The importance of soybean production worldwide

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Introduction

Interest in the impact of agriculture on soil structure or changing soil species inhabitants has increased (Pagano et al., 2011; Wall and Nielsen, 2012). For example, soybean is one of the major crops planted worldwide affecting different aspects of the ecosystem. Among the most important components of the ecosystem are soil microbes. Accordingly, with respect to the high cultivation of soybean crop worldwide, some of the most important parameters related to the production of soybean are presented among which the soil biota including rhizobia and mycorrhizal fungi are of great significance.

Because soybean is among the most important agricultural crop worldwide, more research is being done to find details related to the production of soybean under different conditions including stress. Data indicating the rate of soybean production in different parts of the world can be used to improve production of soybean and alleviate factors including stresses, which adversely affect soybean yield. The role of soil microbes is especially important affecting the production of soybean. Just a few countries such as the USA, Brazil, Argentina, China, and India dominate the production of soybean worldwide.

In particular, it is supposed that the soil biotas do not affect the agro-ecosystem function or the services provided by them (Wall and Nielsen, 2012). Among the most cultivated crops (maize, rice, wheat), soybean (*Glycine max* (L.) Merr.) is the only leguminous species that can be associated with rhizobia and arbuscular mycorrhizal (AM) fungi, with potential to be further exploited.

Pagano and Covacevich (2011) reviewed the current information on the benefit of AM fungi in agro-ecosystems, mentioning that the increasing recognition of the impacts of agricultural intensification and use of agrochemicals adversely affect soil quality, modifying the number, diversity, and activity of the soil microbiota, including the populations of symbiotic fungi. Thus, improved research aimed at crop yield enhancement and sustainability is essential and must be achieved.

Mutualistic associations such as AM fungi have important potentials for soybean production (Pagano, 2012; Simard and Austin, 2010). There is a growing use of beneficial rhizospheric microorganisms as biofertilizers in agriculture and there is a need to better understand the effects of multiple inocula on soybean growth and physiology.

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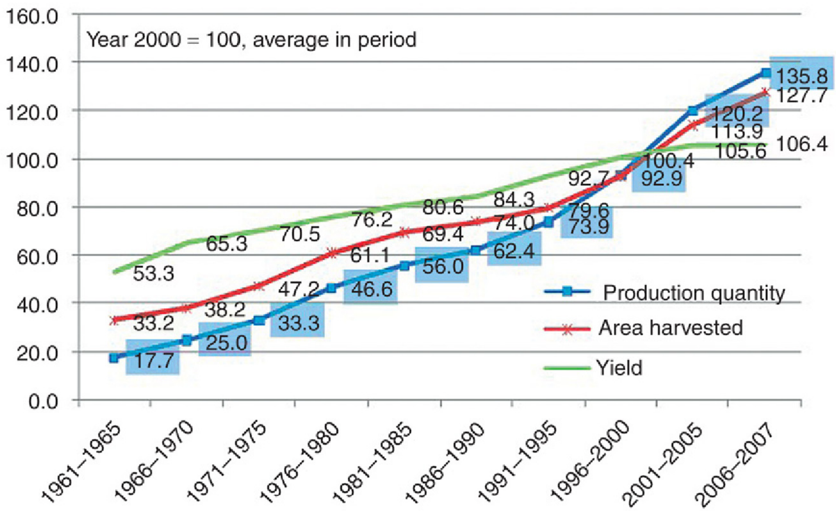

Figure 1.1 World soybean production quantity, area harvested, and yield: 1961–2007. *Source:* FAOSTAT: http://faostat3.fao.org/home/E (Masuda and Goldsmith, 2009).

This chapter explores the current available information relevant to soybean production worldwide (Figure 1.1). Better knowledge of the wide variation in cultivation practices is important for understanding the ecology of soybean crops and for management purposes. How a better management may be related to soil conditions and microbial inocula will also be discussed. Better knowledge of the wide variation in plant interactions is important for understanding the ecology of this crop and for management purposes.

World soybean production

Soybean (*G. max* (L.) Merr.) originated in China and is a major source of protein for humans and as a high-quality animal feed (FAO, 2003). Moreover, the presence of important food supplements in soybean, and growing consumption, has resulted in higher demands for soybean production. Soybean was originally domesticated in China, with about 23,000 cultivars in Asia, and was introduced into the USA and Brazil (López-López et al., 2010). For a brief history of world soybean dissemination, see Rodríguez-Navarro et al. (2011). The term soybean possibly refers to the bean from which soy sauce was manufactured.

Soybean constitutes one of the largest sources of vegetable oil and of animal protein feed in the world (Sugiyama et al., 2015). It has the highest protein content (40–42%) of all other food crops and is second only to groundnut with respect to the oil content (18–22%) among food legumes (Robert, 1986). Moreover, soybean is used for aquaculture and biofuel, as well as a protein source for the human diet (Masuda and Goldsmith, 2009). Moreover, obesity and muscle fatigue can be prevented by soy protein (Agyei et al., 2015).

The USA produced more than 50% of the world soybean yield until the 1980s. However, nowadays Brazil and Argentina are also among the top world nations of producing soybean, following the USA. The major producers of soybean in the world include the USA, Brazil, Argentina, China, and India with more than 92% of the world's soybean production. It has also been produced in Africa since the twentieth century (Rodríguez-Navarro et al., 2011).

Brazil, as one of the tropical food giants, is now among the traditional "big five" grain exporters (America, Canada, Australia, Argentina, and the European Union). Since 1990, a third of world soybean exports has been accomplished by Brazil, second only to America which produces a quarter of the world's total soybean using just 6% of the country's arable land (The Economist, 2010).

Using fertilizer or biofertilizers, large amounts of nitrogen (N) are essential for the production of large soybean yields. The process of biological nitrogen (N_2) fixation by symbiotic soil bacteria, mainly *Bradyrhizobium*, is a less expensive source of N for soybean related to the use of chemical N fertilization. However, different factors determine the efficiency of the biological N fixation (related to the plant, rhizobia, symbiosis, and environmental stresses) (Rodríguez-Navarro et al., 2011). Accordingly, and with respect to the importance of soybean as a strategic crop, several governmental companies, universities centers, and individuals are researching different aspects of soybean production worldwide. Nowadays, more efficient inoculants are being used by farmers, which is the result of recent advances on soybean research, with a high value for the environment and sustainability of agro-ecosystems (Miransari, 2011a, b).

The recognition of soil microbes as important components of soil biodiversity is not largely integrated in strategies to conserve and manage these microorganisms. The financial value of soybean N fixation in Africa was evaluated by Chianu et al. (2010), indicating a higher rate of benefits for smallholder farmers. Accordingly, it was shown by the authors that the N fixing attribute of soybean in Africa is of high financial value.

They especially indicated the promiscuous varieties and recommended options, which may increase the chances of smallholder farmers to benefit from the process of N biological fixation. This is especially the case under those conditions where the quantities of inorganic fertilizers for increased soy productivity are inadequate. They mentioned that the promiscuous soybean varieties are not planted by the 19 African countries that produce soybean. However, the financial benefits from the process of N_2 fixation by promiscuous soybean can suitably illustrate how soil microbial biodiversity can sustain human welfare.

There are plenty of situations to further indicate the benefits of biological N fixation as, interestingly, some inoculated cultivars did not produce a higher yield than the uninoculated promiscuous varieties with the highest rate of production. Accordingly, the authors indicated that plant response to inoculation is complex and their recommendation was related to the selection and breeding of promiscuous soybean varieties in the case of Africa. Legume crops including soybean are able to nodulate with a wide variety of rhizobial strains in the soils being referred to as promiscuous (Mpepereki et al., 2000). Usually some uninoculated promiscuous varieties are able to produce similar yield levels, related to the promiscuous varieties, which are inoculated efficiently with rhizobia (Chianu et al., 2010).

It may not be a priority at this stage to focus on the development and production of inocula, due to the uncertainties resulted by different responses in many places and difficulties related to the production and conservation of inocula. In the future, greater profit may be obtained by the development and use of inocula, similarly to the production in countries such as Brazil, where a yield of 3 t ha^{-1} is relatively common, compared with an average yield of 1.1 t ha^{-1} for Africa (Chianu et al., 2010).

The importance of soybean production

In the future, a global crop demand is unavoidable, as the human population is steadily increasing (Tilman et al., 2011). In addition to population growth, agricultural production has not kept pace with estimated demand. Ray et al. (2013) compiled information on long-term production for maize, rice, wheat, and soybean, representing two-thirds of the total agricultural calorie demand. Those authors projected crop yields to 2050 indicating an increase of 1.3% $year^{-1}$ for soybean, which is not at the level essential for providing people with their food by 2050. Soybean is among the 16 major crops (barley, cassava, groundnut, maize, millet, potato, oil palm, rapeseed, rice, rye, sorghum, soybean, sugar beet, sugarcane, sunflower, and wheat) cultivated worldwide (Foley et al., 2011). Thus, it is crucial that policy makers and land managers improve soybean research (see Masuda and Goldsmith, 2009).

Soybean is one of the major crops in five countries of South America, producing about 63% of the total cropped area (reviewed by Wingeyer et al., 2015). Its expansion resulted in a decrease in the cultivated area of other crops and native vegetation, and increased soybean production at an annual rate of ~6%. The main reason for the increase of soybean yield was a higher production area, related to the lower increase of grain yield (reviewed by Wingeyer et al., 2015).

The cultivation of soybean after maize in Canada is common; however, due to the presence of greater amounts of maize residues, its plantation under no-tillage, which may decrease its production. Such adverse effects are by influencing soil nitrogen and soybean nodulation, soybean emergence, growth, and development, as well as by impacting soil physical properties such as moisture and temperature (Vanhie et al., 2015).

Soybean is also cultivated as an important summer crop in Japan in rotation with winter wheat or as an upland crop fallow (Higo et al., 2013). Increasing the potential yield of soybean, especially with respect to the climate and genetic potential of crop requires more investigation, as well as taking into account the following: (1) maximum yield of a crop cultivar produced under certain environmental conditions; (2) adequate amounts of nutrients and water; and (3) controlling pests and diseases (reviewed by Salvagiotti et al., 2008).

Production and supply, stock levels, and soybean prices have changed along with the high demand of soybean by the population (MAPA, 2015; Masuda and

Goldsmith, 2009). Since 2005, the production of soybean in USA has been at its highest rate (89,507 million tons), over 33,640 million hectares (USDA, 2014).

Masuda and Goldsmith (2009) analyzed the production of soybean worldwide, as well as the area harvested and the related yield. The yearly rate of increase of soybean was at 4.6% from 1961 to 2007, with the average yearly production of 217.6 million tons in 2005–2007. They estimated that the yearly production of soybean will be at 2.2% and approach a yearly production of 371.3 million tons by 2030.

They accordingly indicated the following as the major factors affecting soybean production globally: (1) limitation of cultivable lands, and (2) the need for investment by the public, private concerns, and farmers to increase soybean yield. The substitution for other crops (cotton and sunflower), pasture, and native vegetation increased the cultivated soybean field areas and production by 36%. They mentioned that there has been a shift in the production area from the USA and Asia (China and India) to the USA and South America, including Argentina and Brazil.

Due to technological advances, 49% of grain production in Brazil is related to soybean. It is, especially, cultivated in the midwest and south regions of the country. The research and advances by the Brazilian Agricultural Research Corporation (Embrapa), in partnership with farmers, industry, and private research centers, has made the cultivation of soybean likely in the Cerrado grasslands. Such progress has also resulted in an increase yield production per hectare, competing with the major world production rates. However, the cultivation of soybean is conducted by the use of sustainable agricultural practices such as the use of no-tillage and integrated crop–livestock system (MAPA, 2015).

A single-gene transformation results in the production of genetically modified crops, such as a herbicide resistant crop (e.g., Roundup Ready soybeans) (Sobolevsky et al., 2005). Currently, soybean and corn, followed by canola and cotton, are the main transgenic crops, cultivated in the United States and some other countries (Argentina, Canada, and China). The production of genetically modified crops such as Roundup Ready soybeans is large in Argentina, which is the second biggest transgenic area worldwide; however, the effects of these biotechnologies have still to be further investigated (Qaim and Traxler, 2005).

Microbial associations

Rhizobia

Rhizobia are nitrogen-fixing bacteria classified and characterized by different systems. Beijerinck was able to isolate and cultivate a microorganism, named *Bacillus radiocicola*, from the nodules of legumes in 1888. However, Frank (1889) renamed it *Rhizobium leguminosarum* (Fred et al., 1932), which was retained in *Bergey's Manual of Determinative Bacteriology* (Holt et al., 1994).

Rhizobia are characterized on the basis of their growth rate on certain substrates, as fast and slow growers (Löhis and Hansen, 1921). Mean generation time of the slow and fast growing bacteria is greater and less than 6 h in selective broth media, respectively (Elkan, 1992). Until now, about 750 genera of legumes, containing 16,000–19,000 species, have been recognized; however, only a few have been examined (Allen and Allen, 1981).

The first accepted change in the rhizobial nomenclature was the establishment of *Bradyrhizobium* (Jordan, 1982). The strain of *Bradyrhizobium*, which is able to nodulate soybean, is characterized as *Bradyrhizobium japonicum*, the first recognized group of *Bradyrhizobium* strains (Young and Haukka, 1996). *Bradyrhizobium elkanii* (Kuykendall et al., 1992), possessing some specific phenotypic and genetic characters, indicates a number of species within the soybean nodulating bradyrhizobia.

Bradyrhizobium liaoningense are also among the other extra slow growing soybean rhizobia with the ability of forming a coherent DNA–DNA hybridization group (Xu et al., 1995). Moreover, some *Bradyrhizobium* strains, known as *Bradyrhizobium* sp., are not able to nodulate soybeans (Young, 1991). The current characterization of rhizobia is on the basis of gene sequencing for the 16S or small subunit of ribosomal RNA (Jarvis et al., 1997).

Four recognized species of *Bradyrhizobium* include: *B. japonicum* (Jordan, 1982); *B. elkanii* (Kuykendall et al., 1992); *B. liaoningense* (Xu et al., 1995), and *Bradyrhizobium* sp. (Young, 1991). As suggested by Young (1991), the *Bradyrhizobium* genus will not have new species allocated; however, the host name will be mentioned in parentheses.

The specific and compatible rhizobia nodulating soybean is *B. japonicum* (Cooper, 2007; Long, 1989; Rolfe, 1988). Soybean association with rhizobia, including *B. japonicum* and *B. elkanii*, provide about 50–60% of soybean nitrogen requirement supplied by the bacteria in nodules (Salvagiotti et al., 2008). Rhizobia are the bacteria, which include *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, etc., surviving and reproducing in the soil, and fixing atmospheric N inside the nodules produced in the roots of their specific legume (reviewed by Denison and Kiers, 2004).

Laranjo et al. (2014) reviewed the rhizobial symbioses with the emphasis on mesorhizobia as legume inoculants. They have presented brief details of rhizobia including their rhizobial genomes, taxonomic diversity, and nodulation and nitrogen fixation genes. According to the above-mentioned details the term "rhizobia" includes the genus *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, and *Mesorhizobium*. Moreover, rhizobia include Alphaproteobacteria (Rhizobiales) though some isolates of wild legumes belong to the class of Betaproteobacteria (Laranjo et al., 2014). Some research has also indicated that legumes are able to be nodulated once or several times during evolution (Sprent, 2007).

For a review on developments to improve symbiotic nitrogen fixation and productivity of grain legumes see Dwivedi et al. (2015). The main function of nodules on soybean roots is to fix the atmospheric N by the process of symbiotic nitrogen fixation, supplying nitrogen for plant growth and seed production. Sugiyama et al. (2015) reported changes in the rhizospheric bacteria and especially *Bradyrhizobium* during soybean growth, suggesting that the symbiosis of host plant with rhizobia may be selective.

In the last few years approximately 13,247 peer reviewed journal papers on soybean production have been produced, of which 731 focused on soil management (Table 1.1). Among the studies on soybean interactions with microorganisms (Table 1.1), research

Table 1.1 Journal articles dealing with soybean production worldwide

Keywords	Number of journal articles
Soybean production	13,247
Soybean production + soil	2,300
Soybean production + plant management	501
Soybean production + soil management	731
Soybean production + rhizobia	231
Soybean production + symbioses	147
Soybean production + arbuscular mycorrhizas	39

Database survey conducted on May 2015 (SCOPUS).

on rhizobia predominated (circa 231 reports existing for rhizobia in soybean) over mycorrhizal research (39 reports). Among an increasing number of reviews published on N_2 fixation in legumes, soybean in particular accounts for 20 documents in the SCOPUS database (Miransari et al., 2013; Rao, 2014; Uchida and Akiyama, 2013); however, other reports (Hungria et al., 2005a, b) are also available.

In a review paper, Salvagiotti et al. (2008) analyzed 637 data sets derived from 108 field studies in 17 countries published from 1966 to 2006 including nitrogen fixation and N fertilization in soybean. For a 1 kg increase in N accumulation in above-ground biomass, they found a mean linear increase of 0.013 Mg soybean seed yield. Their meta-analysis indicated that 50–60% of soybean N demand is by the process of biological N_2 fixation; however, the rate of N fixation decreases with increasing N fertilizer.

Moreover, the N that is harvested by soybean grain must be supplied by both the process of N fixation and chemical N fertilization. It was not possible to estimate the actual contribution of below-ground N and its variation, and more research work must be conducted to determine such details. In conclusion, those authors mentioned that the yield response of soybean to N fertilizer is determined by yield production, environment, and abiotic/biotic stresses, which decrease crop growth and the associated N demand. With respect to such constraints, the development of rhizobia, which are able to fix N_2 under stress, is essential for providing the host plant with N (Alves et al., 2003; Hungria and Vargas, 2000).

It has been shown that the efficiency of the symbiotic process depends on many factors including the host plant, bacteria, the process of symbiosis, and the environment. Among the most important constraints affecting plant growth and the process of fixation are the soils, which are not highly fertile, resulting in the limited availability of macro- and micronutrients (Campo et al., 2009).

In the absence of growth constraints and in the presence of soybean genotypes with a high rate of yield at levels above 4.5 Mg ha^{-1}, the response of well-nodulated soybean crops to N fertilization is likely. The deep use of (slow-release) fertilizer underneath the nodulation zone, or using N chemical fertilization during the reproductive stages in high-yielding environments, can significantly improve soybean yield (Salvagiotti et al., 2008).

Diaz et al. (2009) investigated the soybean response to inoculation and N application following long-term grass pasture due to conversion of pastures into soybean fields. They observed that inoculation of soybean host plant with rhizobia increased soybean grain yield, plant dry matter, N concentration, N accumulation, and grain N, although the quality of seed remained constant. In contrast, although the N fertilizer increased plant dry matter, it did not increase grain yield, with or without inoculation. Moreover, no increases in plant N or improved seed quality were detected. They accordingly suggested inoculating soybean seed when planted after long-term grass pasture, without chemical N fertilizer.

Cases of legume introduction in places where rhizobia were not present to nodulate the introduced crop indicate the essentiality of research work to determine rhizobial evolution. One of the most remarkable cases is the introduction of soybean in Brazil (Barcellos et al., 2007). The implications of biserrula, nodulated by *Mesorhizobium ciceri* (typically known for nodulating chickpea), introduced in Australia, is the other example of naturally occurring rhizobia, which are able to evolve and acquire, by the process of lateral gene transfer, genes essential for the inoculation of the introduced legume. A 5-year period was essential for the detection of rhizobia able to nodulate biserrula in Australian soils, different from the original inoculant (Nandasena et al., 2007).

Mycorrhizas

With regard to mycorrhizas, Miranda (2008) compiled information on AM fungi in crops from Cerrado, the Brazilian savannah. In line with earlier studies, she showed that soybean can be inoculated by four species of AM fungi including *Glomus etunicatum*, *Entrophospora colombiana*, *Acaulospora scrobiculata*, and *Gigaspora gigantea* in pots with autoclaved native soil, fertilized with P_2O_5 and lime.

She showed that *G. etunicatum* was the most efficient inoculum followed by *E. colombiana*, increasing soybean production by four times relative to the uninoculated control. She also found that the plant production in the inoculated pastures (*Andropogon guayanus* and *Stylosanthes guianensis*) was more responsive to fungal inoculation. Usually, soybean crop is inoculated with a lesser rate of mycorrhizal colonization than for maize. Hence, the crop rotation can benefit soybean plant with a higher rate of AM fungi in the first year of soybean–maize rotation (Miranda et al., 2005).

Perez-Brandan et al. (2014) reported changes in soil microbial diversity in soybean fields. They analyzed soybean monoculture, soybean–maize rotation, and native vegetation. According to their research, a higher rate of carbon in microbial biomass and a higher rate of glomalin-related soil protein was found under the rotation system than in monoculture. Such results indicate that agricultural intensification can deteriorate soil biological, chemical, and physical properties. They also indicate that functional diversity was less in monocultures than in rotation and native vegetation.

It is known that the intensive use of land can affect biodiversity and as a result the changes in the composition or species diversity of aboveground communities can affect soil communities (Suleiman et al., 2013). Research on glomalin or glomalin-related soil protein is increasing in agro-ecosystems (Curaqueo et al., 2010;

Redmile-Gordon et al., 2014). It is believed that AM hyphae decompose and liberate glomalin residue in the soil (Treseder and Turner, 2007). The protein is extracted from the soil by autoclaving in citrate solutions and their easy evaluation and little soil demand (generally 1 g) support their assessment. Curaqueo et al. (2010) found higher values related to the mycorrhizal hyphae, glomalin-related soil protein, and water stable aggregates under no-tillage relative to the conventional tillage in a rotation experiment with wheat in Chile.

Junior et al. (2013) tested the nodulation and mycorrhization of transgenic soybean under greenhouse conditions after using glyphosate. They determined an increased number of nodules using Roundup until 15 days after the application. However, after that period, the inoculated control presented more nodules. They observed no influence of glyphosate in the root colonization by AM fungi.

It is known that *Bradyrhizobium* strains may not be tolerant to the presence of glyphosate application, thus decreasing the host plant nodulation (Bohm and Rombaldi, 2010; Reis et al., 2010). The process of biological N fixation contributes to the high production of soybean and this technology uses the selected strains of *B. japonicum* and *B. elkanii* as inocula (Hungria et al., 2005a, b).

Malty et al. (2006) tested Roundup on three strains of *Bradyrhizobium* and on three AM fungi (*Glomus etunicatum*, *Gigaspora margarita*, and *Scutellospora heterogama*) in culture and in soil. The growth of *Bradyrhizobium* spp. and AM fungi in culture medium decreased at concentrations greater than the optimum concentration. Germination and growth of AM fungal spores was affected more in the Gigasporaceae representatives than in *Glomus*. In conclusion the results indicated that soil application of herbicide up to a rate equivalent to 10 L ha^{-1} did not affect nodulation and mycorrhization of soybean.

It is known that ecosystem services are affected by soil properties, soil conditions (e.g., moisture, temperature), and the biological processes within soil, as well as management, which will select the strongest and more efficient organisms in the ecosystem (Dominati et al., 2010; Pagano, 2013). However, better soil management will depend on regional understanding and cooperation between researchers, policy makers, and the community.

It is also known that the number, diversity, and activity of both free and symbiotic fungi are modified by crops (Kahiluoto et al., 2009; Nyfeler et al., 2011; Pagano et al., 2011). That is why the ecosystem services of soils need to be given greater recognition as the impact of agriculture on soil structure or changing the inhabitant species of soil is crucial. Efforts to restore ecosystem services need to take into account sustainable rural incomes and community participation.

Among soil ecosystem services, AM fungi protect soil structure and plant roots against disease or drought (Simard and Austin, 2010). Mycorrhizal fungi can significantly affect plant growth (Smith and Read, 2008) as different AM fungal communities are present in different land use systems (Sene et al., 2012; Stürmer and Siqueira, 2011). In mycorrhizal fungal association, 20% of the host plant photosynthetic C can be moved to the fungus (Lerat et al., 2003).

Cotton et al. (2015) analyzed the AM fungal communities in the roots of soybean in fields exposed to higher levels of O_3 and CO_2 (as predicted for 2050). On increasing the rate of CO_2 exposure, there were only differences created in the community composition of AM fungi (increased ratio of Glomeraceae to Gigasporaceae). Due to its importance as a major crop in many parts of the world and in internationally competitive agriculture, more research on soybean management can contribute to a higher yield of soybean worldwide.

Interestingly, Juge et al. (2012) tested the inoculation of three microorganisms (*Azospirillum*, *B. japonicum*, and *Glomus irregulare*) in soybean production. They found different effects of the tested microbes on shoot biomass; however, they mentioned that the fact that coinoculation effects on nodulation are strain dependent and must be considered. Higo et al. (2013) analyzed the diversity and vertical distribution of AM fungi under two soybean rotational systems in Japan. They found the effect of crop rotation on AM fungal communities with specific AM fungi associated with soybean. In Argentina, Grümberg et al. (2015) showed the significant role of AM fungi in alleviating drought effects on soybean. They also pointed out differences between mixtures of AM fungi isolates and single strain inocula, proposing an effective selection of AM fungi for soybean.

The importance of better soybean management

Plant and soil management

Interest in soil management and sustainable production has increased worldwide. Moreover, tillage practices with higher efficiency have contributed to the success of cropland yields, although there has been a recent expansion of monocropping soybean production. Such a method in current agricultural practices can lead to a decrease in soil quality even though the no-tillage practices may improve such effects (Wingeyer et al., 2015).

The removal of pasture from crop cultivations, together with the increased frequency of soybean cultivation, and the conversion of native vegetation into farmland constitute may adversely affect soil quality. In this regard, Vanhie et al. (2015) reviewed the potential strategies to address using the high levels of maize residues for soybean production under no-till. It is a common practice to encourage environmental benefits such as reduced soil erosion, fuel usage, and carbon emissions (Seta et al., 1993; Yiridoe et al., 2000).

Plant residues from the previous crop can suppress the activity of pathogens by enhancing the general microbial activity. Although the debris increases the microbial activity, it can also enhance the activity of pathogens by preventing a decrease in the inoculum density, such as *Macrophomina phaseolina*, which causes charcoal rot in soybean (Baird et al., 2003).

High maize yield significantly increases the amount of residues, which is also a result of changes in the cropping system influencing maize residue decomposition. Such aspects can also decrease the non-till practices affecting no-till and conventional tillage of soybean. Vanhie et al. (2015) suggested the following strategies to manage high quantities of maize residues when planting soybean: (1) removal of residue; (2) proper handling of residue distribution and orientation; (3) instead of no-tillage practices, minimum tillage be used; (4) application of nitrogen; and (5) use of more efficient planting equipment. However, additional research is required to fully work out these options.

Wingeyer et al. (2015) investigated the details related to soil conditions and research affecting soil degradation in South America (Argentina, southern Brazil, Bolivia, Paraguay, and Uruguay). They suggested that such degradation must be controlled by conducting research to prevent the negative effects on soil quality. They indicated that the properties of different regional soils must be evaluated and accordingly scientific recommendations be presented so that the environmental degradation be prevented.

Similarly, because climate change can adversely affect agricultural intensification, more attention is given to the ecologically sustainable use of land (Borie et al., 2006). It is also essential to use more efficient agricultural practices so that the plants can be acclimated to the climate and the increasing population can have their needs (for food, fodder, and fuel) met. The properties of soil have also to be restored and soil fertility enhanced by using proper agricultural practices (reviewed by Lal, 2009). Although increasing the rate of atmospheric CO_2 exposure can promote plant growth and soil C input, it may also affect the decomposition of soil microbes (Covacevich and Berbara, 2010; van Groenigen et al., 2014).

The following indicates how soil may be used in a sustainable manner: (1) suitable method of seed cultivation and planting; (2) rotation of crop; (3) enhancing soil fertility; (4) using proper agricultural practices including mulch residue, no-tillage, and cover crops; (5) appropriate use of nutrients; (6) applying biochar; and (7) use of crops which have been genetically modified and improved (reviewed by Lal, 2009).

Organic cover and the rate of water available in soils and plants are among the imporant parameters that have been better recongized and determine the response of surface and subsurface soil to global change (Torn et al., 2015). Studies on soil aggregate stability and soil resistance are increasingly being investigated (Lal, 2010; Powlson et al., 2011).

Castro and Crusciol (2013) determined the response of soybean under the no-tillage system in Brazil. For the adjustment of soil pH they used limestone or slag (silicates of calcium and magnesium). The chemical attributes of soil were evaluated 6, 12, and 18 months after the application of the chemical compounds and it was indicated that slag is an efficient and effective source for the adjustment of soil acidity. This was because slag increased the grain yield of soybean in the treated plots, related to the control treatment without the use of chemical compounds.

Soybean rhizobial inoculants

With regard to rhizobial inoculants, some reports showed frequent contamination of inocula (Gemell et al., 2005; Herrmann et al., 2013). The inocula of mycorrhizal fungi generally contain a few viable propagules, decreasing the rate of colonization (Faye et al., 2013).

Hungria et al. (2005a, b) evaluated the details related to the inoculant production and application. They indicated that the process of biological nitrogen fixation is an important process preventing degradation and hence the adverse effects of soil on crop yield worldwide, mainly in tropical regions such as Brazil and Africa. Benefits could be enhanced by using efficient and competitive species of rhizobia which are of high quality and available in adequate quantities in the soils under cultivation for legumes including soybean.

Hungria and colleagues briefly mention the long period of rhizobial inoculant production and their related products, which are of poorer quality. Moreover, they explain that for the production of successful inoculants, a selected strain, which has been used for a long time under specific environmental conditions, must be used in the presence of persistent species. Soybean was brought to and cultivated in Brazil in 1882 with cultivation of large rate of fields using bradyrhizobial inoculants from the USA. The important point was the successful use of a bradyrhizobial strain that was tolerant to natural acid soils. Next, the host plant demand for nitrogen increased due to the higher mean production of soybean yields (2765 kg ha^{-1} in 2003).

Inoculated bradyrhizobia are found in most soybean fields; however, strains have to be selected that are more efficient and competitive and are able to provide soybean with most of its essential N. Thus, adapted strains, which can result in the production of higher grain yield, have been selected. Under the conditions of producing commercial soybean, four strains, which are of high capacity for nitrogen fixation, have been selected and used commonly; however, the selection strategies continue to help farm owners. Among the selected strains, the variant strains of SEMIA 566 and CB 1809 resulted in the highest yield of soybean cultivar BR 133 as well as a higher rate of nodulation in fields from south Brazil. The N fixation potential of both strains was not significantly different from that of the fertilized control (200 kg N ha^{-1}) (Hungria et al., 2005a, b).

The number of rhizobia decreases with time as affected by the environmental conditions, properties of soil, and the bacterial strain. However, some research has shown 5–15 years' persistence of inoculant in the soil. Using new and more efficient strains in place of established *Bradyrhizobium* inoculants is difficult and must be done on the basis of frequent reinoculation (Hungria et al., 2005a, b). For example, the supplanting of the CPAC 15 strain must involve reinoculation yearly, which may result in higher costs.

For instance, using molecular methods the strains with a higher persistency and related factors, which may affect such persistency, must be indicated. The rhizobia might be incompatible with the use of micronutrients, seed-applied pesticides, or the size of small seeds, limiting the number of bacteria. The most effective method of using inoculants is to place them near the seed/seedling; hence, they can be inoculated directly in the soil furrow as liquid, peat, or granules (and not mixed with fertilizers) (Hungria et al., 2005a, b).

However, the inoculation of soil may be more costly as a higher rate of inocula is essential. For example, in Brazil inoculating seeds with broth inoculants in the furrow or 2.5 cm underneath the seed may result in a higher rate of soybean nodulation (Hungria et al., 2005a, b). Among the most important parameters affecting the efficiency of inoculant industry is rhizobial biodiversity, which can result in the selection of a higher number of suitable strains. However, the selection of strains with high temperature resistance for soybean in Iran was based only on 56 strains (Rahmani et al., 2009).

The interactions between soybean and soil microbes and the related details of the agronomical and most relevant genetic aspects of soybean rhizobia symbiosis have been reviewed by Rodríguez-Navarro et al. (2011). However, they accordingly mentioned that more details are essential on a molecular basis, indicating the specificity of cultivar–strain and occupancy of nodules by rhizobia competitors. Thus to produce more efficient commercial inoculants and develop symbiotic interactions for the other important agricultural crops, such constraints must be resolved.

Inoculation of soybean, under field conditions, has been efficiently used in the USA, Brazil, and Argentina. However, the high populations of indigenous soil rhizobia can adversely affect the successful use of inoculants in certain areas. More than 105 soybean rhizobia per gram of soil have been found in most Chinese soils, which interfere with the occupancy of nodules by the inoculant (Rodríguez-Navarro et al., 2011).

Due to the need for the sustainable use of agricultural practices, more attention has been given to the process of biological nitrogen fixation and rhizobial symbioses. Several studies have revealed the diversity of *Rhizobium* species with respect to their genetic and phenotypic properties, which can be used for the study of the evolutionary associations among the specific species (reviewed by Laranjo et al., 2014). Advances in molecular genetics of rhizobia have contributed to a better understanding of such plant symbionts. A number of research projects have been conducted on the use of mesorhizobia isolated from the nodules of chickpea (*Cicer arietinum*), which is among the most important legumes and is nodulated by *Mesorhizobium* species (Laranjo et al., 2004, 2008, 2012).

The rapid evolution of mesorhizobia has been shown in a review by Laranjo et al. (2014). They mentioned that the first genetic transfer of *B. elkanii* and *Sinorhizobium fredii* by a strain of *B. japonicum* in symbiosis with soybean was done using the technique of lateral transfer of chromosomal symbiosis islands in the field. However, in *Mesorhizobium* strains, the symbiosis genes are rarely found in plasmids, as they are commonly located in chromosomal symbiosis islands (reviewed by Laranjo et al., 2014).

Bai et al. (2003) isolated three strains of *Bacillus* from inside the nodules of vigorous soybean grown under field conditions and tested their coinoculation with *B. japonicum* on the growth of soybean. The coinoculation of *Bacillus* strains with *B. japonicum* increased the number and weight of soybean nodules, as well as the shoot and root weight, total nitrogen, total biomass, and grain yield (Bai et al., 2003). They recommended a selected strain (*B. thuringiensis* NEB17) for use as plant growth promoting rhizobacteria (PGPR) in soybean production systems under the conditions of suboptimal root zone temperatures. Under the circumstance that the growing season is not long, soybean growth and N fixation are negatively affected; however, PGPR can alleviate such effects on the growth of soybean plants.

In Pakistan, the average yield of soybean is low relative to the other top producing nations. Low soil fertility, as a result of intensive cropping, and cultivating in a small area are important constraints of soybean cultivation. Hence, research on the process of biological fixation is providing more options to increase soybean yields under different conditions including stress. Using N-fixing and P-solubilizing bacteria, such as *Pseudomonas*, resulted in a higher soybean yield relative to the single use of P_2O_5 fertilization (Afzal et al., 2010). In *Pseudomonas sensu stricto*, several species with the ability of solubilizing phosphate *in vitro* (reviewed by Peix et al., 2003) from the ribosomal RNA group I (Palleroni, 1992) are included.

In their experiments, Afzal et al. (2010) indicated that soybean coinoculation with *Pseudomonas* strain 54RB (P-solubilization index of 4.1) resulted in a higher production rate of auxins and gibberellins than with *B. japonicum* strain TAL 377. The strain with the highest rate of phytohormones also increased soybean growth and yield the most (Afzal et al., 2010). The dual inoculation of *Bradyrhizobium–Pseudomonas* (biological fertilization) with the addition of triple superphosphate (P_2O_5) (chemical fertilization) was the most effective treatment on soybean growth, yield (12 and 38% increase compared with the single use of P_2O_5), and yield components.

Although previous experiments have indicated that coinoculation with microbial species may synergistically and antagonistically affect the responses occurring, it has been indicated that the number of soil microbes may increase in the presence of P_2O_5, confirming that P_2O_5 assists the growth and colonization of *Bradyrhizobium*. As an energy source (adenosine triphosphate) affecting the reduction of N_2 to NH_3, phosphorus deficiency can negatively affect the process of photosynthesis, symbiotic N_2 fixation, nodule development, and root growth (Pereira and Bliss, 1989; Vadez et al., 1996).

Accordingly, Afzal et al. (2010) recommended the consortium use of beneficial microbial for important crops in Pakistan as well as the use of this technology by farmers as indicated by extension workers. Additionally, few rhizobial strains may be tolerant under different stresses such as salinity, drought, acidity, and heavy metal, and constitutes unique PGPR (reviewed by Deshwal et al., 2013).

It is also known that AM fungi can significantly enhance phosphorus use efficiency and N accumulation in the host plant. As a result mycorrhizal fungi affect the association between phosphorus P utilization efficiency and symbiotic N fixation (Tang et al., 2001) and the mechanisms, which may affect phosphorus P uptake and utilization by the host plant (Bucher et al., 2001; Jia et al., 2004). It is also indicated that plant phosphorus P utilization determines shoot growth and N_2 fixation (Rodino et al., 2009).

Soybean can establish tripartite symbiotic associations with rhizobia and AM fungi (Lisette et al., 2003); however, few results are available on their effects on plant growth, or their association with root architecture as well as with N and P availability. Xie et al. (1995) reported that soybean coinoculation with *B. japonicum* 61-A-101 and mycorrhizal fungi resulted in a more efficient colonization by *Glomus mosseae*, and increased N and P uptake by the host plant.

Similarly, it was indicated that coinoculation with rhizobia and AM fungi can favor the growth and yield of faba bean (Li et al., 2004). However, none of such favorable effects of coinoculation were reported in green gram (Saxena et al., 1997) and pea (Blilou et al., 1999). With regard to the synergistic association between rhizobia and mycorrhiza, Tajini et al. (2012) tested the benefits of coinoculation with those microbes on common bean as a practical method for agricultural development in marginal lands with P deficiency. As the dual symbiosis with rhizobia and mycorrhizal fungi, under P deficient conditions, may improve symbiotic N fixation in leguminous plants, they suggested this practice is environmentally and economically recommendable.

Wang et al. (2011) investigated the effects of coinoculation with mycorrhizal fungi and rhizobia on soybean growth with respect to the properties of root architecture and availability of N and P in a field experiment. According to their results root architecture and mycorrhizal fungal colonization were positively correlated. They indicated that a soybean genotype with a deep root network had greater mycorrhizal fungal colonization at low P, and more efficient nodulation under high P concentration than the shallow root genotype.

They also found that the synergistic association between rhizobia and AM fungi is dependent on N and P status affecting soybean growth. Such a coinoculation also increased soybean growth under low P and/or low N levels (increased shoot dry weight, along with plant N and P content). Root architecture determined the effects of coinoculation as the genotype with deep roots benefited more from coinoculation than the genotype with shallow roots. Thus, their results clarified some previous unknowns about such a tripartite association when nutrients are limited, indicating a theoretical aspect for planting soybean with coinoculants under field conditions.

It is known that inoculation with efficient rhizobia at ordinary rates cannot greatly increase the seed yield of soybean because the presence of less efficient native rhizobia restricts the occupation ratio of soybean nodules by inoculated rhizobial strains (Kvien et al., 1981; Weaver and Frederick, 1974). Accordingly, a higher rate of nodule occupancy by rhizobial inoculation increases soybean yield. Such an approach may be achieved by, for example, improving the method of inoculation and using the more efficient techniques (Takahashi et al., 1996).

For the screening and production of efficient and competitive strains, a high number of useful strains were isolated from recombinant and mutagenized rhizobia (Maier and Graham, 1990; Williams and Phillips, 1983). Yamakawa and Saeki (2013) compiled the inoculation methods, using effective *Bradyrhizobium* strains, to increase the yield of soybean in the south-west area of Japan.

Some rhizobial strains are capable of solubilizing nonsolubilizing P in the soil, which increases the rate of plant growth. Halder and Chakrabarty (1993) indicated that inorganic phosphate can be solubilized by a large number of *Bradyrhizobium* strains. Moreover, Chabot et al. (1996) found that the solubilization of phosphate by strains of *Rhizobium leguminosarum* bv. *phaseoli* was the most important mechanism enhancing the growth of maize and lettuce.

Antoun et al. (1998) also determined the solubilization of phosphate by *Bradyrhizobium* sp. (*Lupinus*). Similarly, Dashti et al. (1997) indicated phosphate solubilization and the subsequent acceleration of nodulation by PGPR increased N fixation activity in soybean under suboptimal root zone heat. It is known that a successful colonization of the legume rhizosphere is achieved if the *Bradyrhizobium* inocula constitute a large component in relation to the indigenous microorganisms for organic compounds excreted by the root (Van der Merwe et al., 1974). The high rate of indigenous bacteria as well as their rapid or slow grow influences the colonization of the host plant by rhizobial inocula.

In previous research, Anderson (1957) found a reduced number of nodules formed by *R. leguminosarum* biovar *trifolii* in *Trifolium repens* L., which was prevented by several bacteria without the ability to produce antibiotics. Similarly, Plazinski and Rolfe (1985) reported that the strains of *Azospirillium*, which did not produce antibiotics, decreased the nodulation of *Trifolium subterrancum* and *T. repens*. The bacterial strains producing antibiotics adversely affect the activity of many of the indigenous bacteria and, due to the reduced competition, proliferate and nodulate more extensively in the rhizosphere (Li and Alexander, 1988)

Mycorrhizal fungal inoculants of soybean

More research is available on the association of soybean with rhizobia than with mycorrhizal fungal association. Soybean is generally responsive to inoculation with *Glomus*; however, soybean response to inoculation with other genera such as *Gigaspora* has not been great (Nogueira and Cardoso, 2000). This is because the fungus absorbs P, resulting in the inhibition of plant P transporters. An increased concentration of micronutrients in plant tissues can be related to colonization by AM fungi. For example, colonized soybean can have a higher rate of zinc uptake than in plants fertilized with P (Cardoso, 1985).

In their greenhouse experiment, Nogueira and Cardoso (2000) tested the effects of two different mycorrhizal species fungi (*G. margarita* and *Glomus intraradices*), on the production of soybean under increasing P levels (0, 25, 50, 100, and 200 mg kg^{-1}). Increasing rates of P decreased root colonization as well as the total and active external mycelium in both fungal species. Due to a faster growth, *G. intraradices* inoculated soybean roots more efficiently and produced more active external mycelium than *G. margarita*. Soybean inoculation with *G. intraradices* and production of the active external mycelium increased with time and decreased with increasing P rates.

Other researchers, such as Minhoni et al. (1993), also investigated soybean inoculation by mycorrhizal fungi. They found that under increasing levels of P fertilization, root colonization by *Glomus macrocarpum* slowly decreased. Previously, Faquin (1988) indicated that there were no differences at 90 mg $kg^{-1}$of P and Siqueira et al. (1984) also detected an inverse association between P availability and root colonization in a sandy soil.

Moreover, inoculation with AM fungi can alleviate the negative effects of drought on soybean growth and prevent the premature senescence of nodules brought about by stress (Porcel et al., 2003). If mycorrhizal fungi and rhizobia are properly combined, such a combination enhances plant growth and resistance to pathogens (Aysan and Demir, 2009) and improves nodulation and nitrogen fixation (Barea et al., 2002). In the future, the role of mycorrhizal fungi inocula will be better illustrated in sustainable agriculture.

Other soybean inoculants

Rhizospheric ecology is of major interest for agronomists because it constitutes a combination of different interactions among the microorganisms and the environment surrounding roots affecting plant growth (Glick, 2012). Development of new technologies, which help in the understanding of such effects and hence benefit microorganisms, is essential. Legumes are greatly responsive to their rhizospheric microbes, especially rhizobia (Glick, 2012). The microbiota in the legume rhizosphere can be beneficial to plant growth and yield production by enhancing the processes of recycling, mineralization, and nutrient uptake. Moreover, microbes can increase plant growth by the production of plant growth regulating substances such as phytohormones, vitamins, and amino acids (Raaijmakers et al., 2008).

Estimation of crop loss by pathogens is not well documented; however, it may range from 7% to 15%, affecting major world crops (wheat, maize, soybean, potato, and rice) due to fungi and bacteria (Oerke, 2005). The endophytic, symbiotic, or free-living association of soil bacteria, PGPR, results in the promotion of plant growth by enhancing the acquisition of plant nutrients or influencing the intensity of plant hormone, or by alleviating the adverse effects of pathogens (Glick, 2012).

Rhizobial bacteria, as the symbionts of legumes, are able to fix atmospheric N_2 by the process of biological nitrogen fixation, providing one of the major macronutrients to the host plant. The process of biological N fixation is very promising because the production of nitrate fertilizers is expensive and is not recommended environmentally (high amounts of nonrenewable fossil energy are essential for the production of chemical fertilization resulting in the release of greenhouse gases) (reviewed by Laranjo et al., 2014). However, rhizobia may also be used as nonsymbiotic PGPR for the production of nonlegume crops (rice or wheat), which are of economic significance. Such details indicate the importance of rhizobia and the high rate of research on the use of rhizobia as models of mutualistic associations benefiting sustainable agriculture (reviewed by Laranjo et al., 2014).

Interestingly, using soil bacteria, which are nonrhizobia, for the inoculation of plants has also recently become the center of attention. For example, it has been indicated that *Azospirillum* is able to increase plant growth and seed yields under different conditions including stress by the use of different mechanisms, including the production of plant hormones and the increasing phosphate uptake by plant roots. *Azospirillum* coinoculated with rhizobia can enhance nodulation and N fixation in the host plant (Rodríguez-Navarro et al., 2011).

Interaction with biochar

With respect to the use of biochar as a source of soil amendment for the production of soybean, there is an increasing rate of research in this area. Biochar can increase CEC and base saturation nine fold over that in control soils, and significantly increases available K, Ca, Mg, total N, and P (Glaser et al., 2002). Iijima et al. (2015) recommended using nodule bacteria with biochar in the subsoil employing a technique called crack fertilization to enhance soybean yield. However, there are also potentially important differences that necessitate testing biochar for the negative effects it may have. Using biochar affected soybean production by increasing: (1) pH; (2) soil C; and (3) the surface area of subnanopores; and (4) by decreasing soil bulk density compared with the control (Mukherjee et al., 2014).

In Thailand, for example, the effects of quail litter biochar at 0, 24.6, 49.2, 73.8, 98.4, and 123 g per pot were tested on soybean growth. Biochar enhanced soil fertility and increased soybean production an optimum level of 98.4 g per pot mixture. Increasing the amount of biochar increased the nutrient contents in the soil; however, there were no effects on quantities of heavy metal residues in the leaves and seeds. Levels higher than 98.4 g per pot mixture were not recommended for plant growth because of the attendant alkalinity, affecting soil pH (Suppadit et al., 2012). Lastly, there are no adequate data available from which to draw conclusions about the usefulness of biochar. Complementary details can be obtained from other reviews (Biederman and Harpole, 2013; Lehmann et al., 2011).

Conclusions

In the introduction to this chapter, the interest in the impact of agriculture on soil structure or in changing the makeup of soil species was mentioned. It is because such effects can influence the production of soybean worldwide. The importance of soybean production was presented with respect to the parameters involved, which may affect such production. Among such parameters the most important is the use of rhizobial inocula. The use of mycorrhizal fungi is also of significance, which must be investigated further. Preserving agro-ecosystem services can be decisive to buffer the negative effects of global change. Throughout the chapter, the biotic associations of soybean have been pointed out. Mycorrhizal fungi and rhizobia have greater potential as biofertilizers, but further studies are required to understand the full role of soil microbes in association with soybean. Literature has proposed that few rhizobia can survive under unfavorable conditions in soil. Bioinoculants of rhizobial strains efficiently improve soybean growth and productivity. Finally, this chapter showed that soybean management can play a crucial role in the future of soybean production but more research is needed.

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