W. Staniforth. 1958. Effectiveness of the rotary hoe for weed control in soybeans. *Agron J* 50:8621–8625.

Mahaffey, L. and W. Cranshaw. 2007. Some insect/disease control products allowed for use in certified organic production. Colorado State University, Fort Collins, http://www.eaglecounty.us/uploadedFiles/CSU/Horticulture_&_Agriculture/NewOrganicPesticides.pdf

McBride, W. D. and C. Greene. 2008. The profitability of organic soybean production. Paper No. 6449. Agricultural and Applied Economics Association Annual Meeting, Orlando, Florida, 27-29 July, http://purl.umn.edu/6449

Monaco, T. J., S. C. Weller, and F. M. Ashton. 2002. *Weed Science: Principles and Practices*. John Wiley and Sons, New York.

Mutch, D. 2003. Weed control strategies in organic soybeans. Michigan State University Extension, East Lansing, http://www.covercrops.msu.edu/pdf_files/soy_weed_control03.pdf

Nelson, K., R. Smoot, and M. Jones. 2004. Cost-effective organic weed management for clear hilum soybean production. University of Missouri Agriculture Expt Station, Columbia, http://aes.missouri.edu/greenley/fieldday/2004/page76.stm

Organic Materials Review Institute (OMRI). 2008. http://www.omri.org/OMRI_seal_how_why.html

Parish, R. L., R. P. Bracey, D. W. Wells, and P. E. Bergeron. 1990. A comparison on cultivation methods for commercial vegetable crops. *Am J Agric Eng* 6:565–568.

Pester, T. A., O. C. Burnside, and J. H. Orf. 1994. Leaf area expansion rate of soybean genotypes: An indirect indicator of their competitiveness to weeds. *North Central Weed Science Society* 49:119–120.

Porter, P., G. Feyereisen, J. De Bruin, and G. Johnson. 2005. No-till organic soybean production following a fall-planted rye cover crop. Pp. 26–30. In *Proc First Scientific Conf International Society Organic Agriculture Research (ISOFAR)*. Adelaide, Australia, 20-23 September.

Robinson, A. P., S. P. Conley, J. J. Volenec, and J. B. Santini. 2009. Analysis of high yielding, early-planted soybean in Indiana. *Agron J* 101:131–139.

Sullivan, P. 2003. Overview of cover crops and green manures. Appropriate Technology Transfer for Rural Areas-National Center for Appropriate Technology (ATTRA–NCAT), Fayetteville, Arkansas, http://www.attra.ncat.org/attra-pub/PDF/covercrop.pdf

Teasdale, J. R., C. B. Coffman, and R. W. Mangum. 2007. Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement. *Agron J* 99:1297–1305.

Teasdale, J. R, R. W. Mangum, J. Radhakrishnan, and M. A. Cavigelli. 2004. Weed seedbank dynamics in three organic farming crop rotations. *Agron J* 96:1429–1435.

Thelen, K. D., D. R. Mutch, and T. E. Martin. 2004. Utility of interseeded winter cereal rye in organic soybean production systems. *Agron J* 96:281–284.

Trewavas, A. 2004. A critical assessment of organic farming-and-food assertions with particular respect to the UK and the potential environmental benefits of no-till agriculture. *Crop Prot* 23:757–781.

U.S. Department of Agriculture–Agricultural Marketing Service (USDA–AMS). 2008. National Organic Program. USDA–AMS, Washington, D.C., http://www.ams.usda.gov/nop/indexIE.htm

U.S. Department of Agriculture–Economics Research Service (USDA–ERS). 2005b. Organic production. USDA–ERS, Washington, D.C., http://www.ers.usda.gov/data/organic/Data/Beans.xls)

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008a. Quick stats: Agricultural statistics data base. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/QuickStats/

"Weeds controlled by fire in niche soybean market." 2004. *Delta Farm Press* June 2, http://deltafarmpress.com/mag/farming_weeds_controlled_fire/index.html

Welsh, R. 1999. The economics of organic grain and soybean production in the midwestern United States. Policy Studies Report 13. Henry A. Wallace Institute for Alternative Agriculture, Greenbelt, Maryland.

Westgate, L. R., J. W. Singer, and K. A. Kohler. 2005. Method and timing of rye control affects soybean development and resource utilization. *Agron J* 97:806–816.

Zehnder, G., G. M. Gurr, S. Kuhne, M. R. Wade, S. D. Wratten, and E. Wyss. 2007. Arthropod pest management in organic crops. *Ann Rev Entomol* 52:57–80.

6 Economics of U.S. Soybean Production

One of the criteria for determining sustainability of a production system is the profitability of that system. Soybean-producing states publish *enterprise budgets* to help producers and planners determine profitability. Published soybean enterprise budgets for selected states were used to calculate a *breakeven price* per harvested bushel to provide an estimate of the commodity price required to cover all production costs and provide a positive *net return* in a system. These budgets are based on typical production practices and machinery used by soybean producers in those states.

Nonorganic Budgets

Nonorganic budgets in this report are based on using glyphosate-resistant (GR) varieties (except where indicated otherwise) and a mix of glyphosate and nonglyphosate herbicides. Most states compile budgets for only GR varieties. The few states that compile budgets for both nonglyphosate (conventional system) and GR varieties (transgenic system) show nearly identical per-acre costs for each system. In these cases, the lower cost for seed of conventional varieties compared with seed of GR varieties is offset by the higher cost for herbicides in the conventional system compared with the transgenic system.

Breakeven price for nondoublecropped, nonorganic soybean was determined using two methods: the 5-year (2004 to 2008) average yield for each state (USDA–NASS 2008e), and a yield chosen by budget authors (budget yield) and used in their budget calculations. For states that publish both nonirrigated and irrigated budgets, the average yield for each system was apportioned using the 5-year average yield and the percentage of irrigated acres (USDA–NASS 2002b) for those states, and a 20 bu/acre yield advantage for irrigation. Budget yields are those estimated by budget authors to be expected from using the inputs and practices in the shown budgets. Breakeven prices for doublecropped soybean were determined using long-term average yields from late-planted soybean (Heatherly 2005a) and the budget yields.

Land rent in the nonorganic budgets is that paid in 2008 (USDA–NASS 2008f). Taxes and insurance (not crop insurance) and general farm overhead are those paid in 2007 (USDA–ERS 2007b). In the doublecrop budgets, one-half of these costs are allocated to soybean. Management cost was calculated as 10% of the variable cost estimate in each budget. Nonorganic budgets for Iowa and Nebraska are based on soybean in a biennial rotation with corn, whereas Arkansas, Mississippi, and North Carolina nondoublecrop budgets are based on monocropped soybean.

Organic Budget

Organic farms rarely focus on a single crop. Organic soybean is best grown in rotation with several other crops that ideally complement one another. The benefits of rotating soybean with other crops in a nonorganic system have been discussed earlier in this report (Chapter 2, p. 17). Organic production is further enhanced when a livestock enterprise that generates manure is part of the system (Kuepper 2003). Nitrogen (N) is commonly the most limiting fertility element in organic production, especially for corn and small grains that complement soybean in an organic system rotation. Alfalfa is one of the most effective legumes and, when left in place for at least 2 years, can supply a high level of fixed N for nonlegume crops in the rotation.

Iowa State University has compiled crop enterprise budgets that encompass the above tenets for an organic system that includes soybean (Chase, Delate, and Smith 2008). These budgets entail using a 4-year crop rotation, in order, of corn, soybean, oat with alfalfa, and a second year of alfalfa. Cereal rye is seeded in the fall as a cover crop and killed with tillage before planting soybean. Weed control costs include those for rotary hoeing, row cultivation, and hand labor. Manure is applied to corn in the first year of the rotation. It is assumed that manure is readily available without cost from a nearby livestock operation and provides enough N for the corn crop; thus, only the cost of applying the manure is considered.

Table 6.1. Estimated costs ($ per acre) to produce nonirrigated (NI) and irrigated (IRR) soybean in Nebraska (no-till; rotated with corn), and Arkansas and Mississippi (conservation tillage; nonrotated)[a], along with estimated yields (bushels per acre) and average breakeven prices ($ per bushel). Nebraska irrigation by center pivot, and Arkansas and Mississippi irrigation by furrow method

	Nebraska		Arkansas		Mississippi	
Cost Item	NI	IRR	NI	IRR	NI	IRR
Seed	43	46	38	38	33	33
Fertilizers	1	1	35	35	19	24
Pesticides	27	40	16	16	39	47
Fuel and repairs	17	73	18	53	19	45
Labor	7	10	5	8	10	16
Other[b]	7	10	29	43	25	37
Total variable cost	102	180	141	193	145	202
Machinery ownership	17	34	31	63	30	86
Land rent	95	155	61	94	77	103
Taxes and insurance	9	9	8	8	8	8
General farm overhead	14	14	10	10	10	10
Management	10	18	14	19	14	20
Total cost	247	410	265	387	284	429
Average yield, 2004–2008	40	60	25	45	30	50
Breakeven price per bushel	6.18	6.83	10.60	8.60	9.47	8.58
Budget yield	42	63	25	45	40	60
Breakeven price per bushel	5.88	6.51	10.60	8.60	7.10	7.15

[a]Budgets for each state found at the following URLs:
Nebraska: http://cropwatch.unl.edu/archives/2008/crop22/UNLBudgets_crop_2009.htm, compiled 9/08
Arkansas: http://www.aragriculture.org/crops/soybeans/budgets/2008/, compiled 10/07
Mississippi: http://www.agecon.msstate.edu/Research/Budgets/MSUSOY08.pdf, compiled 10/07

[b]Includes hauling, interest on operating capital, crop insurance, and miscellaneous.

There is no reliable estimate of the amount of manure that is obtained with or without compensation in the United States (USDA–ERS 2002b). These budgets also include a cost related to organic certification.

In the soybean enterprise budget for this organic rotation, breakeven price was determined using two methods: an average yield (31 bu/acre; McBride and Greene 2008), and a budget yield (40 bu/acre) assigned by the authors. The budget yield is based on 36 and 4 bushels per acre for cleaned and screened seed, respectively.

Nonirrigated vs. Irrigated Soybean

Nebraska, Arkansas, and Mississippi have a large percentage of irrigated soybean. Therefore, budgets generated by economists in those states are used for this comparison. In Nebraska, breakeven prices for nonirrigated soybean are estimated as $6.18 (average yield) and $5.88 per bushel (budget yield) (Table 6.1). These estimates are somewhat lower than the $6.83 (average yield) and $6.51 (budget yield) breakeven prices estimated for irrigated production. In Arkansas, estimated breakeven prices for nonirrigated soybean are considerably higher than those for irrigated soybean. In Mississippi, breakeven price for nonirrigated soybean was higher than that for irrigated soybean only when using the average yield.

The low breakeven prices in the Nebraska nonirrigated budget are much lower than the estimated breakeven price of $8.22 per bushel estimated in the Iowa nonorganic budget (Table 6.3), which includes a cost for phosphorus (P) and potassium (K) fertilizer. Most growers apply P and K fertilizers before the corn

Table 6.2. Estimated costs ($ per acre) to produce monocropped (MC) and doublecropped (DC) soybean in Mississippi (conservation tillage [MC] and no-till [DC], nonirrigated [NI] and center-pivot irrigated [IRR]) and North Carolina (conventional tillage and varieties, NI)[a], along with estimated yields (bushels per acre) and average breakeven prices ($ per bushel)

	Mississippi			North Carolina	
Cost Item	NI MC	NI DC	IRR DC	MC	DC
Seed	33	40	40	23[b]	23[b]
Fertilizers	19	22	24	46	46
Pesticides	39	30	40	20	28
Fuel and repairs	19	14	52	32	30
Labor	10	7	7	8	7
Other[c]	25	19	26	15	11
Total variable cost	145	132	189	144	145
Machinery ownership	30	22	53	44	41
Land rent	77	39	52	55	28
Taxes and insurance	8	4	4	7	4
General farm overhead	10	5	5	10	5
Management	14	13	19	14	15
Total cost	284	215	322	274	238
Average yield	30	25	45	30	25
Breakeven price per bushel	9.47	8.60	7.16	9.13	9.52
Budget yield	40	25	40	35	30
Breakeven price per bushel	7.10	8.60	8.05	7.83	7.93

[a]Budgets for each state found at the following URLs:
Mississippi: http://www.agecon.msstate.edu/Research/Budgets/MSUSOY08.pdf, compiled 10/07
North Carolina: http://www.ag-econ.ncsu.edu/extension/wheatsoybean.html, compiled 11/07

[b]Conventional varieties.

[c]Includes hauling, interest on operating capital, crop insurance, and miscellaneous.

crop in a soybean–corn rotation, and they may allot the entire P and K costs to the corn crop. When this is done, the estimated cost of producing soybean in the rotation is artificially lowered, which may be the case here. Lower estimated breakeven prices in the Mississippi budgets than in the Arkansas budgets reflect the increased production expected from using the Early Soybean Production System (Heatherly 2005a).

Monocropped vs. Doublecropped Soybean

Estimated differences between breakeven prices for nonirrigated monocropped and doublecropped soybean in both Mississippi and North Carolina depend on whether or not the average yield or the budget yield was used (Table 6.2). Using the average yield for each state (lower than budget yield) resulted in an opposite trend between states. Using the budget yields resulted in considerably lower breakeven yields. It is important to note that total costs allotted to doublecrop soybean are less than those for monocrop soybean because some costs were apportioned between the soybean and wheat crops in the doublecrop system, and this division affected the relationship between monocrop and doublecrop breakeven prices.

In Mississippi, cost and yield estimates project a lower breakeven price for irrigated than for nonirrigated doublecropped soybean. This finding points out the importance of adequate water during the shortened growing season for achieving a reasonable yield from doublecropped soybean.

Budget estimates in Table 6.2 that represent likely

Table 6.3. Estimated costs ($ per bushel) to produce nonorganic and organic soybean in Iowa, along with estimated yields (bushels per acre) and average breakeven prices ($ per bushel)[a]. Conservation tillage used for nonorganic production

Cost Item	Nonorganic	Organic
Seed	43	52[b]
Fertilizers	47	0
Pesticides	31	0
Fuel and repairs	17	30
Labor	19	37
Other[c]	25	36
Total variable cost	182	155
Machinery ownership	23	39
Land rent	165	225
Taxes and insurance	9	9
General farm overhead	14	14
Management	18	16
Total cost	411	458
Average yield	50	31
Breakeven price per bushel	8.22	14.77
Budget yield	50	40
Breakeven price per bushel	8.22	11.45

[a]Budgets found at the following URLs:
Nonorganic: http://www.extension.iastate.edu/agdm/crops/pdf/a1-20.pdf, compiled 10/07
Organic: http://www.extension.iastate.edu/agdm/crops/pdf/a1-18.pdf, compiled 06/08

[b]$45 for soybean seed and $7 for rye cover crop seed.

[c]Includes hauling, interest on operating capital, crop insurance, and miscellaneous.

cost and yield scenarios for doublecropping in the southern United States indicate that breakeven prices will be in the $8.00 to $9.50 per bushel range without irrigation. According to the Mississippi budget estimate, irrigation of doublecropped soybean will lower the breakeven price. Irrigation also decreases the soybean yield variability in southern doublecropping systems that occurs due to summer weather vagaries (Heatherly and Ray 2007).

In Mississippi, total economic returns from an irrigated soybean–wheat doublecrop system are estimated to be similar to those from an irrigated soybean monoculture system (Spurlock 2007). In North Carolina, total returns from a nonirrigated soybean–wheat doublecrop system are estimated to be slightly below those from a nonirrigated soybean monoculture system (Bullen, Dunphy, and Weddington 2008). Because neither enterprise budget projects an economic superiority for the doublecrop system, factors such as winter cover provided by the wheat and the spreading of risk over two crops should be used to determine the value of a doublecrop system in the southern United States.

Yields of soybean in a soybean–winter grain doublecrop system should not be used as the sole benchmark to assess the economic value of this rotation in the southern United States. The lower yield of soybean that is rotated with a small grain vs. that of monocropped soybean (Egli 2008; Kelley 2003; Wesley 1999) and the volatility of commodity price for the two crops dictate that an economic analysis of the total system each year will provide a more informative assessment of the value of the doublecrop rotational system.

Nonorganic vs. Organic Soybean

In Iowa, the breakeven price for nonorganic soybean is estimated to be $8.22 per bushel using both the average and budget yields (Table 6.3). This price is considerably lower than the breakeven prices of

$11.45 (budget yield) and $14.77 (average yield) per bushel estimated for soybean in the organic rotation system. The estimated breakeven prices for organic soybean are considerably below the $23.40 per bushel average commodity price projected in the Iowa State budget and indicate that growing soybean as a component in an organic rotation system is profitable. Using early 2009 organic soybean prices ($20.50 to $24.00 per bushel; USDA-AMS 2009), the magnitude of this premium is similar to that derived from using costs in the organic budget (Table 6.3) and the budget author's $23.40 per bushel commodity price.

There are caveats to consider when using these values to assess long-term profitability of producing organic soybean.

- Consistent weed management can be a challenge, and uncontrolled weeds will decrease yields.
- It is assumed that pest management can be achieved without using any controls, and this is unlikely on a long-term basis.
- High fuel costs will have a greater impact on total costs in an organic system because of higher tillage use.
- The indicated cost of this organic system is sensitive to manure costs and could increase if the cost of obtaining and handling manure increases.
- A relatively high yield and a relatively high premium price for organic food and feed soybean will be required to sustain the high returns.

These concerns for maintaining profitability in a long-term organic system with soybean as a component are supported by results from recent research conducted in Minnesota (Archer et al. 2007).

The McBride and Greene (2008) survey cited earlier found several factors that can affect profitability of organic soybean. First, because of lower yields and higher costs associated with organic soybean production, the total estimated additional costs for producing organic soybean relative to conventional soybean are $6.20 per bushel. This amount is similar to the difference in breakeven prices that was obtained using the average yields in Table 6.3. Second, the average price premium received by organic producers in 2006 was $9.16 per bushel, making organic soybean production a more profitable enterprise than nonorganic soybean on a per acre basis. Data for 2008 indicate a similar ratio between organic and conventional soybean prices. Third, the reason for higher per-acre profits from organic soybean production is the significant price premium paid for organic soybean because demand currently exceeds supply. This premium would disappear quickly if organic production expanded to cause supply to exceed demand. Finally, high conventional soybean prices and high fuel costs will limit expansion of U.S. organic soybean acreage.

Chapter Summary

Enterprise budgets are published annually by economists in most soybean-production states, and most of the nonorganic budgets use only GR varieties for cost calculations. Nonorganic Corn Belt budgets estimate costs for soybean grown in a biennial rotation with corn, whereas nonorganic southern budgets estimate costs for soybean grown as a monocrop. The Iowa organic soybean budget estimates costs for producing soybean in a 4-year crop rotation, in order, of corn, soybean, oat with alfalfa, and a second year of alfalfa.

In the Corn Belt, breakeven price for nonorganic soybean is estimated at $5.88 to $6.18 per bushel (Nebraska, low fertilizer input) and $8.22 per bushel (Iowa normal fertilizer input). In the midsouthern United States, breakeven prices per bushel for nonirrigated nonorganic soybean are estimated to be $7.10 per bushel (Mississippi ESPS, 40 bushels per acre yield) to $10.60 per bushel (Arkansas, 25 bushels per acre yield).

Irrigated vs. nonirrigated budgets estimate a higher breakeven price for irrigated soybean in Nebraska and a lower breakeven price in Arkansas and Mississippi. Estimates of breakeven prices for soybean that is doublecropped with wheat in the southern United States are similar to those estimated for monocropped soybean. Irrigation of doublecropped soybean in Mississippi results in a lower estimated breakeven price than that for nonirrigated doublecropped soybean.

In Iowa, the estimated breakeven price of $8.22 per bushel for nonorganic soybean is considerably lower than the estimated breakeven price of $11.45 (budget yield; 40 bushels per acre) to $14.77 (average yield; 31 bushels per acre) per bushel for organic soybean. Estimated additional costs for producing organic soybean vs. nonorganic soybean total $6.55 per bushel. But the breakeven price estimates for organic soybean are considerably lower than the prices received for organic soybean during the last several years. Profitability of soybean in an organic rotation is dependent on a relatively high yield and a high premium price for organic soybean.

Glossary

Breakeven price. This value represents the per-bushel revenue (or income) that is required to provide an economically sustainable enterprise; it is calculated by dividing a cost (e.g., dollars per acre) by a production quantity (e.g., bushels per acre).

Enterprise budget. A type of farm financial report that owners or managers may use to help make decisions. After defining the specific production techniques to be used by the enterprise (e.g., a crop produced with no-till practices), the budget typically will have a section describing the projected dollar values (usually on a per-acre or per-bushel basis) for gross receipts, operating costs, ownership costs, and returns above costs.

Net returns. The estimated dollar value of the projected gross receipts minus the projected costs that have been allocated to a particular farm enterprise. Net returns (or returns above costs) represent a residual return to all factors of production for which a cost has not already been included. For example, an enterprise budget may include a cost for all inputs except land. In this case, the net return (if positive) would represent the amount available to pay for a land charge. Another example might be a case in which all inputs except management have been included in the cost estimate. Then the net return would be the amount available to pay for the management functions related to the enterprise. Net returns may be negative, indicating that the revenue generated by the enterprise is not capable of covering all allocated costs

Literature Cited

Archer, D. W., A. A. Jaradat, J. M-F. Johnson, S. L. Weyers, R. W. Gesch, F. Forcella, and H. K. Kludze. 2007. Crop productivity and economics during the transition to alternative cropping systems. *Agron J* 99:1538–1547.

Bullen, G., J. Dunphy, and E. Weddington. 2008. Grain budgets. North Carolina State University, Raleigh, http://www.ag-econ.ncsu.edu/faculty/piggott/budget.html

Chase, C., K. Delate, and M. Smith. 2008. Organic crop production enterprise budgets. FM 1876. Iowa State University Extension, Ames, http://www.extension.iastate.edu/agdm/crops/pdf/a1-18.pdf

Egli, D. B. 2008. Soybean yield trends from 1972 to 2003 in midwestern USA. *Field Crops Res* 106:53–59.

Heatherly, L. G. 2005a. Midsouthern USA soybean yield affected by maturity group and planting date. Crop Mgmt 18 April, http://www.plantmanagementnetwork.org/cm/ (online only: limited access)

Heatherly, L. G. and J. D. Ray. 2007. Soybean and corn. Pp. 477–533. In R. J. Lascano and R. E. Sojka (eds.). *Irrigation of Agricultural Crops*. 2nd ed. Agronomy Monograph 30. American Society of Agronomy. Madison, Wisconsin.

Kelley, K. W. 2003. Double-cropping winter wheat and soybean improves net returns in the eastern Great Plains. *Crop Mgmt* 12 Nov, http://www.plantmanagementnetwork.org/sub/cm/research/2003/plains/kelley.pdf (online only; limited access)

Kuepper, G. 2003. Organic soybean production. Pub. CT120. Appropriate Technology Transfer for Rural Areas–National Center for Appropriate Technology (ATTRA–NCAT), Fayetteville, Arkansas, http://attra.ncat.org/attra-pub/PDF/organicsoy.pdf

McBride, W. D. and C. Greene. 2008. The profitability of organic soybean production. Paper No. 6449. Agricultural and Applied Economics Association Annual Meeting, Orlando, Florida, 27–29 July, http://purl.umn.edu/6449

Spurlock, S. R. 2007. Soybeans 2008 planning budgets. Budget Report 2007-02. Department of Agricultural Economics, Mississippi State University, http://www.agecon.msstate.edu/Research/Budgets/MSUSOY08.pdf

U.S. Department of Agriculture–Agricultural Marketing Service (USDA–AMS). 2009. Upper Midwest organic grain and feedstuffs report. USDA–AMS, Washington, D.C., http://www.ams.usda.gov/mnreports/nw_gr113.txt

U.S. Department of Agriculture–Economics Research Service (USDA–ERS). 2002b. Manure table, for soybeans, by all acres, for all available states, for 2002. USDA–ERS, Washington, D.C. http://www.ers.usda.gov/Data/ARMS/app/Crop.aspx

U.S. Department of Agriculture–Economics Research Service (USDA–ERS). 2007b. Soybean production costs and returns per planted acre, excluding government payments, 2006-2007. USDA–ERS, Washington, D.C., http://www.ers.usda.gov/Data/CostsAndReturns/data/current/C-Soyb.xls

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2002b. Table 33. Specified crops harvested-yield per acre irrigated and nonirrigated: 2002. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/Census/Create_Census_US.jsp

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008e. U.S. and all states data—Crops. Planted, harvested, yield, production, price, and value of production. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/index.asp

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008f. Land values and cash rents: 2008 summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/current/AgriLandVa/AgriLandVa-08-04-2008.pdf

Wesley, R. A. 1999. Doublecropping wheat and soybeans. Pp. 143-156. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

7 Conclusions

The objective of this report is to compare the sustainability of conventional, organic, and transgenic (biotech) soybean production systems in the United States and to identify strategies that can be used to sustain and/or enhance economically and environmentally sound production within the systems. This objective might be construed to mean that these are three equally significant production systems that are viable for producing soybean on a scale needed to meet current and future market needs. In fact, evidence presented in this report indicates otherwise.

The original "conventional soybean production system" (defined here as a system that uses nontransgenic soybean varieties) now occupies less than 8% of total U.S. soybean acres and likely will stay at or below this level in the future. This "old" conventional system will only be used by growers to produce nontransgenic soybean for a niche market that pays a premium price, by organic growers who can use only nontransgenic seed by regulation, and by growers who refuse to plant transgenic varieties because these varieties are more expensive or because of their opposition to industry restrictions on the use of transgenic seed. The viability of this present small-acreage system will rely on the continued development and availability of improved nontransgenic varieties, a circumstance that is occurring and likely will continue to occur only on a small scale.

Organic soybean production currently occupies <0.20% of U.S. soybean acreage, and likely will continue to occupy an infinitesmimal acreage in the United States. Reasons for this small acreage are that

- individual operators will only be able to sustain management of small acreages because of the required inputs of hand labor and animal manure;
- stringent initial requirements for establishing an organic cropping system and regulations for maintaining it may require more commitment than many producers are willing or able to make;
- the cost of production is greater and yields are lower than for a nonorganic soybean system, thus requiring a significantly higher product price to sustain profitability; and
- an oversupply of organic soybean will quickly dissipate the premium price required for continued profitability.

The present and anticipated future small organic soybean acreage in the United States will not contribute to long-term sustainability of U.S. soybean production in general, but will be profitable for small-acreage producers at current prices. The organic system will be important in supplying niche markets with seed that have no transgenic trait components and/or seed that possess nontransgenic value-added traits that may be desired by consumers.

The results of this comprehensive literature review indicate that U.S. soybean production now has a "new" conventional system that is based on using transgenic varieties. The preponderance of evidence indicates that most soybean varieties do or will eventually contain one or more transgenic traits. This new conventional system will presumably evolve along the same lines as the "old" conventional system in every aspect except genetics (i.e., management practices will continue to be "conventional.") In other words, producers can still adopt and use new and/or improved management technology (nongenetic inputs) in the same way as they would in the old conventional system.

This new system for the foreseeable future will be genetically sustained by the continued and increasing development of varieties with new transgenic herbicide-resistance traits (now 100% of U.S. transgenic soybean); the incorporation of new genes for pathogen and insect management into productive new varieties (possibly transgenic); and the incorporation of newly discovered drought-resistance traits into forthcoming varieties. The U.S. soybean germplasm collection contains a large amount of variation in genetic material. This material can be screened for new traits and genes that will provide enhanced genetics for improved yield potential, host-plant resistance, and enhanced seed traits in new varieties that will be developed.

Weed management aspects for sustaining the new conventional system will be dominated by the use of glyphosate and glyphosate-resistant varieties. But this approach will, by necessity, be integrated with the use of nonglyphosate herbicides and forthcoming new varieties with resistance to both selective and nonselective nonglyphosate herbicides in a continuing effort to impede selection for weed resistance to glyphosate.

Pest management in U.S. soybean will rely heavily on varietal resistance to manage soybean cyst nematode and diseases. Varietal resistance is the single most important sustainability mechanism for management of these pests. Conceivably, there will eventually be varieties with resistance to soybean rust (Meyer et al. 2009; Pham et al. 2009). Since its first invasion of the United States in 2004, soybean rust has been managed effectively with sentinel plots for early detection and the application of efficacious preventative and curative fungicides when needed; this management tactic presumably will continue. Disease and insect management will continue to use integrated pest management strategies that include the judicious use of highly efficacious fungicides and insecticides that are now available or that are continually being developed.

Sustainability of U.S. soybean production will be enhanced by recognition that underused management technology in the areas of conservation tillage, cover crop management, soil fertility monitoring, and fertilizer application should be incorporated into production systems where economically feasible to abate soil loss and water runoff and contamination. These management aspects include

- adopting conservation tillage practices on a wider scale;
- using rotated soybean in new schemes or with additional crops;
- applying soil nutrients only in the amount needed using variable rate technology to replace crop depletion; and
- determining methods and programs that will enhance the economic feasibility of using cover crops on increased acreage to control erosion, reduce contamination of water runoff, and improve soil productivity.

Sustainability of the present level of irrigated soybean acreage in those areas that will not profitably support dryland production will depend on a continuing effort to monitor and conserve irrigation water resources.

Development of technology that supports soybean production in the United States has been and continues to be robust in both the genetics and production/management areas. Development of new technology that will be needed to address anticipated future soybean production issues depends on the continued vigor of this public and private research and development effort.

Comprehensive Glossary

Abiotic. Environmental factors such as drought, wind, hail, or excess moisture that impact the growth of living organisms.

Accredited certification agency. In the United States this term refers to an agency accredited by the National Organic Program that inspects organic production and handling operations to certify that the operations meet the USDA standards/regulations.

Agricultural Marketing Service (AMS). The branch within the USDA that administers the NOP.

Banded. Fertilizer placed below and to the side of the seed at planting.

Biennial rotation. The practice of growing two different crops in alternating years.

Biological control. Pest management that protects, augments, or releases organisms that are natural enemies of the pest.

Biotic. Biological factors that affect other living organisms.

Breakeven price. This value represents the per-bushel revenue (or income) that is required to provide an economically sustainable enterprise; it is calculated by dividing a cost (e.g., dollars per acre) by a production quantity (e.g., bushels per acre).

Broadcast. Fertilizer spread on the soil surface.

C factor. Cover management factor used in the Revised Universal Soil Loss Equation that is used to reflect the effect of cropping and management practices on erosion rates.

Certified organic. In the United States this term refers to the USDA–AMS–NOP production, handling, and labeling standards for organic agricultural products.

Chemical control. Pest management that uses a chemical toxin or repellent.

Conservation tillage system. Limited mechanical operations with implements that result in the soil surface being covered with >30% plant residue.

Conventional tillage system. A combination of mechanical operations with implements that effectively results in a seedbed that is free of weeds and plant residue cover.

Cover crop. A crop grown to provide soil cover during seasons when an annual grain crop is absent.

Crop rotation. The practice of growing two or more annual crops in a given field in a planned pattern or sequence in successive crop years.

Cultural control. Pest management that uses tillage, sanitation, harvesting, and other techniques to alter the pest's environment. This method also includes practices that enhance plant productivity to overcome the effects of pest injury.

Deep tillage. Mechanical operations with implements that affect soil properties below 6 inches.

Disease. Plant injury from biotic stress resulting from infection of plants by fungi, oomycetes, nematodes, bacteria, or viruses.

Doublecrop. Growing two crops alternately during a 12-month period.

Dryland production system. Growing a crop without supplemental water.

Enterprise budget. A type of farm financial report that owners or managers may use to help make decisions. After defining the specific production techniques to be used by the enterprise (e.g., a crop produced with no-till practices), the budget typically will have a section describing the projected dollar values (usually on a per-acre or per-bushel basis) for gross receipts, operating costs, ownership costs, and returns above costs.

Entomopathogen. A microbe that harms an insect when the microbe invades its body.

Erosion. Undesirable displacement of soil from a site by wind and/or water.

Farm gate value. Value of an agricultural crop when it leaves the farm, usually synonymous with the selling price of the product.

Germplasm. A collection of diverse genetic resources (i.e., soybean seed) that are available to be used in the development of improved breeding lines and varieties.

Herbicide. A chemical substance or cultured biological organism used to kill or suppress the growth of plants.

Herbivory. The consumption of plant tissues by an animal such as an insect.

Host-plant resistance. A genetically controlled innate or bred phenotypic or physiological property of a plant that enables it to withstand injury from insect feeding and pathogenic infection.

Identity preserved (IP). Refers to identification and maintenance through marketing channels (usually through contract-growing for a higher or premium price) of seed with specific traits or characteristics that are sought or preferred by users.

Integrated pest management (IPM). The ecologically based decision support system for managing weeds, plant pathogens, and insect pests while minimizing use of agrichemicals. IPM combines complementary and compatible biological, chemical, and cultural control tactics to make pest management economical, environmentally sound, and socially acceptable.

Micronutrient. An essential nutrient that is needed in small quantities.

National Organic Program (NOP). The program within the USDA responsible for developing, implementing, and administering the U.S. Federal organic standards.

Net returns. The estimated dollar value of the projected gross receipts minus the projected costs that have been allocated to a particular farm enterprise. Net returns (or returns above costs) represent a residual return to all factors of production for which a cost has not already been included. For example, an enterprise budget may include a cost for all inputs except land. In this case, the net return (if positive) would represent the amount available to pay for a land charge.

Another example might be a case in which all inputs except management have been included in the cost estimate. In such a case, the net return would be the amount available to pay for the management functions related to the enterprise. Net returns may be negative, indicating that the revenue generated by the enterprise is not capable of covering all allocated costs.

Nitrification inhibitors. Chemical compounds added to nitrogen fertilizer for the purpose of reducing the rate of conversion of ammonium form of fertilizer to nitrate form.

Nodules. Small organelles that contain the rhizobium bacteria on the soybean root surface.

Nonselective herbicide. An herbicide that is generally toxic to all plants treated. Some selective herbicides may become nonselective if used at very high rates.

Organic seed. Nontransgenic seed that has been grown using production practices consistent with the USDA–NOP standards and has been certified by an accredited certification agency (this certification is not to be confused with "certified seed" which is a class of seed described in the Federal Seed Act).

Oxidation of organic matter. Breakdown of organic matter by microbial activity.

Plant introduction. Germplasm brought to the United States from other parts of the world to provide new genes for potential improvement of crop productivity.

Plant pathogen. Refers to fungi, oomycetes, nematodes, bacteria, or viruses that infect plants and cause injury.

Plant residue cover. Plant material remaining on the soil surface after crop harvest.

Reduced tillage system. Limited mechanical operations with implements that result in the soil surface being covered with 15 to 30% plant residue.

Residual herbicide. An herbicide that persists in the soil and injures or kills germinating weed seedlings for a relatively short period of time after application.

Resistance to herbicides. The inherited ability of a plant population to survive and reproduce following repeated exposure to a dose of herbicide normally lethal to the wild type. Resistance also may be induced by such techniques as genetic engineering or selection of variants produced by tissue culture or mutagenesis (HRAC 2005).

Ridge tillage. Soil is mounded up (a ridge is built) in the fall of the year and the crop is then planted on top of this shallow ridge.

Soil persistence. Refers to the length of time that an herbicide applied to or in soil remains effective; to some degree phytotoxic to some species (HRAC 2005).

Stale seedbed planting system. A seedbed that has received no seedbed preparation tillage just prior to planting. It may or may not have been tilled since harvest of the preceding crop. Any tillage conducted in the fall, winter, or early spring will have occurred sufficiently ahead of planting time to allow the seedbed to settle or become stale. A crop is planted in this unprepared seedbed, and weeds present before or at planting are killed with herbicides. This system does not preclude tillage because it is a minimum or reduced tillage concept rather than a no-till concept.

Symbiotic nitrogen fixation. The conversion of N_2 from the atmosphere to inorganic nitrogen to a form that plants can use by microorganisms that live in nodules on the roots of soybean plants.

Tillage system. A combination of mechanical operations with implements that alter the soil environment to effect crop production.

Tolerant. The inherent ability of a plant to survive and reproduce after herbicide treatment. This implies that there was no selection or genetic manipulation to make the plant tolerant; it is naturally tolerant.

Value-added trait. A quality trait or characteristic that increases the value of a crop product relative to its typical or commodity version, and that requires a uniform and uncontaminated end product; in soybean, commonly referred to as specialty varieties with specific physical or chemical characteristics that are required for specific markets.

Variable rate technology.Using computerized fertilizer applications connected to global positioning systems to apply fertilizers at varying rates to specific areas of a field.

Varietal resistance. Resistance of a particular variety to injury caused by herbicides, pathogens, or insects. Resistance to the same pest is expressed at different levels among different varieties.

Weed control. The process of reducing weed growth and/or infestation to an acceptable level.

Comprehensive Bibliography

A&L Great Lakes Laboratories, Inc. 2005. Sample preparation—foundation of quality. Ft. Wayne, Indiana, http://www.algreatlakes.com/pdf/newsletters/05_spring.pdf

Albrecht, H. and H. Sommer. 1998. Development of the arable weed seed bank after the change from conventional to integrated and organic farming. *Aspects Appl Biol* 51:279–288.

Allen, J. and J. Fischer. 2008. Development of Liberty Link soybean trait technology. *North Central Weed Science Society Proc* 63:87, http://www.ncwss.org/

American Soybean Association (ASA). 2008. ASA welcomes EU soybean import approval. *Southeast Farm Press*, Dec 5, http://southeastfarmpress.com/soybeans/soybean-exports-1205/

Arce, G. D., P. Pedersen, and R. G. Hartzler. 2009. Soybean seeding rate effects on weed management. *Weed Technol* (in press).

Archer, D. W., A. A. Jaradat, J. M-F. Johnson, S. L. Weyers, R. W. Gesch, F. Forcella, and H. K. Kludze. 2007. Crop productivity and economics during the transition to alternative cropping systems. *Agron J* 99:1538–1547.

Ashford, D. L. and D. W. Reeves. 2003. Use of a mechanical roller-crimper as an alternative kill method for cover crops. *Am J Alternative Ag* 18:37–45.

Ateh, C. M. and J. D. Doll. 1996. Spring planted winter rye (*Secale cereal*) as a living mulch to control weeds in soybean (*Glycine max*). *Weed Technol* 10:347–353.

Barker, D. W. and J. E. Sawyer. 2005. Nitrogen application to soybean at early reproductive development. *Agron J* 97:615–619.

Bastidas, A. M., T. D. Setiyono, A. Dobermann. K. G. Cassman, R. W. Elmore, G. L. Graef, and J. E. Specht. 2008. Soybean sowing date: The vegetative, reproductive, and agronomic impacts. *Crop Sci* 48:727–740.

Baum, J. A., T. Boaert, W. Clinton, G. R. Heck, P. Feldmann, O. Hagan, S. Johnson, G. Plaetinck, T. Munyikwa, M. Pleau, T. Vaughn, and J. Roberts. 2007. Control of coleopteran insect pests through RNA interference. *Nat Biotech* 25:1322–1326.

Baur, M. E., D. J. Boethel, M. L. Boyd, G. R. Bowers, M. O. Way, L. G. Heatherly, J. Rabb, and L. Ashlock. 2000. Arthropod populations in early soybean production systems in the Mid-South. *Environ Entomol* 29:312–328.

Bennett, D. 2009. More conventional soybean acres? *Delta Farm Press* 66(6):33, http://deltafarmpress.com/soybeans/conventional-acres-0210/

Bergerou, J. A., L. E. Gentry, M. B. David, and F. E. Below. 2004. Role of N_2 fixation in the soybean N credit in maize production. *Plant and Soil* 262:383–394.

Bermudez, M. and A. P. Mallarino. 2007. Impacts of variable-rate phosphorus fertilization based on dense grid sampling on soil-test phosphorus and grain yield of corn and soybean. *Agron J* 99:822–832.

Bernards, M. L., L. Perim, and I. L. Schleufer. 2008. Glyphosate-resistant and conventional soybean response to foliar manganese fertilizer. *Proc North Cent Weed Sci Soc* 63:186, http://www.ncwss.org/

Bhangoo, M. S. and D. J. Albritton. 1975. Nodulating and non-nodulating Lee soybean isolines response to applied nitrogen. *Agron J* 68:643–645.

Bigler, F., D. Babendreier, and U. Kuhlmann (eds.). 2006. *Environmental Impact of Invertebrates for Biological Control of Arthropods: Methods and Risk Assessment*. CABI Publishing, Switzerland.

Binford, G. D., B. K. Hearn, M. A. Isaacs, D. J. Hansen, and R. W. Taylor. 2004. Foliar fertilization of roundup ready soybeans. *Crop Mgmt* 24 Nov, http://www.plantmanagementnetwork.org/pub/cm/research/2004/rr/ (Online only, limited access)

Bliss, R. M. 2008. Drought-hardy soybean lines show their stamina. *Agric Res Magazine* 56(10):14–15, http://www.ars.usda.gov/is/AR/archive/nov08/soybean1108.htm

Boerboom, C. and M. Owen. 2006. Facts about glyphosate-resistant weeds. Purdue Extension GWC-1. Purdue University Extension, West Lafayette, Indiana, http://www.ces.purdue.edu/extmedia/GWC/GWC-1.pdf

Boethel, D. J. 2004. Integrated management of soybean insects. Pp. 853–881. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*, 3rd ed. Agronomy Monograph 16. American Society of Agronomy, Madison, Wisconsin.

Boethel, D. J., J. S. Mink, A. T. Wier, J. D. Thomas, B. R. Leonard, and F. Gallardo. 1992. Management of insecticide resistant soybean loopers (*Pseudoplusia includens*) in the southern United States. Pp. 66–67. In L. G. Copping, M. B. Green, and R. T. Rees (eds.). *Pest Management in Soybean*. Elsevier, Essex, England.

Bond, W. and A. C. Grundy. 2001. Non-chemical weed management in organic farming systems. *Weed Res* 41:383–405.

Boquet, D. J. 1998. Yield and risk utilizing short-season soybean production in the mid-southern USA. *Crop Sci* 38:1004–1011.

Borges, R. and A. Mallarino. 2000. Grain yield, early growth, and nutrient uptake of no-till soybean as affected by phosphorus and potassium placement. *Agron J* 92:380–388.

Borges, R. and A. Mallarino. 2003. Broadcast and deep-band placement of phosphorus and potassium for soybean managed with ridge tillage. *Soil Sci Soc Am J* 67:1920–1927.

Bott, S., T. Tesfamariam, H. Candan, I. Cakmak, V. Romheld, and G. Neumann. 2008. Glyphosate-induced impairment of plant growth and micronutrient status in glyphosate-resistant soybean. *Plant Soil* 312:185–194.

Boyd, M. L., D. J. Boethel, B. R. Leonard, R. J. Habetz, L. P. Brown, and W. B. Hallmack. 1997. Seasonal abundance of arthropod populations on selected soybean varieties grown in early season production systems in Louisiana. *La Agric Exp Stn Bull* 860. Louisiana State University, Baton Rouge.

Bradley, C. A. 2008. Fungicide resistance management in soybean.

Pp. 57–60. In A. E. Dorrance, M. A. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Bridges, D. C. 1992. *Crop Losses Due to Weeds in the United States*—1992. Weed Science Society of America, Champaign, Illinois.

Brim, C. A. 1966. A modified pedigree method of selection in soybeans. *Crop Sci* 6:220.

Brim, C. A. 1973. Quantitative genetics and breeding. Pp. 155–186. In B. E. Caldwell (ed.). *Soybeans: Improvement, Production and Uses*. American Society of Agronomy, Madison, Wisconsin.

Broders, K. D., P. E. Lipps, P. A. Paul, and A. E. Dorrance. 2007. Characterization of *Pythium* spp. associated with corn and soybean seed and seedling disease in Ohio. *Plant Dis* 91(6):727–735.

Buah, S. J., T. A. Polito, and R. Killorn. 2000. No-tillage soybean response to banded and broadcast and direct and residual fertilizer phosphorus and potassium applications. *Agron J* 92: 657–662.

Buhler, D. D., M. Liebman, and J. J. Obrycki. 2000. Theoretical and practical challenges to an IPM approach to weed management. *Weed Sci* 48:274–280.

Bullen, G., J. Dunphy, and E. Weddington. 2008. Grain budgets. North Carolina State University, Raleigh, http://www.agecon.ncsu.edu/faculty/piggott/budget.html

Bullock, D. G., R. G. Hoeft, P. Dorman, T. Macy, and R. N. Olson. 1994. Nutrient management with intensive soil sampling and differential fertilizer spreading. *Better Crops with Plant Food* 78:10–12.

Burton, M., R. Weisz, A. York, and M. Hamilton. 2007. Organic field crop production and marketing in North Carolina: Weed management in organic grain. Center for Environmental Farming Systems, North Carolina State University Cooperative Extension, Raleigh, http://www.organicgrains.ncsu.edu/pestmanagement/organicweedmanagement.htm

Bussan, A. J., O. C. Burnside, J. H. Orf, E. A. Ristau, and K. J. Puettmann. 1997. Field evaluation of soybean (*Glycine max*) genotypes for weed competitiveness. Weed Sci 45:31-37.

Carpenter, J., A. Felsot, T. Goode, M. Hammig, D. Onstad, and S. Sankula. 2002. *Comparative Environmental Impacts of Biotechnology-derived and Traditional Soybean, Corn, and Cotton Crops*. Council for Agricultural Science and Technology, Ames, Iowa.

Carter, T. E. Jr., R. L. Nelson, C. H. Sneller, and Z. Cui. 2004. Genetic diversity in soybean. Pp. 303–416. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*. Agronomy Monograph, 3rd ed. American Society of Agronomy, Madison, Wisconsin.

Cavigelli, M. A., J. R. Teasdale, and A. E. Conklin. 2008. Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. *Agron J* 100:785–794.

Cerdeira, A. L., and S. O. Duke. 2006. The current status and environmental impact of glyphosate-resistant crops: A review. *J Environ Qual* 35:1633–1658.

Chase, C., K. Delate, and M. Smith. 2008. Organic crop production enterprise budgets. FM 1876. Iowa State University Extension, Ames, http://www.extension.iastate.edu/agdm/crops/pdf/a1-18.pdf

Chen, P., C. H. Sneller, L. C. Purcell, T. R. Sinclair, C. A King, and T. Ishibashi. 2007. Registration of soybean germplasm lines R01-416F and R01-581F for improved yield and nitrogen fixation under drought stress. *J Plant Registration* 1:166–167.

Chen, S. 2007. Tillage and crop sequence effects on *Heterodera glycines* and soybean yields. *Agron J* 99:797–807.

Clark, A. (ed.). 2007. *Managing Cover Crops Profitably*. 3rd ed. Handbook Series Book 9. Sustainable Agriculture Research and Education (SARE), USDA-CSREES, Beltsville, Maryland, http://www.sare.org/publications/covercrops/covercrops.pdf

Coker, C., J. Rupe, S. Monfort, and T. Kirkpatrick. 2008. Arkansas plant disease control products guide: Soybean seed treatments. MP 154. University of Arkansas Extension Service, Little Rock, http://www.uaex.edu/other_areas/publications/pdf/mp154/soybseedtreat.pdf

Conservation Technology Information Center (CTIC). 2006. Crop Residue Management Survey, http://www.conservationinformation.org/pdf/2006CRMSurveyHiRes.pdf

Conservation Technology Information Center (CTIC). 2007. Crop Residue Management Survey. 2007 Amendment to the National Crop Residue Management Survey Summary, http://www.conservationinformation.org/pdf/National_Summary_2007_Amendment.pdf

Costamagna, A. C. and D. A. Landis. 2007. Quantifying predation on soybean aphid through direct field observations. *Biol Ctrl* 42:16–24.

Crookston, R. K. 2006. A top 10 list of developments and issues impacting crop management and ecology during the past 50 years. *Crop Sci* 46:2253–2262.

Crouse, K. and W. McCarty. 2006. Soil testing for the farmer. Information sheet 346. Mississippi State University Extension, http://msucares.com/pubs/infosheets/is0346.pdf

Dadson, R. B., I. Javaid, F. M. Hashem, and J. M. Joshi. 2007. Antibiosis in soybean breeding lines for the management of corn earworm for sustainable soybean production. *J Sustain Ag* 30:137–146.

Davis, E. L., R. S. Hussey, M. G. Mitchum, and T. J. Baum. 2008. Parasitism proteins in nematode-plant interactions. *Curr Opin Plant Biol* 11:360–366.

De Bruin, J. L. and P. Pedersen. 2008. Response of old and new soybean varieties to Heterodera glycines Ichinohe. *Agron J* 100:1347–1353.

De Bruin, J. L., P. M. Porter, and N. R. Jordan. 2005. Use of a rye cover crop following corn in rotation with soybean in the upper-Midwest. *Agron J* 97:587–598.

Decker, A. M., A. J. Clark, J. J. Meisinger, F. D. Mulford, and M. S. McIntosh. 1994. Legume cover crop contributions to no-tillage corn production. *Agron J* 86:126–135.

DeFelice, M. S., P. R. Carter, and S. B. Mitchell. 2006. Influence of tillage on corn and soybean yield in the United States and Canada. *Crop Mgmt* 26 June, http://www.plantmanagementnetwork.org/sub/cm/research/2006/tillage/CornSoybean.pdf (online only; limited access)

Deibert, E. J., M. Bijeriego, and R. A. Olson. 1979. Utilization of ^{15}N fertilizer by nodulating and non-nodulating soybean isolines. *Agron J* 71:717–723.

Dekker, J. 1997. Weed diversity and weed management. *Weed Sci* 45:357–363.

Delate, K. 1999. The effect of tillage on organic soybean production following CRP land. Iowa State University Extension Service, Ames, http://extension.agron.iastate.edu/organicag/researchreports/mcnaycrp99.pdf

Delate, K., J. DeWitt, A. McKern, and R. Turnbull. 2005. Integrated approaches to organic pest management in the Midwestern

USA: Case studies of three crops. I*PM in Organic Systems Symposium, XXII International Congress of Entomology,* Brisbane, Australia, 15–21 August, 2004, http://www.organicresearch.com/Reviews.asp?action=display &openMenu=relatedItems&ReviewID=1172&Year=2005#

Derksen, D. A., R. L. Anderson, R. E. Blackshaw, and F. Maxwell. 2002. Weed dynamics and management strategies for cropping systems in the northern Great Plains. *Agron J* 94:174–185.

DeWitt, J., M. Duffy, G. Miller, J. Sawyer, J. Creswell. 2002. Crop rotation. NMEP 5. Iowa State University Extension Service, Ames, http://www.extension.iastate.edu/Publications/NMEP5.pdf

Dill, G. M. 2005. Glyphosate resistant crops: History, status, and future. Pest Manage Sci 61:219-224.

Dill, G. M., C. A. CaJacob, and S. R. Padgette. 2008. Glyphosate-resistant crops: Adoption, use and future considerations. *Pest Manage Sci* 64:326–331.

Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agron J* 94:153–171.

Ditsch, D. C. and L. W. Murdock. 1987. Soil erodibility: how is it determined and used. AGR-125. University of Kentucky Cooperative Extension Service, Lexington, http://www.ca.uky.edu/agc/pubs/agr/agr125/agr125.htm

Dodd, J. R. and A. P. Mallarino. 2005. Soil-test phosphorus and crop grain yield responses to long-term phosphorus fertilization for corn-soybean rotations. *Soil Sci Soc Am J* 69:1118–1128.

Donald, P. A., R. Hayes, and E. Walker. 2007. Potential for soybean cyst nematode reproduction on winter weeds and cover crops in Tennessee. *Plant Health Progress* 26 Feb, http://www.plantmanagementnetwork.org/pub/php/research/2007/scn/ (online only; limited access)

Downs, H. W. and R. W. Hansen. 2007. Estimating farm fuel requirements. Pub. No. 5.006. Colorado State University Extension, Fort Collins, http://www.ext.colostate.edu/pubs/farmmgt/05006.html

Egli, D. B. 2008. Soybean yield trends from 1972 to 2003 in midwestern USA. *Field Crops Res* 106:53–59.

Ennis, W. B., Jr. 1958. The challenges of modern weed control. *Weeds* 6:363–369.

Erickson, B. 2008. Corn/soybean rotation literature summary, http://www.agecon.purdue.edu/pdf/Crop_Rotation_Lit_Review.pdf

Eubank, T. W., D. H. Poston, V. K. Nandula, C. H. Koger, D. R. Shaw, and D. B. Reynolds. 2008. Glyphosate-resistant horseweed (*Conyza Canadensis*) control using glyphosate-, paraquat-, and glufosinate-based herbicide programs. Weed Technol 22:16–21.

Extension Toxicology Network (EXTOXNET). 2008. Pesticide Information Profiles. Oregon State University, Corvallis, http://extoxnet.orst.edu/pips/ghindex.html

Faghihi, J., V. Ferris, P. Donald, G. Noel, and T. Welacky. 2008. Changes in resistance of PI88788 to field populations of soybean cyst nematode (SCN). *Proc 4th National Soybean Cyst Nematode Conference*, Tampa, Florida, 6–7 March.

Feenstra, G., C. Ingels, and D. Campbell. 1997. What is sustainable agriculture? Sustainable agriculture research and education program, University of California, Davis, http://www.sarep.ucdavis.edu/Concept.htm

Fehr, W. R. 1987a. Breeding methods for variety development. Pp. 249–293. In J. R. Wilcox (ed.). *Soybeans: Improvement, Production and Uses*. 2nd ed. Agronomy Monograph 16. ASA, CSSA, WSSA, Madison, Wisconsin.

Fehr, W. R. 1987b. *Principles of Variety Development: Theory and Technique*. McMillan Publishing, New York.

Ferguson, R. B. and G. W. Hergert. 2000. Soil sampling for precision agriculture. EC 00-154. University of Nebraska Cooperative Extension Service, Lincoln, http://www.ianrpubs.unl.edu/epublic/live/ec154/build/ec154.pdf

Flores, A. 2009. ARS-developed riparian zones reduce atrazine contamination in water. *Agric Res Magazine* 57(1):20, http://www.ars.usda.gov/is/AR/archive/jan09/zones0109.htm?pf=1

Follett, P. A. and J. J. Duan. 2000. *Nontarget Effects of Biological Control*. Kluwer Academic Publishers, Boston, Massachusetts.

Franz, J. E., M. K. Mao, and J. A. Sikorski. 1997. *Glyphosate—A Unique Global Herbicide*. American Chemical Society, Washington, D.C.

Franzluebbers, A. J. and C. A. Francis. 1995. Energy output:input ratio of maize and sorghum management systems in eastern Nebraska. *Ag Ecosys Environ* 53:271–278.

Franzluebbers, A. J., C. A. Francis, and D. T. Walters. 1994. Nitrogen fertilizer response potential of corn and sorghum in continuous and rotated crop sequences. *J Prod Agric* 7:277–284.

Franzluebbers, A. J., F. M. Hons, and V. A. Saladino. 1995. Sorghum, wheat, and soybean production as affected by long-term tillage, crop sequence, and N fertilization. *Plant Soil* 173:55–65.

Frederick, J. R., P. J. Bauer, W. J. Busscher, and G. S. McCutcheon. 1998. Tillage management for doublecropped soybean grown in narrow and wide row width culture. *Crop Sci* 38:755–762.

Fuller, V. L., C. J. Lilley, and P. E. Urwin. 2008. Nematode resistance. *New Phytologist* 180:27–44.

Funderburk, J. E., F. M. Rhoads, and I. D. Teare. 1994. Modifying soil nutrient level affects soybean insect predators. *Agron J* 86:581–585.

Fungicide Resistance Action Committee (FRAC). 2008. List of pathogens with field resistance towards QoI fungicides. FRAC, CropLife International, Brussels, Belgium, http://www.frac.info/frac/meeting/2008/Pathogens_with_field-resistance_towards_2008.pdf

Gevens, A., D. Wright, A. Blount, R. Mizell, R. Sprenkel, C. Mackowiak, S. Olson, J. A. Smith, J. Marois, and L. Datnoff. 2008. Alternatives for organic soybean production. Pp. 81–82. In A. E. Dorrance, M. A. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Gianessi, L. 2005. Economic and herbicide use impacts of glyphosate-resistant crops. *Pest Manage Sci* 61:241–245.

Gianessi, L. 2009. The benefits of insecticide use: Soybeans. CropLife Foundation, Washington, D.C., http://www.croplifefoundation.org/Insecticide_Benefits/Crop_Studies/Combined_Document_Soybeans.pdf

Gianessi, L. and S. Sankula. 2003. The value of herbicides in U.S. crop production. CropLife Foundation, Washington, D.C., http://www.croplifefoundation.org/Documents/Pesticide%20Benefits/Herbicides/HerbBeniExecSum.pdf

Gianessi, L. P. and N. P. Reigner. 2006. The value of herbicides in U.S. crop production, 2005 update. CropLife Foundation, Washington, D.C., http://www.croplifefoundation.org/cpri_benefits_herbicides.htm

Gianessi, L. P. and N. P. Reigner. 2007. The value of herbicides in U.S. crop production. *Weed Technol* 21:559–566.

Gibson, K. D., W. G. Johnson, and D. E. Hillger. 2005. Farmer perceptions of problematic corn and soybean weeds in Indiana. *Weed Technol* 19:1065–1070.

Giesler, L. J. and A. D. Ziems. 2008. Seed treatment fungicides for soybeans. G1852. University of Nebraska-Lincoln Extension, http://www.ianrpubs.unl.edu/epublic/live/g1852/build/g1852.pdf

Giesler, L., R. Kemerait, and L. Sconyers. 2008. The sentinel plot system: Monitoring movement of an invasive pathogen. Pp. 35–38. In A. E. Dorrance, M. A. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust.* 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Givens, W. A., D. R. Shaw, W. G. Johnson, S. C. Weller, B. G. Young, R. G. Wilson, M. D. K. Owen, and D. Jordan. 2009. A grower survey of herbicide use patterns in glyphosate-resistant cropping systems. *Weed Technol* (in press).

Gold, M. V. 2007a. Sustainable agriculture: Definitions and terms. Alternative Farming Systems Information Center. U.S. Department of Agriculture–National Agricultural Library, Washington, D.C., http://www.nal.usda.gov/afsic/pubs/terms/srb9902.shtml

Gold, M. V. 2007b. Organic production/organic food: Information access tools. Alternative Farming Systems Information Center. U.S. Department of Agriculture–National Agricultural Library, Washington, D.C., http://www.nal.usda.gov/afsic/pubs/ofp/ofp.shtml

Gold, M. V. 2008. Sustainable agriculture: Information access tools. Alternative Farming Systems Information Center. U.S. Department of Agriculture–National Agricultural Library, Washington, D.C., http://www.nal.usda.gov/afsic/pubs/agnic/susag.shtml

Gordon, B. 2007. Manganese nutrition of glyphosate-resistant and conventional soybeans. *Better Crops with Plant Food* 4:12–13.

Gordon, B., D. A. Whitney, and D. L. Fjell. 2001. Effects of cropping system and nitrogen fertilization on no-tillage grain sorghum production. Pp. 60–63. In 2001 *Agric Res Report of Progress 876*. Kansas State University, Manhattan, http://www.oznet.ksu.edu/library/crpsl2/srp876.pdf

Green, C. J., and A. M. Blackmer. 1995. Residue decomposition effects on nitrogen availability to corn following corn or soybean. *Soil Sci Soc Am J* 59:1065–1070.

Green, J. M. 2007. Review of glyphosate and ALS-inhibiting herbicide crop resistance and resistant weed management. *Weed Technol* 21:547–558.

Green, S. V., M. A. Cavigelli, T. H. Dao, and D. C. Flanagan. 2005. Soil physical properties and aggregate-associated C, N, and P distributions in organic and conventional cropping systems. *Soil Sci* 170:822–831.

Gunsolus, J. L. 1990. Mechanical and cultural weed control in corn and soybeans. *Am J Altern Ag* 5:114–119.

Ham, G. E. and A. C. Caldwell. 1978. Fertilizer placement effects on soybean seed yield, N_2 fixation, and ^{33}P uptake. *Agron J* 70:779–783.

Ham, G. E., I. E. Liener, S. D. Evans, R. D. Frazier, and W. W. Nelson. 1975. Yield and composition of soybean seed as affected by N and S fertilization. *Agron J* 67:293–297.

Hanna, M. 2001. Fuel required for field operations. PM 709. Iowa State University Extension, Ames, http://www.extension.iastate.edu/Publications/PM709.pdf

Haq, M. U. and A. P. Mallarino. 2000. Soybean yield and nutrient composition as affected by early season foliar fertilization. *Agron J* 92:16–24.

Harder, D. B., C. L. Sprague, and K. A. Renner. 2007. Effect of soybean row width and population on weeds, crop yield, and economic return. *Weed Technol* 21:744–752.

Hartman, G. L., L. L. Domier, L. M. Wax, C. G. Helm, D. W. Onstad, J. T. Shaw, L. F. Solter, D. J. Voegtlin, C. J. D'Arcy, M. E. Gray, K. L. Steffey, S. A. Isard, and P. L. Orwick. 2001. Occurrence and distribution of *Aphis glycines* on soybeans in Illinois in 2000 and its potential control. *Plant Health Prog* 5 Feb, http://www.plantmanagementnetwork.org/pub/php/brief/aphisglycines/ (online only; limited access)

Heap, I. 2008. *International Survey of Herbicide Resistant Weeds.* WeedScience.org, http://www.weedscience.org/In.asp

Heatherly, L. G. 1999a. The stale seedbed planting system. Pp. 93–102. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Heatherly, L. G. 1999b. Early soybean production system (ESPS). Pp. 103–118. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Heatherly, L. G. 1999c. Soybean irrigation. Pp. 119–141. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Heatherly, L. G. 2005a. Midsouthern USA soybean yield affected by maturity group and planting date. *Crop Mgmt* 12 Nov, http://www.plantmanagementnetwork.org/cm/ (online only: limited access)

Heatherly, L. G. 2005b. Soybean development in the midsouthern USA related to date of planting and maturity classification. *Crop Mgmt* 21 April, http://www.plantmanagementnetwork.org/cm/ (Online only, limited access)

Heatherly, L. G. 2005c. Mid-south soybean yield trends up. *Delta Farm Press* 62(50):12.

Heatherly, L. G. 2007. "Boosting soybean yields requires attention to local conditions." *Success Farm* March 12, http://www.agriculture.com/ag/story.jhtml? storyid=/templatedata/ag/story/data/1173711714526.xml

Heatherly, L. G. and G. R. Bowers (eds.). 1998. *Early Soybean Production System Handbook*. USB-6009-09 1998-11000. United Soybean Board, St. Louis, Missouri.

Heatherly, L. G. and R. W. Elmore. 2004. Managing inputs for peak production. Pp. 451–536. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*, 3rd ed. Agronomy Monograph 16. American Society of Agronomy, Madison, Wisconsin.

Heatherly, L. G. and J. D. Ray. 2007. Soybean and corn. Pp. 477–533. In R. J. Lascano and R. E. Sojka (eds.). *Irrigation of Agricultural Crops*, 2nd ed. Agronomy Monograph 30. American Society of Agronomy, Madison, Wisconsin.

Heatherly, L. G., and S. R. Spurlock. 1999. Yield and economics of traditional and early soybean production system (ESPS) seedings in the midsouthern USA. *Field Crops Res* 63:35–45.

Heatherly, L. G., S. R. Spurlock, and K. N. Reddy. 2003. Weed management and early-season nitrogen for conventional and glyphosate-resistant soybean grown with and without irrigation. *Agron J* 95:446–453.

Herbicide Resistance Action Committee (HRAC). 2005. Glossary.

HRAC, CropLife International, Brussels Belgium, http://www.hracglobal.com/Glossary/tabid/369/default.aspx

Hershman, D. E., R. D. Heinz, and B. S. Kennedy. 2008. Soybean cyst nematode, *Heterodera glycines*, populations adapting to resistant soybean varieties in Kentucky. *Plant Dis* 92:1475–1476.

Hewezi, T., P. Howe, T. R. Maier, and T. J. Baum. 2008. Arabidopsis small RNAs and their targets during cyst nematode parasitism. *Mole Plant Microbe Interactions* 12:1622–1634.

Higley, L. G. and D. J. Boethel. 1994. *Handbook of Soybean Insect Pests*. Entomological Society of America, Lanham, Maryland.

Hill, C. B., Y. Li, and G. L. Hartman. 2004a. Resistance to the soybean aphid in soybean germplasm. *Crop Sci* 44:98–106.

Hill, C. B., Y. Li, and G. L. Hartman. 2004b. A single dominant gene for resistance to the soybean aphid in the soybean cultivar Dowling. Crop Sci 44:1601-1605.

Hill, C. B., Y. Li, and G. L. Hartman. 2004c. Soybean aphid resistance in soybean Jackson is controlled by a single dominant gene. *Crop Sci* 44:1606–1608.

Hively, W. D. and W. J. Cox. 2001. Interseeding cover crops into soybean and subsequent corn yields. *Agron J* 93:308–313.

Hock, S. M., S. Z. Knezevic, A. R. Martin, and J. L. Lindquist. 2006. Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. *Weed Sci* 54:38–46.

Hoeft, R. G. 2002. Soil testing and fertility. Pp. 91–131. In *Illinois Agronomy Handbook*, 23rd ed. University of Illinois Extension Service, Champaign.

Hoeft, R. G., E. D. Nafziger, R. R. Johnson, and S. R. Aldrich. 2000. *Modern Corn and Soybean Production*. 1st ed. MCSP Publications, Savoy, Illinois. 353 pp.

Horak, M. J. and D. E. Peterson. 1995. Biotypes of Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) are resistant to imazethapyr and thifensulfuron. Weed Technol 9:192–195.

Huber, D. M., J. D. Leuck, W. C. Smith, and E. P. Christmas. 2004. Induced manganese deficiency in GM soybeans. In R. G. Hoeft (ed.). *Proc 34th North Cent Extension-Industry Soil Fert Conf* 20:80–83. Potash & Phosphate Inst., Brookings, South Dakota.

Intarapapong, W., D. Hite, and D. Hudson. 2003. Economic and environmental impacts of variable-rate fertilizer application in Mississippi. Bull. #1129. Mississippi Agricultural & Forestry Experiment Station, Mississippi State University, http://msucares.com/pubs/bulletins/b1129.pdf

Jannink, J. L., J. H. Orf, N. R. Jordon, and R. G. Shaw. 2000. Index selection for weed suppressive ability in soybean. *Crop Sci* 40:1087–1094.

Johnson, T. J., T. C. Kaspar, K. A. Kohler, S. J. Corak, and S. D. Logsdon. 1998. Oat and rye overseeded into soybean as fall cover crops in the upper Midwest. *J Soil Water Cons* 53:276–279.

Johnson, W. G., K. D. Gibson, and S. P. Conley. 2007. Does weed size matter? An Indiana grower perspective about weed control timing. *Weed Technol* 21:542–546.

Kang, S-T., M.A. Rouf Mian, and R. B. Hammond. 2008. Soybean aphid resistance in PI 243540 is controlled by a single dominant gene. *Crop Sci* 48:1744–1748.

Karlen, D. L. and J. W. Doran. 1991. Cover crop management effects on soybean and corn growth and nitrogen dynamics in an on-farm study. *Amer J Sustain Ag* 6:71–82.

Karlen, D. L., K. Delate, R. Turnbull, and J. Boes. 2004. Organic soybean production: Challenges and perspectives of an increasing trend. Pp. 319–327. In *Proc World Soybean Research Conference VII*, Foz do Iguacu, Brazil.

Kaspar, T. C., D. B. Jaynes, T. B. Parkin, and T. B. Moorman. 2007. Rye cover crop and gamagrass strip effects on NO_3 concentration and load in tile drainage. *J Environ Qual* 36:1503–1511.

Kaspar, T. C., E. J. Kladivko, J. W. Singer, S. Morse, and D. Mutch. 2008. Potential and limitations of cover crops, living mulches, and perennials to reduce nutrient losses to water sources from agricultural fields in the upper Mississippi basin. Pp. 129–148. In *Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop*, Ames, Iowa, 26-28 September 2005. ASABE, St. Joseph, Michigan.

Katsvairo, T. W. and W. J. Cox. 2000a. Economics of cropping systems featuring different rotations, tillage, and management. *Agron J* 92:485–493.

Katsvairo, T. W. and W. J. Cox. 2000b. Tillage x rotation x management interactions in corn. *Agron J* 92:493–500.

Kelley, K. W. 2003. Double-cropping winter wheat and soybean improves net returns in the eastern Great Plains. *Crop Mgmt* 12 Nov, http://www.plantmanagementnetwork.org/pub/cm/research/2003/plains/kelley.pdf (online only; limited access)

Kelley, K. W. 2005. Grain sorghum and soybean cropping sequence affect yield and fertilizer N requirement. *Crop Mgmt* 22 Sept, http://www.plantmanagementnetwork.org/sub/cm/research/2005/sequence/cropping.pdf (online only; limited access)

Kelley, K. W. and D. W. Sweeney. 2008. Influence of tillage, row spacing-population system, and glyphosate herbicide timing on soybean production in the eastern Great Plains. *Crop Mgmt* 14 November, http://www.plantmanagementnetwork.org/sub/cm/research/2008/production/ (online only; limited access)

Kessavalou, A. and D. T. Walters. 1997. Winter rye as a cover crop following soybean under conservation tillage. *Agron J* 89:68–74.

Kessavalou, A. and D. T. Walters. 1999. Winter rye cover crop following soybean under conservation tillage: Residual soil nitrate. *Agron J* 91:643–649.

Kladivko, E. J., J. R. Frankenberger, D. B. Jaynes, D. W. Meek, B. J. Jenkinson, and N. R. Fausey. 2004. Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system. *J Environ Qual* 33:1803–1813.

Kluchinski, D. and J. W. Singer. 2005. Evaluation of weed control strategies in organic soybean production. *Crop Mgmt* 3 May, http://www.plantmanagementnetwork.org/pub/cm/research/2005/organic/ (online only; limited access)

Knezevic, S. Z., S. P. Evans, and M. Mainz. 2003. Row spacing influences the critical timing for weed removal in soybean (*Glycine max*). *Weed Technol* 17:666–673.

Kogan, M. 1998. Integrated pest management: Historical perspectives and contemporary developments. *Ann Rev Entomol* 43:243–270.

Kogan, M. and S. G. Turnipseed. 1987. Ecology and management of soybean arthropods. *Ann Rev Entomol* 32:507–538.

Kolpin, D. W., E. M. Thurman, and S. M. Linhart. 1998. The environmental occurrence of herbicides: The importance of degradates in ground water. *Arch Environ Contam Toxicol* 35:385–390.

Kornecki, T. S., R. L. Raper, and A. J. Price. 2004. Effectiveness of terminating cover crops using different roller implements.

Pp. 336–345. In D. Jordan and D. Caldwell (eds.). *Proc 26th Annual Southern Conservation Tillage Conf for Sustainable Agriculture*, 7–9 June, Raleigh, North Carolina.

Kruger, G. R., W. G. Johnson, S. C. Weller, M. D. K. Owen, D. R. Shaw, J. W. Wilcut, D. L. Jordan, R. G. Wilson, M. L. Bernards, and B. G. Young. 2009. U.S. grower views on problematic weeds and changes in weed pressure in glyphosate-resistant corn, cotton, and soybean cropping systems. *Weed Technol* (in press).

Kuepper, G. 2001. Organic control of white mold on soybeans. Pub. IP133. Appropriate Technology Transfer for Rural Areas–National Center for Appropriate Technology (ATTRA–NCAT), Fayetteville, Arkansas, http://attra.ncat.org/attra-pub/whitemold.html

Kuepper, G. 2003. Organic soybean production. Pub. CT120. Appropriate Technology Transfer for Rural Areas–National Center for Appropriate Technology (ATTRA–NCAT), Fayetteville, Arkansas, http://attra.ncat.org/new_pubs/attra-pub/organicsoy.html?id=DC

Kuepper, G., S. Diver, and J. Sampson. 2004. Sources of organic fertilizer amendments. Appropriate Technology Transfer for Rural Areas–National Center for Appropriate Technology (ATTRA–NCAT), Fayetteville, Arkansas, http://attra.ncat.org/attra-pub/orgfert.php

Lampkin, N. 1990. *Organic Farming*. Farming Press, Ipswich, United Kingdom.

Landis, D. A., M. M. Gardiner, W.v.d. Werf, and S. M. Swinton. 2008. Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. *Proc Nat Acad Sci* 105:20552–20557.

Langdale, G. W., R. L. Blevins, D. L. Karlen, D. K. McCool, M. A. Nearing, E. L. Skidmore, A. W. Thomas, D. D. Tyler, and J. R. Williams. 1991. Cover crop effects on soil erosion by wind and water. Pp. 15–22. In W.L. Hargrove (ed.). *Cover Crops for Clean Water*. Soil and Water Conservation Society, Ankeny, Iowa.

Laughlin, D. H. and S. R. Spurlock. 2007. User's Guide for the Mississippi State Budget Generator, Version 6.0 for Windows. Department of Agricultural Economics, Mississippi State University, http://www.agecon.msstate.edu/laughlin/msbg/userguide6.pdf

Lauzon, J. D., I. P. O'Halloran, D. J. Fallow, A. P. von Bertoldi, and D. Aspinall. 2005. Spatial variability of soil test phosphorus, potassium and pH of Ontario soils. *Agron J* 97:524–532.

Legleiter, T. R., K. W. Bradley, and R. E. Massey. 2009. Glyphosate-resistant waterhemp (*Amaranthus rudis*) control and economic returns with herbicide programs in soybean. *Weed Technol* (in press).

Leikam, D., R. E. Lamond, L. C. Bonczkowski, J. S. Hickman, and D. A. Whitney. 2007. Using legumes in crop rotations. L-778. Department of Agronomy, Kansas State University, Manhattan, http://www.oznet.ksu.edu/library/crpsl2/l778.pdf

Levine, E., J. L. Spencer, S. A. Isard, D. W. Onstad, and M. E. Gray. 2002. Adaptation of the western corn rootworm to crop rotation: Evolution of a new strain in response to a management practice. *Amer Entomol* 48:94–107.

Li, Y., C. B. Hill, S. R. Carlson, B. W. Diers, and G. L. Hartman. 2007. Soybean aphid resistance genes in the soybean varieties Dowling and Jackson map to linkage group M. *Molec Plant Breed* 19:25–34.

LibertyLink Soybeans. 2008. *Farm Industry News*, October 1. Penton Media, Inc., New York, http://farmindustrynews.com/seed/soybeans/1003_libertylink_soybeans/

Liebl, R. A., F. W. Simmons, L. M. Wax, and E. W. Stoller. 1992. Effect of rye (*Secale cereal*) mulch on weed control and soil moisture in soybean (*Glycine max*.). *Weed Tech* 6:838–846.

Liebman, M. and A. S. Davis. 2000. Integration of soil, crop and weed management in low-external-input farming systems. *Weed Res* 40:27–47.

Lin, C. H., R. N. Lerch, H. E. Garrett, W. G. Johnson, D. Jordan, and M. F. George. 2003. The effect of five forage species on transport and transformation of atrazine and isoxaflutole (Balance) in lysimeter leachate. *J Environ Qual* 32:1992–2000.

Lin, C. H., R. N. Lerch, H. E. Garrett, C. J. Gantzer, and S. H. Anderson. 2007. Utilizing vegetative buffer strips to remove dissolved and sediment-bound atrazine, metolachlor and glyphosate from surface water runoff. *Proc 10th North American Agroforestry Conf*, June 9–14, Quebec City, Quebec, Canada.

Lin, C. H., R. N. Lerch, H. E. Garrett, and M. F. George. 2008. Bioremediation of atrazine-contaminated soil by forage grasses: Transformation, uptake, and detoxification. *J Environ Qual* 37:196–206.

Lovely, W. G., C. R. Weber, and D. W. Staniforth. 1958. Effectiveness of the rotary hoe for weed control in soybeans. *Agron J* 50:8621–8625.

Lubowski, R. N., M. Vesterby, S. Bucholtz, A. Baez, and M. J. Roberts. 2002. Major uses of land in the United States. EIB-14. U.S. Department of Agriculture-Economic Research Service, Washington, D.C., http://www.ers.usda.gov/publications/EIB14/eib14d.pdf

Lyons, J. C. and F. B. Early. 1952. The effect of ammonium nitrate applications to field soils on nodulation, seed yield, and nitrogen and oil content of the seed of soybeans. *Soil Sci Soc Am J* 16: 259–263.

MacRae, T. C., M. E. Baur, D. J. Boethel, B. J. Fitzpatrick, A.-G. Gao, J. C. Gamundi, L. A. Harrison, V. T. Kabuye, R. M. Mcpherson, J. A. Miklos, M. S. Paradise, A. S. Toedebusch, and A. Viegas. 2005. Laboratory and field evaluations of transgenic soybean exhibiting high-dose expression of a synthetic *Bacillus thuringiensis cry1A* gene for control of Lepidoptera. *J Econ Entomol* 98:577–587.

Mahaffey, L. and W. Cranshaw. 2007. Some insect/disease control products allowed for use in certified organic production. Colorado State University, Fort Collins, http://www.eaglecounty.us/uploadedFiles/CSU/Horticulture_&_Agriculture/NewOrganicPesticides.pdf

Mallarino, A. P., E. Ortiz-Torres, and K. Pecinovsky. 2005. Effects of crop rotation and nitrogen fertilizer on crop production. Publ. ISRF04-13. *Annual Progress Report*, Northern Research and Demonstration Farm, Iowa State University, Ames, http://www.agronext.iastate.edu/soilfertility/info/NERF_AnnRepo2004_Nrotation_Publ-2005.pdf

Mallarino, A. P., E. Ortiz-Torres, and D. Rueber. 2006. Grain yield of corn, soybeans, and oats as affected by crop rotation and nitrogen fertilization for corn. Publ. ISRF05-22. *Annual Progress Report*, Northern Research and Demonstration Farm, Iowa State Univ., Ames, http://www.ag.iastate.edu/farms/05reports/n/GrainYield.pdf

Maringanti, C., I. Chaubey, M. Arabi, and B. Engel. 2008. A multi-objective optimization tool for selection and placement of BMP's for pesticide control. *Hydrol Earth Syst Sci Discuss* 5:1821–1862, www.hydrol-earth-syst-sci-discuss.net/5/1821/2008/

Maryland Cooperative Extension Service (MCES). 2006. Soil sampling procedures for nutrient management. College Park, http://anmp.umd.edu/Advisors/Soil_Sampling_Advisors.pdf

Maryland Department of Agriculture. 2008. Maryland's Winter Cover Crop Program, http://www.mda.state.md.us/resource_conservation/financial_assistance/cover_crop/index.php

McBride, W. D. and C. Greene. 2008. The profitability of organic soybean production. Paper No. 6449. Agricultural and Applied Economics Assoc Annual Meeting, Orlando, Florida, 27–29 July, http://purl.umn.edu/6449

McCarthy, J. R., D. L. Pfost, and H. D. Currence. 1993. Conservation tillage and residue management to reduce soil erosion. Pub. G1650. University of Missouri Extension, Columbia.

McDonald, P. B., J. W. Singer, and M. H. Wiedenhoeft. 2008. Establishment and growth of self-seeded winter cereal cover crops in a soybean-corn rotation. *Agron J* 100:432–439.

McPherson, R. M. and K. Bondari. 1991. Influence of planting date and row width on abundance of velvetbean caterpillars (*Lepidoptera: Noctuidae*) and southern green stink bugs (*Heteroptera: Pentatomidae*) in soybean. *J Econ Entomol* 84:311–316.

McPherson, R. M., J. S. Russin, and B. G. Harrville. 1996. Impact of early season soybean production on pest management in the southern region. *Proc Fourth Ann Southern Soybean Conf*, Memphis, Tennessee, 7–9 February. United Soybean Board, St. Louis, Missouri.

McPherson, R. M., R. C. Layton, W. J. McLaurin, and W. A. Mills. 1998. Influence of irrigation and maturity group on the seasonal abundance of soybean arthropods. *J Entomol Sci* 33:378–392.

Mensah, C., C. DiFonzo, and D. Wang. 2008. Inheritance of soybean aphid resistance in PI 567541B and PI 567598B. *Crop Sci* 48:1759–1763.

Mensah, C., C. DiFonzo, R. L. Nelson, and D. Wang. 2005. Resistance to soybean aphid in early maturing soybean germplasm. *Crop Sci* 45:2228–2233.

Meyer, J. D. F., D. C. G. Silva, C. Yang, K. F. Pedley, C. Zhang, M. van de Mortel, J. H. Hill, R. C. Shoemaker, R. V. Abdelnoor, S. A. Whitham, and M. A. Graham. 2009. Identification and analyses of candidate genes for Rpp4-mediated resistance to Asian soybean rust in soybean (*Glycine max* [L.] Merr.). *Plant Physiol*, Feb. 27 (online, open access) http://www.plantphysiol.org/cgi/rapidpdf/pp.108.134551v1

Miklos, J. A., M. F. Alibhai, S. A. Bledig, D. C. Connor-Ward, A-G. Gao, B. A. Holmes, K. H. Kolacz, V. T. Kabuye, T. C. MacRae, M. S. Paradise, A. S. Toedebusch, and L. A. Harrison. 2007. Characterization of soybean exhibiting high expression of a synthetic *Bacillus Thuringiensis cry1A* transgene that confers a high degree of resistance to lepidopteran pests. *Crop Sci* 47:148–157.

Mitchum, M. G., J. A. Wrather, R. D. Heinz, J. G. Shannon, and G. Danekas. 2007. Variability in distribution and virulence phenotypes of Heterodera glycines in Missouri during 2005. Plant Dis 91:1473-1476.

Monaco, T. J., S. C. Weller, and F. M. Ashton. 2002. *Weed Science: Principles and Practices*. John Wiley and Sons, New York.

Montgomery, D. R. 2007. Soil erosion and agricultural sustainability. *Proc Nat Acad Sci* 14:13268–13272, http://www.pnas.org/content/104/33/13268.full.pdf

Moore, M. J., T. J. Gillespie, and C. J. Swanton. 1994. Effect of cover crop mulches on weed emergence, weed biomass, and soybean development. *Weed Technol* 8:512–518.

Morrison, L. 2009. Know your nematode numbers. *Corn Soybean Digest* 69(1):26–28.

Mueller, D. 2008. Fungicides for soybean rust. Pp. 107–110. In A. E. Dorrance, M. D. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Mueller, T. C., and A. R. Womac. 1997. Effect of formulation and nozzle type on droplet size with isopropylamaine and trimesium salts of glyphosate. *Weed Technol* 11:639–643.

Mulla, D. J. 1993. Mapping and managing spatial patterns in soil fertility and crop yield. Pp. 15–26. In P. C. Robert, R. H. Rust, and W. E. Larson (eds.). P*roc of Soil Specific Crop Management: A Workshop on Research and Development Issues*. Minneapolis, Minnesota. ASA, CSSA, SSSA, Madison, Wisconsin, 14–16 April 1992.

Mutch, D. 2003. Weed control strategies in organic soybeans. Michigan State University Extension, East Lansing, http://www.covercrops.msu.edu/pdf_files/soy_weed_control03.pdf

National Information System–Regional Integrated Pest Management Centers (NIS–RIPMC). 2008. NIS–RIPMC, Washington, D.C. and Raleigh, North Carolina, http://www.ipmcenters.org/cropprofiles/

Nelson, K. A., P. P. Motavalli, and M. Nathan. 2005. Response of no-till Soybean [*Glycine max* (L.) Merr.] to timing of preplant and foliar potassium applications in a claypan soil. *Agron J* 97:832–838.

Nelson, K., R. Smoot, and M. Jones. 2004. Cost-effective organic weed management for clear hilum soybean production. University of Missouri Agriculture Expt Station, Columbia, http://aes.missouri.edu/greenley/fieldday/2004/page76.stm

Newsom, L. J. and D. R. Shaw. 1994. Influence of cultivation timing on weed control in soybean (*Glycine max*) with AC 263,222. *Weed Technol* 8:760–765.

Niblack, T. L. 2005. Soybean cyst nematode management reconsidered. *Plant Dis* 89:1020–1026.

Niblack, T. L. and G. L. Tylka (eds.). 2008. *Soybean Cyst Nematode Management Guide*. 5th ed. North Central Soybean Research Program, Urbandale, Iowa, http://www.planthealth.info/pdf_docs/SCNGuide_5thEd.pdf

Niblack, T. L., A. L. Colgrove, K. Colgrove, and J. P. Bond. 2008. Shift in virulence of soybean cyst nematode is associated with use of resistance from PI 88788. *Plant Health Prog* 18 Jan, http://www.plantmanagementnetwork.org/sub/php/research/2008/virulence/ (online only; limited access)

Nolte, S. A. and B. G. Young. 2002. Efficacy and economic return on investment for conventional and herbicide-resistant soybean (*Glycine max*). *Weed Technol* 16:388-395.

Oerke, E. C. 2006. Crop losses to pests. *J Agri Sci* 144:31–43.

Omay, A. B., C. W. Rice, L. D. Maddux, and W. B. Gordon. 1997. Changes in soil microbial and chemical properties under long-term crop rotation and fertilization. *Soil Sci* 61:1672–1678.

Onstad, D. W. 2001. Biology of Asian soybean aphid. Publ. 31. *Proc 31st Soybean Seed Res Conf* Dec 5–7, Chicago, Illinois. American Seed Trade Association, Alexandria, Virginia.

Onstad, D. W. 2008. *Insect Resistance Management: Biology, Economics and Prediction*. Academic Press, Burlington, Massachusetts.

Onstad, D. W. and M. L. McManus. 1996. Risks of host-range expansion by insect-parasitic biocontrol agents. *BioSci* 46:430–435.

Orf, J. H., B. W. Diers, and H. R. Boerma. 2004. Genetic improvement: Conventional and molecular-based strategies. Pp. 417–450. In J. Specht and R. Boerma (eds.). *Soybean: Improvement, Production, and Uses*. Agronomy Monograph, 3rd ed. American Society of Agronomy, Madison, Wisconsin.

Organic Materials Review Institute (OMRI). 2008. http://www.omri.org/OMRI_seal_how_why.html

Owen, M. D. K. 2008. Weed species shifts in glyphosate-resistant crops. *Pest Manage Sci* 64:377–387.

Parish, R. L., R. P. Bracey, D. W. Wells, and P. E. Bergeron. 1990. A comparison on cultivation methods for commercial vegetable crops. *Am J Agric Eng* 6:565–568.

Parker, M. B., N. A. Minton, O. L. Brooks, and C. E. Perry. 1975. Soybean yields and lance nematode populations as affected by subsoiling, fertility, and nematicide treatments. *Agron J* 67:663–666.

Parrott, W. A. and T. E. Clemente. 2004. Transgenic soybean. Pp. 265–302. In H. R. Boerma and J. E. Specht (eds.). *Soybeans: Improvement, Production and Uses*. 3rd ed. Agronomy Monograph 16. ASA, CSSA, WSSA, Madison, Wisconsin.

Pedersen, P. 2007. Fungicide seed treatments. Iowa State University Extension, Ames, http://extension.agron.iastate.edu/soybean/seedfungtmt.html

Pedersen, P. and J. G. Lauer. 2003. Corn and soybean response to rotation sequence and tillage system. Pp. 35–41. In *Proc 15th Annual Integrated Crop Mgmt Conf*, Iowa State University, Ames, 3-4 December 2002.

Pester, T. A., O. C. Burnside, and J. H. Orf. 1994. Leaf area expansion rate of soybean genotypes: An indirect indicator of their competitiveness to weeds. *North Central Weed Science Society* 49:119–120.

Peters, E. J., D. L. Klingman, and R. E. Larson. 1959. Rotary hoeing in combination with herbicides and other cultivations for weed control in soybeans. *Weeds* 7:449–458.

Peters, E. J., F. S. Davis, D. L. Klingman, and R. E. Larson. 1961. Interrelations of cultivations, herbicides and methods of application for weed control in soybeans. *Weeds* 9:639–645.

Pham, T. A., M. R. Miles, R. D. Frederick, C. B. Hill, and G. L. Hartman. 2009. Differential responses of resistant soybean entries to isolates of *Phakopsora pachyrhizi*. *Plant Dis* 93:224–228.

Pike, D. R., M. D. McGlamery, and E. L. Knake. 1991. A case study of herbicide use. *Weed Technol* 5:639–646.

Pike, D. R., K. L. Steffey, M. E. Gray, H. W. Kirby, D. I. Edwards, and R. H. Hornbaker. 1995. *Biologic and Economic Assessment of Pesticide Use on Corn and Soybeans*. National Agriculture Pesticide Impact Assessment Program Report No. 1-CA-95, USDA, Washington, D.C. 132 pp.

Pitre, H. N. 1983. *Natural Enemies of Arthropod Pests in Soybean*. South. Coop. Ser. Bull. 285. Southern Association of Agricultural Experiment Station Directors, Raleigh, North Carolina.

Popp, M. P., T. C. Keisling, C. R. Dillon, and P. M. Manning. 2001. Economic and agronomic assessment of deep tillage in soybean production on Mississippi River valley soils. *Agron J* 93:164–169.

Porter, P. M., J. G. Lauer, W. E. Lueschen, J. H. Ford, T. R. Hoverstad, E. S. Oplinger, and R. K. Crookston. 1997. Environment affects the corn and soybean rotation effect. *Agron J* 89:441–448.

Porter, P., G. Feyereisen, J. De Bruin, and G. Johnson. 2005. No-till organic soybean production following a fall-planted rye cover crop. Pp. 26–30. In *Proc First Scientific Conf International Society of Organic Agriculture Research (ISOFAR)*. Adelaide, Australia, 20–23 Sept.

Purcell, L. C., and C. A. King. 1996. Drought and nitrogen source effects on nitrogen nutrition, seed growth, and yield in soybean. *J Plant Nutr* 19:949–966.

Radosevich, S. R., C. M. Ghersa, and G. Comstock. 1992. Concerns a weed scientist might have about herbicide tolerant crops. *Weed Technol* 6:635–639.

Ragsdale, D., K. Koch, and C. R. Grau. 2008. Secondary effects of fungicides. Pp. 83–85. In A. E. Dorrance, M. A. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Rains, G. C. and D. L. Thomas. 2001. Soil-sampling issues for precision management of crop production. Bull. #1208. University of Georgia Cooperative Extension Service, Athens, http://pubs.caes.uga.edu/caespubs/pubs/PDF/B1208.pdf

Randall, G. W. and J. Vetsch. 2005a. Optimum tillage systems for corn and soybean production and water quality protection in south central Minnesota-Minnesota River Basin. BU-08315. University of Minnesota, St. Paul, http://www.extension.umn.edu/distribution/cropsystems/DC8315.html

Randall, G. W., and J. A. Vetsch. 2005b. Nitrate losses in subsurface drainage from a soybean-corn rotation as affected by fall and spring application of nitrogen and nitrapyrin. *J Environ Qual* 34:590–597.

Randall, G. W., J. A. Vetsch, and J. R. Huffman. 2003. Nitrate losses in subsurface drainage from a soybean-corn rotation as affected by time of nitrogen application and use of nitrapyrin. J Environ Qual 32:1764-1772.

Randall, G. W., D. R. Huggins, M. P. Russelle, D. J. Fuchs, W. W. Nelson, and J. L. Anderson. 1997. Nitrate losses through subsurface tile drainage in conservation reserve program, alfalfa, and row crop systems. *J Environ Qual* 26:1240–1247.

Randall, G. W., T. L. Wagar, N. B. Senjem, L. M. Busman, and J. F. Moncrief. 2002. Tillage best management practices for water quality protection in southeastern Minnesota. WW-07694. University of Minnesota Extension, St. Paul, http://www.extension.umn.edu/distribution/cropsystems/DC7694.html

Rathke, G. W., B. J. Wienhold, W. W. Wilhelm, and W. Diepenbrock. 2007. Tillage and rotation effect on corn-soybean energy balances in eastern Nebraska. *Soil Tillage Res* 97:60–70.

Ray, J. D., L. G. Heatherly, and F. B. Fritschi. 2006. Influence of large amounts of nitrogen on nonirrigated and irrigated soybean. *Crop Sci* 46:52–60.

Reddy, K. N. 2001. Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean. *Weed Technol* 15:660–668.

Reddy, K. N. 2003. Impact of rye cover crop and herbicides on weeds, yield, and net return in narrow-row transgenic and conventional soybean. *Weed Technol* 17:28–35.

Reddy, K. N. and K. Whiting. 2000. Weed control and economic comparisons of glyphosate-resistant, sulfonylurea-tolerant, and conventional soybean (*Glycine max*) systems. *Weed Technol* 14:204–211.

Reddy, K. N., L. G. Heatherly, and A. Blaine. 1999. Weed management. Pp. 171–195. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Reetz, H. 2008. Agrifacts: New ideas and reminders on soil sampling, http://www.back-to-basics.net/agrifacts/pdf/b2b13.pdf (online only)

Rehm, G. W., A. Mallarino, K. Reid, D. Franzen, and J. Lamb. 2001. Soil sampling for variable rate fertilizer and lime application. SB-7647. University of Minnesota Extension, St. Paul, http://www.extension.umn.edu/distribution/cropsystems/DC7647.html

Reinbott, T. M. and D. G. Blevins. 1995. Response of soybean to foliar-applied boron and magnesium and soil-applied boron. *J Plant Nutr* 18:179–200.

Reynolds, D. B., D. L. Jordan, P. R. Vidrine, and J. L. Griffin. 1995. Broadleaf weed control with trifluralin plus flumetsulam in soybean (*Glycine max*). *Weed Technol* 9:446–451.

Rhoton, F. E., M. J. Shipitalo, and D. L. Lindbo. 2002. Runoff and soil loss from midwestern and southeasthern U.S. silt loam soils as affected by tillage practice and soil organic matter content. *Soil Tillage Res* 66:1–11.

Robinson, A. P., S. P. Conley, J. J. Volenec, and J. B. Santini. 2009. Analysis of high yielding, early-planted soybean in Indiana. *Agron J* 101:131–139.

Roder, W., S. C. Mason, M. D. Clegg, and K. R. Kniep. 1989. Yield-soil water relationships in sorghum-soybean cropping systems with different fertilizer regimes. *Agron J* 81:470–475.

Ross, M. A. and C. A. Lembi. 2009. *Applied Weed Science*. 3rd ed. Pearson Prentice Hall, Upper Saddle River, New Jersey.

Rouf Mian, M.A., R. B. Hammond, and S. K. St. Martin. 2008. New plant introductions with resistance to the soybean aphid. *Crop Sci* 48:1055–1061.

Ruffo, M. L., D. G. Bullock, and G. A. Bollero. 2004. Soybean yield as affected by biomass and nitrogen uptake of cereal rye in winter cover crop rotations. *Agron J* 96:800–805.

Rupe, J. C., W. E. Sabbe, R. T. Robbins, and E. E. Gbur, Jr. 1993. Soil and plant factors associated with sudden death syndrome of soybean. *J Prod Agric* 6:218–221.

Sawyer, J. E. 1994. Concepts of variable rate technology with considerations for fertilizer application. *J Prod Agric* 7:195–201.

Scharf, P. C. and W. J. Wiebold. 2003. Soybean yield responds minimally to nitrogen applications in Missouri. 17 Nov, http://www.plantmanagementnetwork.org/pub/cm/research/2003/soy/ (online only; limited access)

Schmidt, J. P., R. K. Taylor, and G. A. Milliken. 2002. Evaluating the potential for site-specific phosphorus application without high-density soil sampling. *Soil Sci Soc Am J* 66:276–283.

Schmitt, M. A., J. A. Lamb, G. W. Randall, J. H. Orf, and G. W. Rehm. 2001. In-season fertilizer nitrogen applications for soybean in Minnesota. *Agron J* 93:983–988.

Schneider, R., E. Sikora, B. Padgett, and G. Sciumbato. 2008. Managing late-season soybean diseases and soybean rust: A southern perspective. Pp. 72–77. In A. E. Dorrance, M. A. Draper, and D. E. Hershman (eds.). *Using Foliar Fungicides to Manage Soybean Rust*. 2nd ed. Bulletin SR-2008. Ohio State University, Columbus, http://oardc.osu.edu/soyrust/

Scribner, E. A., Battaglin, W. A., Gilliom, R. J., and Meyer, M. T. 2007. Concentrations of glyphosate, its degradation product, aminomethylphosphonic acid, and glufosinate in ground- and surface-water, rainfall, and soil samples collected in the United States, 2001-06. *Scientific Investigations Report 2007-5122*. U.S. Dept. of the Interior, U.S. Geological Survey, Reston, Virginia.

Senseman, S. A. 2007. *Herbicide Handbook*. 9th ed. Weed Science Society of America, Lawrence, Kansas.

Serraj, R. and T.R. Sinclair. 2002. Osmolyte accumulation: Can it really help increase crop yield under drought conditions? *Plant, Cell, Environ* 25:333–341.

Shannon, J. G., P. R. Arelli, and L. D. Young. 2004. Breeding for resistance and tolerance. Pp. 157–180. In D. P. Schmitt, J. A. Wrather, and R. D. Riggs (eds.). *Biology and Management of Soybean Cyst Nematode*. 2nd ed. University of Missouri-Delta Center, Portageville.

Shipitalo, M. J., W. M. Edwards, and L. B. Owens. 1997. Herbicide losses in runoff from conservation-tilled watersheds in a corn-soybean rotation. *Soil Sci Am J* 61:267–272.

Simpson, D. M., T. R. Wright, R. S. Chambers, M. A. Peterson, C. Cui, A. E. Robinson, J. S. Richburg, D. C. Ruen, S. Ferguson, B. E. Maddy, and E. F. Schreder. 2008. DowAgroSciences herbicide tolerance traits in corn and soybean. *North Central Weed Science Society Proc* 63:85, http://www.ncwss.org/

Sinclair, J. B., M. Kogan, and M. D. McGlannery. 1997. Guidelines for the integrated pest management of soybean pests. National Soybean Research Laboratory Publication 2. University of Illinois, Urbana-Champaign.

Sinclair, T. R. and M. M. Ludlow. 1986. Influence of soil water supply on the plant water balance of four tropical grain legumes. *Aust J Plant Phys* 13:329–341.

Sinclair, T. R., L. C. Purcell, C. A. King, C. H. Sneller, P. Chen, and V. Vadez. 2007. Drought tolerance and yield increase of soybean resulting from improved symbiotic N_2 fixation. *Field Crops Res* 101:68–71.

Sindhu, A. S., T. R. Maier, M. G. Mitchum, R. S. Hussey, E. L. Davis, and T. J Baum. 2009. Effective and specific in planta RNAi in cyst nematodes: Expression interference of four parasitism genes reduces parasitic success. *J Expt Botany* 60a:315–324.

Singer, J. W. 2008. Corn belt assessment of cover crop management and preferences. *Agron J* 100:1670–1672.

Singer, J. W. and K. A. Kohler. 2005. Rye cover crop management affects grain yield in a soybean-corn rotation. *Crop Mgmt* 24 Feb, http://www.plantmanagementnetwork.org/pub/cm/research/2005/rye/ (online only; limited access)

Singer, J., T. Kaspar, and P. Pedersen. 2005. Small grain cover crops for corn and soybean. PM 1999. Iowa State University Extension, Ames, http://www.extension.iastate.edu/Publications/PM1999.pdf

Singer, J. W., K. A. Kohler, and P. B. McDonald. 2007. Self-seeding winter cereal cover crops in soybean. *Agron J* 99:73–79.

Southeast Farm Press (SEFP). 2009. Researchers identify drought-hardy soybeans. Feb 3, http://southeastfarmpress.com/soybeans/soybean-research-0203/index.html

Spurlock, S. R. 2007. Soybeans 2008 planning budgets. Budget Report 2007-02. Department of Agricultural Economics, Mississippi State University, http://www.agecon.msstate.edu/Research/Budgets/MSUSOY08.pdf

Staggenborg, S. A., K. C. Dhuyvetter, and W. B. Gordon. 2008. Grain sorghum and corn comparisons: Yield, economic, and environmental responses. *Agron J* 100:1600–1604.

Stanger, T. F., J. G. Lauer, and J. P. Chavas. 2008. The profitability and risk of long-term cropping systems featuring different rotations and nitrogen rates. *Agron J* 100:105–113.

Strock, J. S., P. M. Porter, and M. P. Russelle. 2004. Cover cropping to reduce nitrate loss through subsurface drainage in the northern U.S. Corn Belt. *J Environ Qual* 33:1010–1016.

Sullivan, P. 2003. Overview of cover crops and green manures.

Appropriate Technology Transfer for Rural Areas–National Center for Appropriate Technology (ATTRA–NCAT), Fayetteville, Arkansas, http://www.attra.ncat.org/attra-pub/PDF/covercrop.pdf

Swink, S. N., Q. M. Ketterings, and W. J. Cox. 2007. Nitrogen fertilizer replacement value of soybean for corn. *Crop Mgmt* 5 Oct, http://www.plantmanagementnetwork.org/sub/cm/review/2007/replace/replace.pdf (online only; limited access)

Taylor, R. S., D. B. Weaver, C. W. Wood, and E. van Santen. 2005. Nitrogen application increases yield and early dry matter accumulation in late-planted soybean. *Crop Sci* 45:854–858.

Teasdale, J. R., C. B. Coffman, and R. W. Mangum. 2007. Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement. *Agron J* 99:1297–1305.

Teasdale, J. R, R. W. Mangum, J. Radhakrishnan, and M. A. Cavigelli. 2004. Weed seedbank dynamics in three organic farming crop rotations. *Agron J* 96:1429–1435.

Thelen, K. D. and R. H. Leep. 2002. Integrating a double-cropped winter annual forage into a corn-soybean rotation. *Crop Mgmt* 18 Dec, http://www.plantmanagementnetwork.org/pub/cm/research/winterforage/ (online only; limited access)

Thelen, K. D., D. R. Mutch, and T. E. Martin. 2004. Utility of interseeded winter cereal rye in organic soybean production systems. *Agron J* 96:281–284.

Thomas, J. D. and D. J. Boethel. 1994. Synergism of insecticides in tests with resistant soybean looper larvae (*Lepidoptera:Noctuidae*) in the laboratory and field. *J Econ Entomol* 87:1416–1422.

Trewavas, A. 2004. A critical assessment of organic farming-and-food assertions with particular respect to the UK and the potential environmental benefits of no-till agriculture. *Crop Prot* 23:757–781.

Triplett, G. B. and S. M. Dabney. 1999. Soil erosion and soybean production. Pp. 19–39. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

University of Minnesota Extension. 2008. Soybean aphid. In *Minnesota Soybean Production*. St. Paul, http://www.soybeans.umn.edu/crop/insects/aphid/aphid.htm

U.S. Department of Agriculture–Agricultural Marketing Service (USDA–AMS). 2008. National Organic Program. USDA–AMS, Washington, D.C., http://www.ams.usda.gov/nop/indexIE.htm

U.S. Department of Agriculture–Agricultural Marketing Service (USDA–AMS). 2009. Upper Midwest organic grain and feedstuffs report. USDA–AMS, Washington, D.C., http://www.ams.usda.gov/mnreports/nw_gr113.txt

U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS). 1965. Losses in Agriculture. Agricultural Handbook 291. USDA-ARS, Washington, D.C.

U.S. Department of Agriculture–Economics Research Service (USDA–ERS). 2002a. Crop residue management practices, for soybeans, by tillage system, for all available states, for 2002. USDA–ERS, Washington, D.C., http://www.ers.usda.gov/Data/ARMS/app/Crop.aspx

U.S. Department of Agriculture–Economics Research Service (USDA–ERS). 2002b. Manure table, for soybeans, by all acres, for all available states, for 2002. USDA–ERS, Washington, D.C. http://www.ers.usda.gov/Data/ARMS/app/Crop.aspx

U.S. Department of Agriculture–Economic Research Service (USDA–ERS). 2005a. Agricultural chemicals and production technology: Genetically engineered crops. USDA–ERS, Washington, D.C., http://www.ers.usda.gov/Briefing/AgChemicals/geneticengineered.htm

U.S. Department of Agriculture–Economics Research Service (USDA–ERS). 2005b. Organic production. USDA–ERS, Washington, D.C., http://www.ers.usda.gov/data/organic/Data/Beans.xls)

U.S. Department of Agriculture–Economics Research Service (USDA–ERS). 2007a. Agricultural chemicals and production technology: Glossary—crop residue management and tillage definitions. USDA–ERS, Washington, D.C., http://www.ers.usda.gov/Briefing/AgChemicals/glossary.htm

U.S. Department of Agriculture–Economics Research Service (USDA–ERS). 2007b. Soybean production costs and returns per planted acre, excluding government payments, 2006–2007. USDA–ERS, Washington, D.C., http://www.ers.usda.gov/Data/CostsAndReturns/data/current/C-Soyb.xls

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 1996. Agricultural Chemical Use 1995 Field Crops Summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1560

U.S. Department of Agriculture–National Agriculture Statistics Service (USDA–NASS). 2002a. Agricultural Chemical Usage 2001 Field Crops Summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC//2000s/2002/AgriChemUsFC-08-07-2002.pdf

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2002b. Table 33. Specified crops harvested-yield per acre irrigated and nonirrigated: 2002. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/Census/Create_Census_US.jsp

U.S. Department of Agriculture–National Agriculture Statistics Service (USDA–NASS). 2003. Agricultural Chemical Usage 2002 Field Crops Summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC//2000s/2003/AgriChemUsFC-05-14-2003.pdf

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2007. Agricultural Chemical Usage 2006 Field Crops Summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/nass/AgriChemUsFC/2000s/2007/AgricChemUsFC-05-16-2007_revision.pdf

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008a. Quick stats: Agricultural statistics data base. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/QuickStats/

U.S. Department of Agriculture-National Agricultural Service (USDA-NASS). 2008b. Acreage. USDA-NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-30-2008.pdf

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008c. National crop progress. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/Publications/National_Crop_Progress/index.asp

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008d. Agricultural Chemical Usage—Field Crops. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1560

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008e. U.S. and all states data—Crops. Planted, harvested, yield, production, price, and value of production. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/index.asp

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS). 2008f. Land values and cash rents: 2008 summary. USDA–NASS, Washington, D.C., http://usda.mannlib.cornell.edu/usda/current/AgriLandVa/AgriLandVa-08-04-2008.pdf

U.S. Department of Agriculture–National Agriculture Statistics Service (USDA–NASS). 2009. Census of Agricultural Quick Stats. USDA–NASS, Washington, D.C., http://www.nass.usda.gov/index.asp.

U.S. Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS). 2000. Residue management choices: A guide to managing crop residues in corn and soybeans. GWQ029. USDA–NRCS and University of Wisconsin Extension, Madison. http://learningstore.uwex.edu/pdf/GWQ029.pdf

U.S. Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS). 2008. Energy Estimator for Tillage. USDA–NRCS, Washington, D.C., http://ecat.sc.egov.usda.gov/Fuel.aspx

U.S. Department of Agriculture–Office of the Chief Economist (USDA–OCE). 2008. World agricultural supply and demand estimates. WASDE-463. USDA–OCE, Washington, D.C., http://www.usda.gov/oce/commodity/wasde/latest.pdf

VanGessel, M. J. 2001. Glyphosate-resistant horseweed from Delaware. *Weed Sci* 49:703–705.

VanGessel, M. J., A. O. Ayeni, and B. A. Majek. 2000. Optimum glyphosate timing with or without residual herbicides in glyphosate-resistant soybean (*Glycine max*) under full-season conventional tillage. *Weed Technol* 14:140–149.

Varvel, G. E. 1995. Precipitation use efficiency of soybean and grain sorghum in monoculture and rotation. *Soil Sci Soc Am J* 59:527–531.

Varvel, G. E. 2000. Crop rotation and nitrogen effects on normalized grain yields in a long-term study. *Agron J* 92:938–941.

Varvel, G. E. and W. W. Wilhelm. 2003. Soybean nitrogen contribution to corn and sorghum in western Corn Belt rotations. *Agron J* 95:1220–1225.

Varvel, G. E. and W. W. Wilhelm. 2008. Soil carbon levels in irrigated western Corn Belt rotations. *Agron J* 100:1180–1184.

Vetsch, J. A., G. W. Randall, and J. A. Lamb. 2007. Corn and soybean production as affected by tillage system. *Agron J* 99:952–959.

Vidrine, P. R., D. B. Reynolds, and D. C. Blouin. 1995. Grass control in soybean (*Glycine max*) with gaminicides applied alone and in mixtures. *Weed Technol* 9:68–72.

Villamil, M. B., G. A. Bollero, R. G. Darmody, F. W. Simmons, and D. G. Bullock. 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. *Agron J* 70:1936–1944.

Wada, T., N. Endo, and M. Takahashi. 2006. Reducing seed damage by soybean bugs by growing small-seeded soybeans and delaying sowing time. *Crop Protect* 25:726–731.

Walker, D. R., J. N. All, R. M. McPherson, H. R. Boerma, and W. A. Parrott. 2000. Field evaluation of soybean engineered with a synthetic cry1Ac transgene for resistance to corn earworm, soybean looper, velvetbean caterpillar (Lepidoptera: Noctuidae), and lesser cornstalk borer (Lepidoptera: Pyralidae). *J Econ Entomol* 93:613–622.

Watson, S. 2003. Long-term tillage and rotation study: Ashland Bottoms. Kcare environmental news no. 22. June 25, Kansas State University, Manhattan, http://www.oznet.ksu.edu/ctec/newsletter/06_25_03.htm

Weber, C. R. 1966. Nodulating and nonnodulating soybean isolines: ii. Response to applied nitrogen and modified soil conditions. *Agron J* 58:46–49.

Webster, T. M. and H. D. Coble. 1997. Changes in the weed species composition of the southern United States: 1974 to 1995. *Weed Technol* 11:308–317.

"Weeds controlled by fire in niche soybean market." 2004. *Delta Farm Press* June 2, http://deltafarmpress.com/mag/farming_weeds_controlled_fire/index.html

Welch, L. F., L. V. Boone, C. G. Chambliss, A. T. Christiansen, D. L. Mulvaney, M. G. Oldham, and J. W. Pendleton. 1973. Soybean yields with direct and residual nitrogen fertilization. *Agron J* 65:547–550.

Welsh, R. 1999. The economics of organic grain and soybean production in the midwestern United States. Policy Studies Report 13. Henry A. Wallace Institute for Alternative Agriculture, Greenbelt, Maryland.

Wesley, R. A. 1999. Doublecropping wheat and soybeans. Pp. 143–156. In L. G. Heatherly and H. F. Hodges (eds.). *Soybean Production in the Midsouth*. CRC Press, Boca Raton, Florida. 416 pp.

Wesley, R. A., C. D. Elmore, and S. R. Spurlock. 2001. Deep tillage and crop rotation effects on cotton, soybean, and grain sorghum on clayey soils. *Agron J* 93:170–178.

Wesley, T. L., R. E. Lamond, V. L. Martin, and S. R. Duncan. 1998. Effects of late-season nitrogen fertilizer on irrigated soybean yield and composition. *J Prod Agric* 11:331–336.

Westgate, L. R., J. W. Singer, and K. A. Kohler. 2005. Method and timing of rye control affects soybean development and resource utilization. *Agron J* 97:806–816.

Westhoven, A. M., J. M. Stachler, M. M. Loux, and W. G. Johnson. 2008. Management of glyphosate-tolerant common lambsquarters (*Chenopodium album*) in glyphosate-resistant soybean. *Weed Technol* 22:628–634.

Whalon, M. E., D. Mota-Sanchez, R. M. Hollingsworth, and L. Duynslager. 2008. Arthropod Pesticide Resistance Database. Michigan State University Extension, East Lansing, http://www.pesticideresistance.org/

Wiebold, B. and T. Belt. 2006. Effect of rotation on soybean and corn yield planted without tillage. University of Missouri Extension Service, Columbia, http://plantsci.missouri.edu/soyx/research/2006/notill_rotation2006.pdf

Wilhelm, W. W. and C. S. Wortmann. 2004. Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. *Agron J* 96:425–432.

Williams, M. M. II, D. A. Mortensen, and J. W. Doran. 1998. Assessment of weed and crop fitness in cover crop residues for integrated weed management. *Weed Sci* 46:595–603.

Wilson, R. G., S. D. Miller, P. Westra, A. R. Kniss, P. W. Stahlman, G. W. Wicks, and S. D. Kachman. 2007. Glyphosate-induced weed shifts in glyphosate-resistant corn or a rotation of glyphosate-resistant corn, sugarbeet, and spring wheat. *Weed Technol* 21:900–909.

Wollenhaupt, N. C., R. P. Wolkowski, and M. K. Clayton. 1994. Mapping soil test phosphorus and potassium for variable-rate fertilizer application. *J Prod Agric* 7:441–448.

Wortmann, C. S., M. Mamo, and A. Dobermann. 2007. Nitrogen response of grain sorghum in rotation with soybean. *Agron J* 99:808–813.

Wrather, J. A. and S. R. Koenning. 2006. Estimates of disease effects on soybean yields in the United States 2003-2005. *J Nematol* 38:173–180.

Wrather, J. A., S. R. Koenning, and T. R. Anderson. 2003. Effect of diseases on soybean yields in the United States and Ontario (1999–2002). *Plant Health Prog* 4 March, http://www.plantmanagementnetwork.org/pub/php/review/2003/soybean/ (online only; limited access)

Wrather, J. A., L. E. Sweets, and W. J. Wiebold. 2008. Soybean disease management. Publ. G0442. University of Missouri Agric. Exp. Sta., Columbia, http://aes.missouri.edu/delta/muguide/g4452.stm

Yamoah, C. F., M. D. Clegg, and C. A. Francis. 1998. Rotation effect on sorghum response to nitrogen fertilizer under different rainfall and temperature environments. *Ag Ecosys Environ* 68:233–243.

Yin, X. and T. J. Vyn. 2002. Soybean responses to potassium placement and tillage alternatives following no-till. *Agron J* 94:1367–1374.

Yiridoe, E. K., T. J. Vyn, A. Weersink, D. C. Hooker, and C. Swanton. 2000. Farm-level profitability analysis of alternative tillage systems on clay soils. *Can J Plant Sci* 80:65–73.

Young, B. G. 2006. Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301-307.

Young, B. G., K. L. Schmoll, R. W. Steffen, and W. Moon. 2003. Survey of herbicide drift in Illinois. *Abst Weed Sci Soc Amer* 43:66–67.

Zehnder, G., G. M. Gurr, S. Kuhne, M. R. Wade, S. D. Wratten, and E. Wyss. 2007. Arthropod pest management in organic crops. *Ann Rev Entomol* 52:57–80.

Zhu, Y. and R. H. Fox. 2003. Corn-soybean rotation effects on nitrate leaching. *Agron J* 95:1028–1033.

Index