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ORIGINAL PAPER

Crops that feed the World 2. Soybean—worldwide production, use, and constraints caused by pathogens and pests

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Abstract The soybean crop is one of the most important crops worldwide. Soybean seeds are important for both protein meal and vegetable oil. The crop is grown on an estimated 6% of the world's arable land, and since the 1970s, the area in soybean production has the highest percentage increase compared to any other major crop. Recent increases in production coincide with increases in demand for meal and oil. Soybean production was 17 million metric tons (MMT) in 1960 and increased to 230 MMT in 2008. Future soybean production is expected to increase more than other crops, due to expanded production area and higher yields. There are a number of important abiotic and biotic constraints that threaten soybean production by directly reducing seed yields and/or seed quality. Abiotic constraints include extremes in nutrients, temperatures and moisture. These may reduce production directly, but also indirectly through increases in pathogens and pests. Biotic constraints tend to be geographically and environmentally restricted. Some diseases like soybean rust may be explosive by producing copious amounts of air-borne spores. This disease, more so than most, caused great concern when first found invading soybean production areas in Brazil and the United States of America. In contrast, red leaf blotch is a disease restricted to a few countries in Africa, but deserving attention since it has not been intensely studied and adequate management strategies, such as the use of resistant varieties, are not available. Significant losses in soybean yield beyond current levels may have implications for food security because of our dependence on the soybean crop, directly and indirectly for food products. In addition, because the crop is highly nutritious and versatile it offers resources to address world food issues through current and future utilization practices. Future soybean production is expected to increase in proportion to increased demand, and with application of newer genomic technologies, the crop has enormous potential to improve dietary quality for people throughout the world whether consumed as a vegetable crop or processed into various soybean food products.

Keywords Soybean · Soybean production · Abiotic and biotic constraints

Introduction

The soybean story is a long and interesting one that is full of dualities: Eastern Hemisphere (origin of soybean) and Western Hemisphere (introduced crop), industrial scale and small-scale production, pesticides and organic production, oil and protein, exports and imports, industrial products and consumables, biofuels and food uses, animal feed and human food, whole beans and processed products, traditional and modern foods, and whole food nutrition and isolated botanical nutraceuticals. Soybean has risen to one of the top-traded commodities, with a multitude of uses. This paper highlights the value of the soybean crop to world food security by first reviewing its history, current worldwide production, the many uses of the crop, and then reviewing, by example, the threats posed to the crop by

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some selected pathogens and pests. We conclude with a discussion on future considerations.

History

One of the first thorough reviews of the origin and history on the domestication of the soybean was by Hymowitz (1970), which has recently been updated (Hymowitz 2008; Qiu and Chang 2010). An extensive searchable collection of soybean history, uses, and bibliographies has also been compiled by the Soyinfo Center (www.soyinfocenter.com). Considering the vast history of this crop, intertwined with humans for so long in various ways, what follows is a brief synopsis.

Legends exist claiming use of domesticated soybeans as early as 2500–2300 B.C., though the first historical evidence places the emergence of soybean as a food crop in Northeastern China around 1700–1100 B.C. Whole beans were cooked or fermented into a paste and used in various dishes. By the 16th century A.D., soybeans were used in Burma, India, Indonesia, Korea, Japan, Malaysia, Nepal, the Philippines, Thailand, and Vietnam. The first record of soybeans in Europe was in Linnaeus's *Hortus Cliffortianus* completed in 1737. Soybeans were grown for ornamental purposes in France in 1739 and England in 1790. In 1804, a planting of soybeans in Yugoslavia was used as a supplement in animal feed. The first documentation of soybean usage in the USA dates back to 1765 in the present-day state of Georgia. Soybeans were grown and processed to make products for export, such as margarine or shortening, which had gained popularity in Europe and the USA. Soybeans continued to be used in the western hemisphere for vegetable oil, primarily in the manufacturing of processed food products, though many investigators championed the crop as a solution for human food needs and tested the crop for that purpose (Lennox 1942). In 1917 came the discovery that heating soybean meal made it suitable as livestock feed, which led to the growth of the soybean processing industry and the dual-purpose protein and oil crop of today. After that time, the USA expanded its production and by the 1970s supplied two thirds of the world's soybean needs. The expansion of the crop to South America resulted in the emergence of Brazil and Argentina as the second and third most important soybean-producing countries, respectively, in the world.

The USA, Brazil, and Argentina now dominate global soybean production. These three countries harvested 81% of the world production in 2006 (Fig. 1; FAOstat, faostat.fao.org). Compared to other major food crops, soybean has experienced the highest percentage of yearly increases in production area over the last 40 years, up from 29 million ha in 1968 to 97 million ha in 2008 (Fig. 2). This represents about 6% of the world's arable land, but still trails wheat, rice, and maize in world production area (Fig. 2). China has steadily decreased in importance as a world producer of soybean despite being the country that domesticated soybean and continued high consumption. However, several South American countries show very rapid growth and if this expansion continues, Brazil could overtake the USA as the world production leader. Compared to other crops, soybeans are the third most heavily traded crop with almost 75 MMT traded in 2007 (Fig. 3). As demand continues to rise, soybean production area and soybean trade are likely to increase more rapidly than most other major crops. Most exports of soybean originate in South American countries, followed by the USA; China is the primary importer followed by the European Union (Fig. 4). While much of the soybean grown in the USA (and virtually all soybean grown in China) is used domestically, the vast majority of soybeans grown in South America are exported to China.

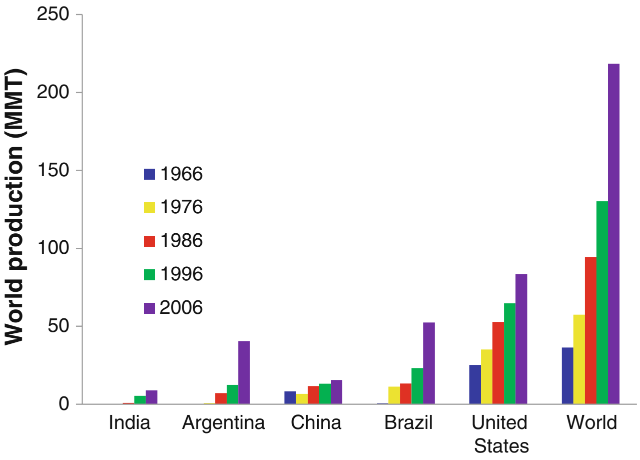

Fig. 1 Volume of soybean production in the highest soybean producing countries and total world production in million metric tonnes (MMT) from 1966 to 2006. From FAO statistics

The multiple uses of soybean

Today, most of the world's soybeans are processed or crushed into soybean meal and oil (Ali 2010). It is estimated that 2% of soybean production is consumed by humans directly as food (Goldsmith 2008), which amounts to an estimated 3 MMT.

Soybean seeds contain about 18% oil and 38% protein. Of the oil fraction, 95% is consumed as edible oil with the rest used for industrial products from cosmetics and hygiene products to paint removers and plastics (Liu 2008). Due to its high protein level, about 98% of the soybean meal is used in livestock and aquaculture feeds. A smaller percentage is processed to make soy flour and protein for human consumption. An even smaller percentage is used as a fresh vegetable known as "mao dou" in China, "edamame" in Japan, and green vegetable soybean or edamame in the USA

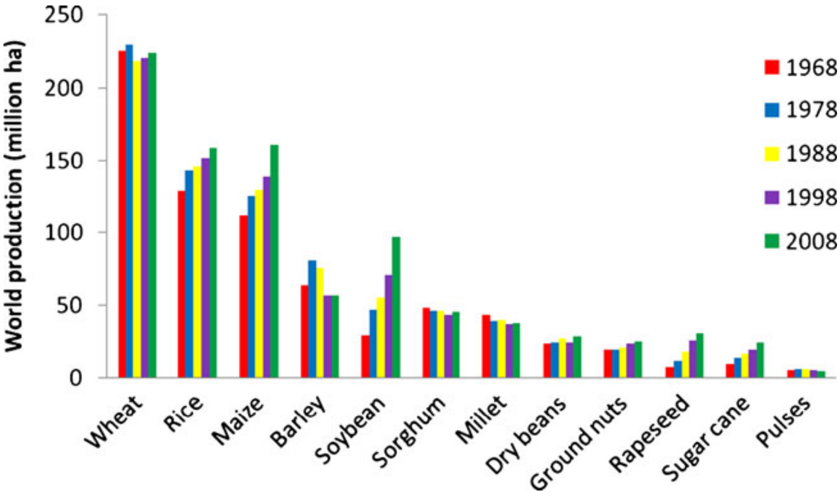

Fig. 2 Production area of the major field crops in hectares (ha) from 1968 to 2008. From FAO statistics

and other countries (Shanmugasundaram and Yan 2010). The vegetable soybean seeds are higher in sucrose, comparable in protein and lower in tocopherols than grain soybeans, and are higher in protein and lower in sucrose compared to green peas. The immature seeds (still green) are blanched, boiled or steamed and eaten in a number of different ways including as a side dish to mix with other foods. The soybean edamame types are selected or bred large-seeded, sweet tasting varieties that are now grown in vegetable gardens in many parts of the world.

Soybean oil is used in making numerous processed food products like margarine and in preparation of fried foods. Consumption of soybean oil increased dramatically with the realization of the link between animal fats and cardiovascular disease. In order to have stable flavor and freshness for use as commercial oil, soybean oil was hydrogenated. However, awareness in recent years of the detrimental effects of transfats initiated the development of new soybean varieties with lower linolenic content that are more stable without hydrogenation. Linolenic acid is an omega-3 polyunsaturated fatty acid that humans must obtain from food. Soybean varieties with high oleic acid, up to 80% of the oil content, have been developed recently, but commercially are not widely available.

Soybeans are unique among crop plants in that they supply protein equal in quality to that of animal sources. For this reason, soybeans have long been consumed in Asia as a primary source of protein in such traditional foods as tofu, soymilk, tempeh, natto, sprouts, green vegetable soybeans, and many others (www.soyinfocenter.com). In recent years, many of these foods have greatly increased in popularity outside of Asia, while advances in food

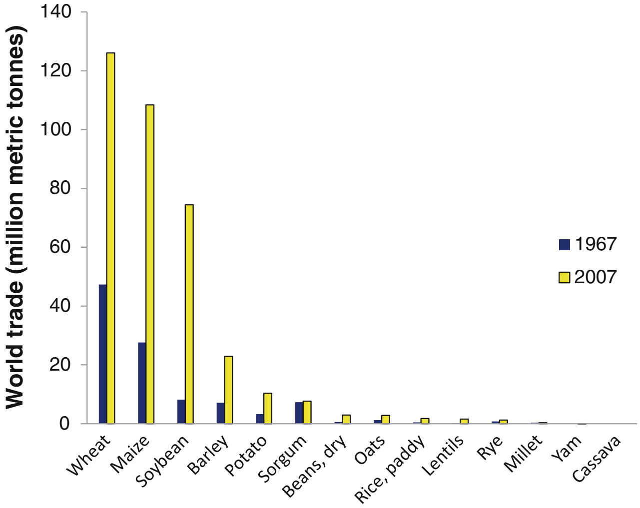

Fig. 3 Trade quantity showing import and exports of the world's major food crops in 1967 and 2007. From FAO statistics

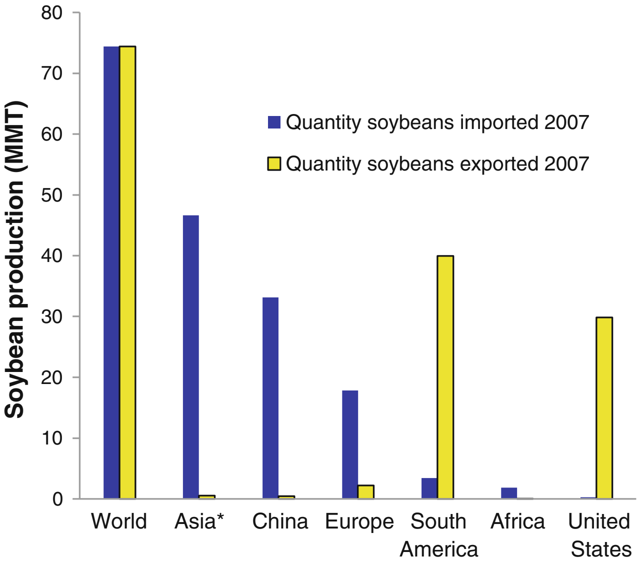

Fig. 4 Trade in million metric tonnes (MMT) of imports and exports of soybeans by region in 2007. Data for Asia includes China. From FAO statistics

technology have made it possible to use soybean in new ways, creating foods that are familiar to consumers but that contain soybean for nutritional purposes. Soybean-based dairy analogs are increasingly popular substitutes for individuals with dairy allergies or with preferences for a vegan diet. High-protein soybean flour enhances a variety of foods, including baked goods, snack bars, noodles, and infant formula. Soy protein is a primary component in meat analogues consumed by people who prefer foods that are animal-free or lower in saturated fat.

There are many functional components in soybeans, and long before the development of the nutraceutical industry in the West, soybeans were considered to have medicinal value (Raghuvansh and Bisht 2010). In ancient China, soybeans were used as a preventive medicine. The famous *Materia Medica*, *Pen Ts'ao Kang Mu*, written by Li Shih-Chen in 1596, describes soybean consumption as important for the proper functioning of many organs and as a purifying food. Fresh green soybeans and black soybeans were each ascribed a number of medicinal properties with the latter still widely used today by Chinese doctors for maintaining health. Recent studies have confirmed in part some of the ancient health claims for soybeans, such as: dietary supplements for diabetics (Azadbakht et al. 2003; Villegas et al. 2008); use in weight loss (Maskarinec et al. 2008); aiding women suffering bone loss (Chen et al. 2003); lowering cancer risks (Guo et al. 2004; Hamilton-Reeves et al. 2007); reducing cholesterol (Rosell et al. 2004); and increasing iron in the blood (Murray-Kolb et al. 2003). In 1999, the U.S. Food and Drug Administration approved a health claim stating that consuming 25 g of soy protein a day as part of a diet low in saturated fat and cholesterol may reduce the risk of heart disease. This further advanced consumer interest and provided industry with the impetus to develop foods containing soybeans.

Soybeans are a rich source of nutraceuticals including but not limited to bioflavanoids, lecithins, oligosachharides, phytosterols, saponins, and tocopherols. An important group within the bioflavonoids are the isoflavones, which have been shown to benefit human health (Kumar et al. 1996). In support of the use of soybean as a nutraceutical, the “9th International Symposium on the Role of Soybean in Health Promotion and Chronic Disease Prevention” (www.soysymposium.org/) provides a forum on various topics including whether and how phytoestrogens from soybeans affect various human tissues, influence gene expression or other cellular processes, increase or decrease the growth and metastasis of breast cancer tumors, influence bone loss or alter the rate of cognitive decline in aging and how the various compounds are utilized in the body.

In conclusion, whether for oil, protein, whole food or a functional component, soybeans play an important role in the diet of humans worldwide, and have the potential to nourish people in the near and distant future. Whether or not this potential is realized will depend upon several factors. Some of the obstacles and challenges that hinder soybean production are discussed below as specific examples of diseases and pests that pose threats to production.

Challenges and threats to production

The challenges growers face in crop production, including unpredictable weather, diseases, pests, weeds and variable soil quality were previously reviewed (Lal 2009; Strange and Scott 2005). Soybean is affected by all of these variables. Researchers and growers work together on each of these challenges to improve and ensure the quantity and quality of soybean production. Some strategies for increasing yields include the use of fertilizers and pesticides, while others involve developing new plant varieties that best suit the needs of the farmers. In soybean, localized variety development is important so that growers use varieties that are well adapted to local conditions such as weather, preferred agronomic practices and photoperiod (Panthee 2010). However, increases in crop production due to varietal improvements are often offset by constraints caused by broadly categorized abiotic and/or biotic factors.

Abiotic constraints

Abiotic constraints affecting soybean production are those caused by the physical environment. This includes weather-related phenomena, soil nutrient availability, salinity, and response to photoperiod. Farming practices may control some of these abiotic constraints, but many, such as drought, flooding, and frost, have few if any remedies.

In more arid climates, drought can reduce both vegetative growth and time to maturation, causing fewer pods to form with fewer and/or smaller seeds per pod. In parts of the world, including the southeastern USA, drought can be the primary cause of yield loss (Hufstetler et al. 2007). Irrigation may prevent such losses in drought years, but water availability and the expense of installing and maintaining irrigation equipment may be limiting. Flooding can also be problematic, as soybean cannot survive many days with fully submerged roots (Oosterhuis et al. 1989). If plants do survive, development and seed production may be decreased, resulting in significant yield loss when plants either die or exert energy rebuilding damaged root systems rather than producing vegetative growth and pods. Fields with good drainage are less susceptible to flooding, but given enough rain, most crops will suffer water damage. In addition, soybeans are particularly susceptible to frost and will be damaged when temperatures are below freezing (Meyer and Badaruddin 2001). A killing frost can occur in many temperate climates either soon after emergence or before the plants fully mature towards the end of the growing season. There is no treatment for frost-damaged plants, although early season damage can, in part, be remedied by replanting.

Another abiotic constraint is nutrient availability in the soil; soybeans need a proper supply of soil nutrients to grow to full potential. Fertilizers can be applied where nutrient levels of fields are low, and other sustainable practices like proper crop rotation, tillage treatments, and soil amendments, also may help in producing a healthy crop. Soybeans are sensitive to high soil salinity, and in some locations this can be a constraint resulting in poor root development, leaf chlorosis, and reduced plant vigor and yield (Katerji et al. 2003).

Growth and flowering in soybean is regulated by photoperiod (Zhang et al. 2001). Maturity is an important trait for breeding programs (Orf 2008). In the USA, there are 13 recognized soybean maturity groups (MG) ranging from 000 to X. Varieties that grow well in the northernmost growing regions (northern USA) are designated as MG 000 and those that achieve optimum production closer to the equator are designated as MG X, with the rest of the range of MGs occurring in between. Photoperiodic response is the most important factor separating cultivars into various MGs. If seeds from a MG 000 variety were sown in a zone with a shorter photoperiod, the resulting plants would flower very early when still small, resulting in low yield. Conversely, if seeds from a MG X variety were sown in a zone with a longer photoperiod, the resulting plants would continue in vegetative growth, resulting in large plants that may not flower or produce seed before they were killed by frost.

Finally, global climate change will have a major impact on agriculture as new weather patterns emerge causing shifts in temperatures and rainfall that will affect agroecological zones (Nelson 2009). Some changes like increased levels of CO_2 may increase the photosynthetic productivity of crops (Cure and Acock 1986; Mendelsohn et al. 1994), and specifically may decrease or increase the importance of some diseases (Eastburn et al. 2010). Other changes like temperature and rainfall extremes are less positive and will have direct and indirect effects on plant productivity as shown on soybeans in China (Zheng et al. 2009), and major food crops worldwide (Lobell and Field 2007). A three-year study of soybeans exposed to elevated levels of CO_2 found a decrease in soil organic matter in all plots and an increase in soil organic turnover, which may have long-term implications for soil productivity (Peralta and Wander 2008).

Biotic constraints

Biotic constraints, such as pathogens, pests and weeds, can be detrimental to soybean production and result in significant negative impacts on yield. Though weeds are known to be a major detrimental factor, especially considering the resistance found in some weed species to glyphosate (Powles 2010), they are beyond the scope of our review. Rather, this section focuses on a number of economically important pathogens and pests, including one, soybean rust, recently introduced into major soybean producing regions and another, red leaf blotch, that is considered a threat, but has yet to occur in any major soybean-producing region outside of Africa.

The increased importance and knowledge of soybean pathogens becomes apparent when one compares information contained in the first *Soybean Disease Compendium* (Sinclair and Shurtleff 1975), covering 50 diseases, to the latest edition of this book that lists more than 300 diseases (Hartman et al. 1999). Some of the more important diseases have recently been reviewed (Grau et al. 2004; Hartman and Hill 2010). The increase in number of diseases and their expansion are the result of intense production and increased acreage in new regions of the world. In production areas where soybean is grown every year or even every other year, propagules of various types produced by pathogens have increased to densities that cause economic yield losses. Parasitic micro-organisms, such as bacteria, fungi, nematodes, Oomycetes, and viruses all contribute to economic damage caused to soybeans each year. A similar story occurs for soybean pests as well; many pests such as aphids, beetles, mites, and stinkbugs cause considerable economic damage to the soybean crop (O'Neal and Johnson 2010).

Pathogens and pests of soybean infect and/or attack all parts of the plants from roots to seeds. The extent of economic plant damage depends upon the type of pathogen/pest, plant tissue being attacked, number of plants affected, severity of attack, environmental conditions, host plant susceptibility, plant stress level, and stage of plant development (Hartman and Hill 2010). Losses due to diseases are estimated at 11% (Hartman et al. 1999), although these estimates may not be very precise because of the lack of data comparing severity yield losses, and to the lack of worldwide monitoring of disease and pest outbreaks. To successfully reduce losses due to pathogens and pests, a number of practices used alone or in combination may needed. These would include cultural and seed sanitation techniques, pesticide applications, and deployment of resistance (Hartman and Hill 2010).

Soybean rust

Soybean rust, caused by *Phakopsora pachyrhizi*, is a major disease limiting soybean production in many areas of the world. The pathogen primarily infects leaves causing small lesions, usually 2–5 mm in diameter, from which uredinia develop that produce copious numbers of urediniospores

(Fig. 5). Yield losses of up to 80% have been reported in experimental plots in Taiwan (Hartman et al. 1991). Recent experiments in southern Africa, South America, and the USA have shown yield losses of up to 55% (Miles et al. 2007; Mueller et al. 2009). Rust has the potential to cause major losses in most soybean producing countries in the world if left unchecked.

The pathogen was first described in Japan in 1902 as a pathogen of yam bean (*Pachyrhizus ahipa*) (Hennings 1903). For almost 100 years, the disease was limited to countries in the Eastern Hemisphere (Hartman et al. 1999). By 1994, the disease had moved beyond the Eastern Hemisphere and was reported in Hawaii (Killgore and Heu 1994). In addition, many new reports came from countries in Africa from 1996 to 2001 (Levy 2005). In 2001, rust was discovered in the Parana River basin of Paraguay. By 2002, the pathogen had spread throughout Paraguay and into nearby areas of Brazil, causing severe rust in both countries (Yorinori et al. 2005). In 2004, *P. pachyrhizi* was found in the state of Louisiana in the continental USA (Schneider et al. 2005). In the USA, the rust pathogen over winters in frost-free or nearly frost-free areas on host plants like kudzu, moving back to soybeans planted in southern states the following spring. Over the course of the growing season, soybean rust gradually spreads from south to north infecting kudzu and soybeans. In some years the disease has spread from the gulf-coast states to the main USA soybean production regions such as Illinois, Iowa, and even into Canada, and as far west as Nebraska (www.sbrusa.net), though this has occurred primarily on late-planted double-cropped soybeans.

Fig. 5 Soybean rust (*Phakopsora pachyrhizi*) lesions on soybean leaves

Other hosts, called bridge or alternative hosts, are important for *P. pachyrhizi* as they provide the fungus with an expanded geographic range and/or allow it to over-season while the annual soybean crop is unavailable. The pathogen has only been reported on plants in the subfamily Papilionoideae within the Fabaceae family. Prior to the introduction of *P. pachyrhizi* to North America in 2004, the fungus was reported on 93 hosts in 42 genera (Ono et al. 1992). A number of new hosts were reported in 2008, including 75 species representing 12 genera (Slaminko et al. 2008a, b), bringing the host number to approximately 160 species in 53 genera.

Studies on soybean rust management began over 50 years ago. A review and a number of recent studies have shown the success of using fungicides to control soybean rust (Miles et al. 2007; Mueller et al. 2009; Miles et al. 2003). Although the use of fungicides to manage soybean rust has not been intensive in the USA, it has been in Brazil where a large percentage of the crop has been treated with fungicides, often more than once per season, since 2003.

Although fungicides have been effective in managing soybean rust, another approach to manage rust is through host plant resistance. A number of recent studies mapped pathotype-specific genes for resistance to soybean rust to five loci (Garcia et al. 2008; Hyten et al. 2009; Hyten et al. 2007; Silva et al. 2008). Effectiveness of pathotype-specific resistance genes has been short-lived, as all of the known single dominant genes have been overcome by at least some isolates of *P. pachyrhizi* (Bonde et al. 2006; Paul and Hartman 2009; Pham et al. 2009). There are other approaches that differ from pathotype-specific resistance, including the use of partial resistance or tolerance; both of which were reviewed (Hartman et al. 2005), but are currently not used in breeding because of the lack of markers associated with these traits. To continue managing soybean rust with plant resistance, all three of these approaches, single gene, partial resistance, and tolerance, need to be pursued along with new biotechnological approaches.

New approaches to manage soybean rust include the use of non-host resistance or engineered disease resistance via plant transformation. There are several examples of engineered resistance in other crops (Collinge et al. 2008). Although genetically engineered rust resistance has not been accomplished in soybean, potential novel genes were found through transcriptome analysis in *Glycine tomentella*, a wild perennial relative of soybean (Soria-Guerra et al. 2010). Resistance genes from this species and/or other species may provide new stable resistance genes to combat soybean rust. Whether through traditional approaches or genetically engineered resistance, results are likely to be produced that assist in the long-term management of soybean rust.

Sclerotinia stem rot

The fungus, *Sclerotinia sclerotiorum*, causes wilt and death of plants or portions of plants. Lesions can girdle the stem and block vascular flow limiting pod and seed development (Fig. 6). Any part of the plant that comes in contact with infected tissue can also become infected. The diagnostic feature of Sclerotinia stem rot includes the white, cottony mycelia present on infected plant parts; shredded and bleached petioles and stems, and large, black, irregular-shaped sclerotia in or associated with the infected tissue. Yield losses in soybean can be substantial, and were shown to range from 0 to nearly 100% depending upon the level of infection (Hoffman et al. 1998).

Although restricted to geographic areas with cooler growing conditions, Sclerotinia stem rot is distributed worldwide and has a broad host range including numerous dicotyledonous plants such as beans, canola, and sunflowers (Hartman et al. 1999). Optimum environmental conditions for disease development are cool and moist. Ascospores that are borne in apothecia arising from sclerotia are forcibly ejected into the air. The spores that land on senescing flowers will then germinate and produce oxalic acid which causes live tissue to die, allowing colonization by the fungus. Sclerotia are dark melanized structures that overwinter in the soil or plant debris. The pathogen can infect seed and infest seed lots (Hartman et al. 1998), thereby expanding its distribution beyond local ascospore showers.

Management of this disease can only be partially achieved through fungicides and partial resistance. Proper timing of fungicide application before peak vulnerability of blossoms has provided protection against *S. sclerotiorum* in potato (Johnson and Atallah 2006) and peanut (Smith et al. 2008), and in soybean when inoculum levels were low (Mueller et al. 2002). Partial resistance to Sclerotinia stem rot exists (Diers et al. 2006), but is not widely deployed in commercial cultivars. Several quantitative trait loci (QTLs) that control partial resistance to the disease have been mapped in the soybean genome (Guo et al. 2008; Zhao et al. 2006; Vuong et al. 2008). With the sequencing of the soybean genome completed, new approaches to control Sclerotinia stem rot, including genetic engineering, have the potential to provide higher levels of resistance to the disease in the future (Dickman 2007; Lu 2003). In addition, detoxification of oxalic acid has been successful in limiting disease development in canola (Dong et al. 2008), and now more recently in transformed soybeans expressing an oxalate carboxylase gene (Cunha et al. 2010).

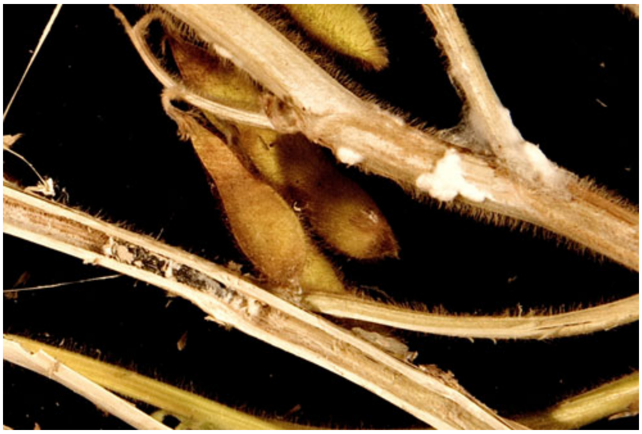

Fig. 6 Sclerotinia stem rot (*Sclerotinia sclerotiorum*) on soybean stems. Note fungal sclerotia in pith of the split stems

Red leaf blotch

There are only a few known soybean diseases not found in the major soybean producing countries. One of these that deserves mention is red leaf blotch, caused by the fungal pathogen *Phoma glycinicola* (Boerema et al. 2004) formerly known as *Dactuliochaeata glycines* (Hartman and Sinclair 1988). Symptoms of red leaf blotch include lesions on foliage, petioles, pods, and stems (Hartman et al. 1987). Lesions expand and coalesce to form large necrotic blotches up to 2 cm in diameter (Fig. 7). Heavily diseased plants defoliate and senesce prematurely. Within older lesions, sclerotia develop primarily on the lower leaf surface while pycnidia develop primarily on the upper surface. The fungus appears not to be seedborne, but may be transported along with soil and other debris in grain. Yield losses of up to 50% were documented in Zambia and Zimbabwe in the 1980s (Hartman and Sinclair 1996). Although the disease has only been reported in Africa, if the pathogen were introduced into major soybean producing countries, losses could become substantial, as resistance to this disease is not known.

The fungus produces well-defined melanized sclerotia that can either germinate to form infectious mycelia, or produce pycnidial structures on the outer surface that produce infectious conidia (Hartman and Sinclair 1992). Because the fungus is not seedborne and trade of soybeans out of Africa is limited, the pathogen has not spread to new locations. Unlike *P. pachyrhizi*, it does not produce copious amounts of airborne spores. Rain-splashed conidia spread the pathogen, with additional dispersal caused by other abiotic factors such as wind, or attachment to tools or clothing, and by other biotic factors that may include animals. The pathogen would most likely survive and overseason in any of the yet unaffected production regions, whether introduced as sclerotia, or possibly pycnidia, in infected plant debris and/or soil.

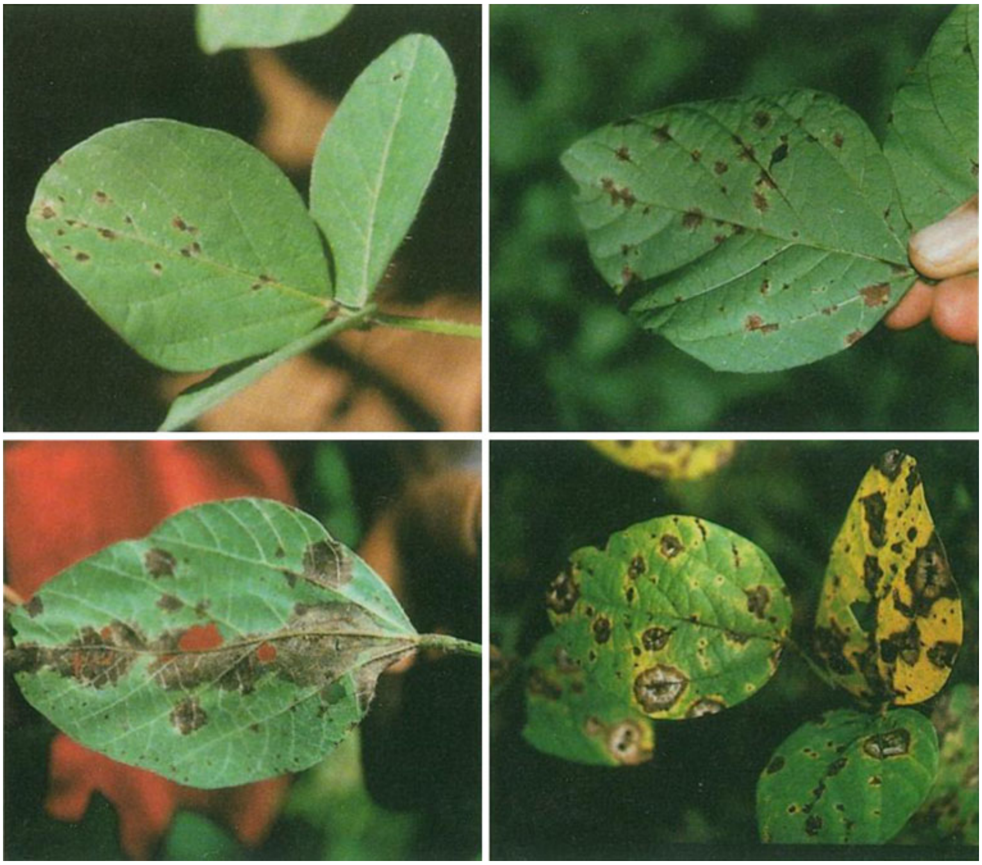

Fig. 7 Red leaf blotch (*Phoma glycinicola*) showing a progression of symptoms on soybean leaves from low severity (upper left and right) to an increase in severity (lower left and right)

Because red leaf blotch is not a well-known disease, there is a need to develop educational materials to broaden awareness of this disease among producers and crop specialists. This may result in quicker detection and limited spread should the disease become transported to a new geographical location. More research is needed on developing molecular diagnostic techniques to identify *P. glycinicola* from other common foliar soybean pathogens, providing better information on fungicide chemistry and application timing, developing varietal resistance, and gathering more data for developing predictive models for potential containment and management. In the USA, primarily because of the value of the soybean crop and the perceived threat of this pathogen to cause economic yield losses, a recovery plan through the USDA-APHIS program was developed which outlines a course of action to follow should the pathogen ever be discovered in the country (Hartman et al. 2009).

Soybean cyst

Soybean cyst, caused by the plant parasitic nematode *Heterodera glycines*, occurs in most soybean growing regions (Hartman et al. 1999). Symptoms on the root system range from slight discoloration to severe necrosis. Diagnosis is confirmed when white or yellow females are observed attached to roots. Above ground symptoms, often not readily apparent, include slight to severe plant stunting and leaf chlorosis. Symptoms may be enhanced or repressed in association with other pathogens (Gao et al. 2006). The importance of this disease is probably underrated, as obtaining information on severity of infestation and relating that to yield losses is difficult; however, soybean cyst currently is the most important disease in the USA.

The pathogen most likely evolved or co-evolved with soybeans or related legumes in Asia and was first reported in the USA in 1954 (Riggs 2004). *H. glycines* is a sedentary root endoparasite that invades the root and partially redirects root cell functions to satisfy its nutritional demands for development and reproduction (Riggs 2004). Inside each cyst are 50–200 eggs which hatch into second-stage juveniles, equipped with robust stylets that allow them to invade soybean roots. Once mature, the nematodes form cysts that are durable and survive long periods in the soil. Cysts can be disseminated by water, wind, soil peds mixed in seed, and machinery (Fig. 8). Pathogenicity of the nematode is highly variable and a number of pathotypes have been identified based on their ability to reproduce on a set of soybean differentials (Niblack et al. 2008; Niblack and Riggs 2004). During the growing season, soybean cyst nematodes reproduce up to four generations in warmer climates and as few as two in cooler climates.

The most effective and common means of management includes host resistance and crop rotation (Niblack and Chen

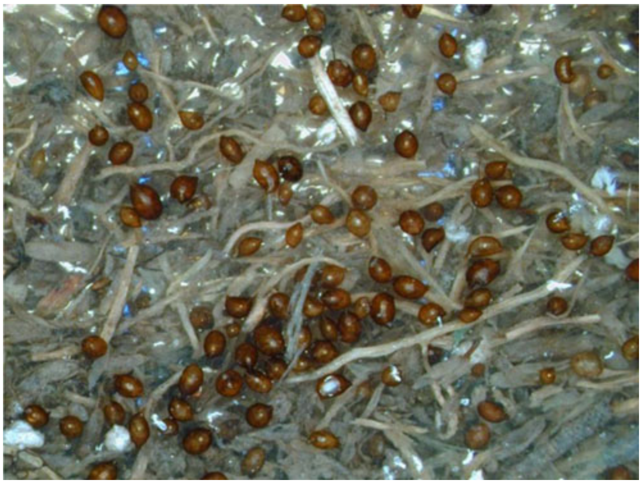

Fig. 8 Soybean cyst nematode (*Heterodera glycines*) cysts mixed with soybean roots

2004; Schmitt et al. 2004). Complete resistance has not been found, and currently deployed resistance genes have not proved to be durable over time due to their being overcome by adaptation of populations of *H. glycines*. Gene rotation, along with crop rotation, may improve durability of resistance. Novel approaches using genetic engineering such as RNA interference technology (Widholm et al. 2010), may prove to be effective in the future.

Soybean aphid

The soybean aphid (*Aphis glycines*), a native to Asia, was first observed in the USA in 2000 (Ragsdale et al. 2004). Since its introduction into the USA, it has spread throughout the midwestern USA and southern Canada (Venette and Ragsdale 2004), but is not known in South America. *Rhamnus cathartica* (buckthorn) is the primary over-wintering host. Soybean is the most important secondary or summer host (Hill et al. 2004a).

The soybean aphid (Fig. 9) causes stunting, leaf distortion, and reduced pod set (Hartman et al. 2001; Hill et al. 2004a). An additional threat posed by the soybean aphid is its ability to transmit soybean viruses (Domier et al. 2003). Honeydew excreted by soybean aphids onto leaves leads to the development of sooty mold that restricts photosynthesis (Hartman et al. 2001). A recent economic analysis of the impact of the soybean aphid on soybean production predicted that, without effective plant resistance, US$3.6 to $4.9 billion in soybean production could be lost annually depending upon the cost of insecticide applications, the size of the aphid outbreak, and the price elasticity of soybean supply (Kim et al. 2008).

Insecticides, if properly timed, can provide some level of protection against the loss of yield, although plant resistance may be more effective and environmentally acceptable. Plant resistance to the soybean aphid was discovered in soybean germplasm in 2004 (Hill et al. 2004b). Resistance was described as strong antibiosis that limited aphid colonization on plants in non-choice tests and reduced aphid survival, longevity, fecundity, and development of nymphs (Li et al. 2004). The first aphid resistance was shown to be controlled by a single dominant gene named *Rag1* (Hill et al. 2006) and was subsequently mapped (Li et al. 2007). Another resistance gene that was named *Rag2* was identified and mapped as well (Hill et al. 2009).

No biotypes of the soybean aphid were known until recently when an isolate was reported to colonize plants with *Rag1* (Kim et al. 2008). More recently, another isolate was reported to colonize plants with the *Rag2*, distinguishing it from the two previously characterized biotypes (Hill et al. 2010). The identification of soybean aphid biotypes that can overcome *Rag1* and *Rag2* resistance suggests that there is variability in virulence within soybean aphid populations present in North America that may allow the aphid to adapt and potentially reduce the effectiveness of resistance genes deployed in production. The search for new soybean aphid resistance genes must continue along with development of alternative sustainable strategies to manage the pest. New sources of resistance will be needed to offset aphid adaptation to host resistance genes whether these come from traditional or bioengineering approaches.

Discussion and future considerations

Soybeans, consumed directly or indirectly, will play a major role in our continued quest to feed people. Production and consumption of the crop will increase as the world population grows from 6 billion people today to an estimated 8.3 billion people in 2030. Production increases will come from both increased production area and yield. The greatest potential for

Fig. 9 Soybean aphid (*Aphis glycines*) colonizing soybean stems

expansion of production area is in Brazil, but other countries in South America and parts of sub-Saharan Africa, also show potential for increase. Increased land use devoted to growing soybeans in other parts of the world may be at the expense of other crops, but may be justified because of the potential high nutritional value of the soybean crop. As production increases globally, it is likely that soybeans will advance from the third most highly traded food crop in the world to the mostly highly traded food commodity.

Along with the future increase in production area, increased yield will come from both better agronomic practices and genetic improvements. These genetic improvements, both traditional and bioengineered, will be instrumental in boosting the management of abiotic and biotic constraints through better levels of tolerance to moisture stresses, pH, fertility-depleted soil, temperature extremes, and increased resistance to diseases and pests. Improvements in soybean varieties will help adapt soybean to underutilized areas like sub-Saharan Africa. The utilization of genes from the unexploited wild annual, *G. soja*, and those in the perennial *Glycine* species (Chung and Singh 2008), may play a role in this genetic improvement. At the current time, these related *Glycine* species represent a gene bank that may be tapped to provide better levels of resistance and/or tolerance to abiotic and biotic constraints. In addition, with the recent sequencing of the soybean genome (Schmutz et al. 2010), targeted development of specific traits, like specific seed composition and pathogen and pest resistance, will allow more rapid development of new varieties. Also, since soybean transformation has become more routine (Widholm et al. 2010), it is expected that useful transformation events will play a major role in increasing production and reducing the threat of diseases and pests. This transformation technology has already been widely adapted for weed control, although not without controversy (Powles 2010).

Soybeans are widely grown, heavily traded and have an exceptional nutritional and functional food profile, yet as little as 2% of the yearly production is used directly for human food. Nonetheless the crop is likely the most important source of plant protein in the world. Not only does it provide the highest protein yield per hectare (Fig. 10), but also offers a high quality, complete protein unlike seeds of other crops.

Estimates show that about 925 million individuals are undernourished worldwide (FAO 2010b). Soybean has the potential to address the needs of these individuals through increased local production and consumption of the crop. Development of locally adapted soybean varieties consumed either as cooked mature seeds or immature green seeds would offer vital nutrients and bring balance to the undernourished diet. Expanded home and community gardening strategies have been recommended toward increased dietary diversity and improved micronutrient supply (Faber and Benade 2003). Soybeans could be introduced easily into kitchen gardens and smallholder farm systems, recommended as part of the world hunger solution and may help to enrich soil.

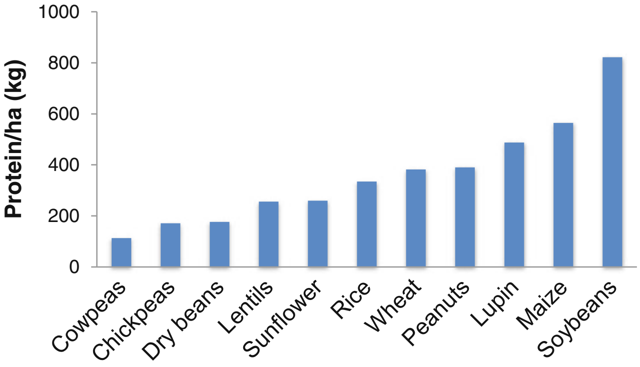

Fig. 10 Estimated protein production per hectare for crops based on dry seed harvest. Computation of protein per hectare uses 2009 yield data from FAO statistics (www.fao) and protein values per 100 g of raw, uncooked seed of each crop from the USDA Nutrient Database (www.nal.usda.gov/fnic/foodcomp). Protein values for kidney beans and long-grain brown rice were used for computed protein/ha values of dry beans and rice

Beyond current issues of undernourishment, worldwide per person calorie intake has increased, from 2360 kcal per person in the mid-1960s to 2800 kcal per person in 2010, and is expected to further increase to 3050 kcal per person by 2030 (FAO 2010a). Soybeans can play a role in supplying the need for these extra calories. In addition, they will continue to be exploited for their healthful benefits, as a cholesterol-free protein source, an economical and sustainable source of omega-3 fatty acids, and as a source of nutriceutical elements that continue to emerge via ongoing research. This will be of special benefit to the overnourished of the world who suffer from diabetes, cardiovascular disease, obesity, and other maladies.

In conclusion, future soybean production is expected to increase proportionally to increased demand. The soybean crop has enormous potential to improve the dietary quality of people throughout the world either as a vegetable crop or through soy-based or soy-enhanced food products. Increased use of genetic resources, both through traditional breeding and bioengineering, may provide the solutions needed to combat future problems caused by abiotic and biotic constraints.

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