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# Organically Grown Soybean Production in the USA: Constraints and Management of Pathogens and Insect Pests

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**Abstract:** Soybean is the most produced and consumed oil seed crop worldwide. In 2013, 226 million metric tons were produced in over 70 countries. Organically produced soybean represents less than 0.1% of total world production. In the USA, the certified organic soybean crop was grown on 53 thousand ha or 0.17% of the total soybean acreage in the USA (32 million ha) in 2011. A gradual increase in production of organically grown soybean has occurred since the inception of organic labeling due to increased human consumption of soy products and increased demand for organic soybean meal to produce organic animal products. Production constraints caused by pathogens and insect pests are often similar in organic and non-organic soybean production, but management between the two systems often differs. In general, the non-organic, grain-type soybean crop are genetically modified higher-yielding cultivars, often with disease and pest resistance, and are grown with the use of synthetic pesticides. The higher value of organically produced soybean makes production of the crop an attractive option to some farmers. This article reviews production and uses of organically grown soybean in the USA, potential constraints to production caused by pathogens and insect pests, and management practices used to reduce the impact of these constraints.

**Keywords:** soybean; edamame; soymilk; tofu; aphids; rust; Sclerotinia stem rot; stink bugs; sudden death syndrome; cyst nematode

## 1. Introduction

Worldwide, soybean [*Glycine max* (L.) Merr.] is one of the most widely grown crops with 226 million metric tons produced in over 70 countries in 2013 [1]. Soybean was grown for organic oilseed production on 0.22 million ha in 2013 representing 29% of the total ha of organically grown oilseed crops worldwide [2].

In 2015, soybean was grown on 33.3 million ha or about 26% of the total USA cropland [3]. Since the USDA National Organic Program was implemented in 2002, the total area of organic crop production has increased from 0.5 million ha in 2002 to 1.3 million ha in 2011 with major growth in organically produced corn, soybean, and wheat; for soybean, 53 thousand ha were certified organic in 2011, which represents 0.17% of the total ha in soybean production [4]. In addition to domestic production, organic product imports added up to nearly 1.3 billion USD, and organic soybean products were among the top imports into the USA along with coffee, wine, and olive oil [2]. In general, there has been a gradual increase in production of organically grown soybeans worldwide. This is due in part to the increase in soybean products for human consumption such as edamame, organic vegetable oil, soybean milk, and tofu, and the increased need for organic soybean meal used to feed animals in organic production.

## 2. Uses and Production of Organically Produced Soybeans in the USA

### 2.1. Uses

Soy foods have been among the traditional staple foods in a number of Asian countries for centuries. These foods include okara, miso, natto, soymilk, soy sauce, soy sprouts, tempeh, tofu, and yuba [5]. In the last few decades, not only has the popularity of these foods spread throughout the world and been adapted to local diets, but uses for soybean in other human food products has been increasing. From its beginnings as an enterprise involving several family run businesses in the 1980s, the USA retail soy foods industry has grown dramatically, reaching a value of one billion USD in 1997 and 4.5 billion USD in 2013 [6]. Increased consumption may in part be due to the U.S. Food and Drug Administration's claim that consuming 25 grams of soy protein per day reduces the risk of cardiovascular disease. In addition, the increased popularity of low carbohydrate diets, the fact that soybean is one of the few plant-sourced complete proteins, and that it is perceived as a sustainable food choice, all contribute to the increased consumption of foods made from soybean [7]. Widespread and increasing use may also be due to its great versatility.

Soybean seeds are packaged as canned whole soybeans or processed into soy nuts or soy nut butter. A soy protein isolate is used to make soy meat analogs, infant formulas, baked goods, breakfast cereals, soups and sauces, cereal bars, snack bars, and fitness foods and drinks [6]. Soymilk can be used in liquid or powdered forms to make soy beverages, soy yogurts and cheeses, soy whipped toppings, and non-dairy frozen desserts. Soy flours (full-fat, low-fat and defatted) are utilized in baked goods or can be reconstituted into soy beverage products, and can also be made into textured vegetable protein. Food grade soy oil is utilized in the commercial food industry and is also packaged for the consumer market. For all of these products, food grade non-genetically modified clear hilum seeds are required. Food grade soybean cultivars have higher protein (40%–45% dry matter) and lower oil content (18%–20% dry matter) and may have other specialty traits including high sucrose or low lipoxygenase. These attributes are desirable to processors and manufacturers. Higher protein content translates to higher product yield and higher sucrose levels translate to faster fermentation and increased throughput in production. Another desirable attribute of food grade cultivars is uniform seed size, which translates to uniform absorption and higher yields in production of food products.

Another niche for the utilization of organic soybeans is edamame (soybean pods harvested in the fresh green vegetable stage [8]). Generally, edamame are processed for sale as a frozen vegetable product. With a long history of use in Japan and more recent history in several other Asian countries, popularity of edamame has now expanded worldwide. In the USA, they are one of the most consumed soy food, second only to soymilk and ahead of soy meat analogs and tofu [6]. Sales of frozen edamame in the USA went from 18 million USD in 2003 to 30 million USD in 2007 [9] reaching 84 million USD in 2013 [6]. Historically, product for this market was mainly sourced from China with an estimate of 70% in 2001 [10] and 97% in 2012 [11] imported for sale in the USA. In recent years there has been an effort in response to consumer demand to supply the market with more USA grown edamame [12]. Soybean cultivars suitable for edamame are large-seeded with high sugar content and little to no pubescence. Because the harvest window is very narrow for edamame, soybeans that cannot be harvested for edamame may be allowed to fully ripen to be harvested as food grade seeds.

Despite the expanding variety of food products and increasing consumer interest in such products that have created more demand for food grade organic soybean in the market, perhaps the biggest force currently affecting the market for organic soybean is the rapidly expanding market for organic animal products. Recent data shows 1.1 billion USD worth of organic milk was sold in the USA and 400 million USD worth of organic chicken eggs [13]. In 2015, the largest producer of organic meat in the USA, formerly privately owned, was purchased by an established food giant for about $775 million [14].

For an idea of market size and the need for soybean meal, in one week in mid-October 2015 there were 11 million hens producing over 56 million eggs and 350,000 chickens slaughtered [15], and for August 2015, 87 million kg of milk products were produced. Certified organic meat production requires certified organically grown feed, and organically grown soybean meal is utilized for this purpose. Since appearance is not an issue in feed, organic feed grade soybean cultivars are higher yielding dark hilum seeds [4] with a protein concentration slightly lower than food grade at greater than 39% dry weight. Discolored, split or irregularly sized food grade beans can however be incorporated into feed grade lots.

The USDA does not track exports Bethesda [16of organic food or feed grade soybean seeds, although several elevators reported international sale of organic soybeans (pers. comm.). In 2014, USA imports of organic soybean (food and feed grade) were valued at 184 million USD, up from 41 million USD in 2011, with India supplying the most beans to the market after USA domestic production (Figure 1). The beans are imported whole and distributed to buyers as whole beans or crushed bean meal.

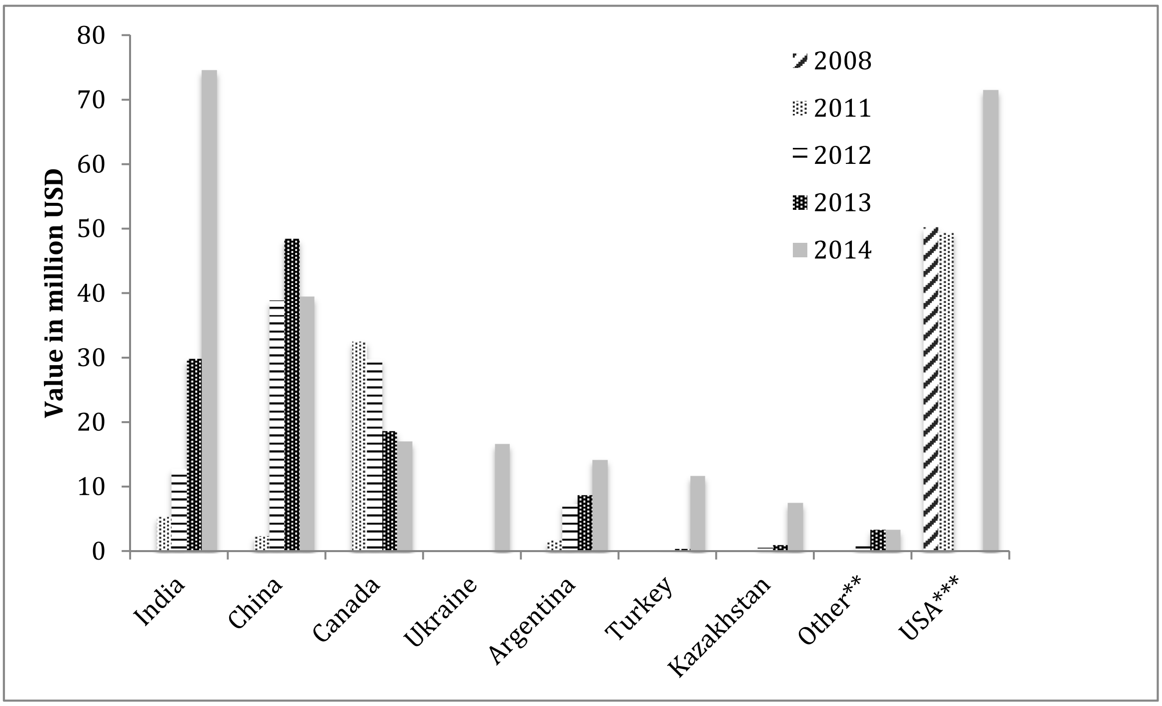


**Figure 1.** Value of organic soybean seeds imported into the USA from various countries from 2011 to 2014, and includes the value of USA *** produced organic soybean seeds. ** Includes seven other countries [16].

## *2.2. Production, Processing, and Pricing in the US*

Certified organically produced soybean was grown on 53 thousand ha in the USA in 2011 [4]. The states that produce the most certified organically grown soybean include Iowa, Minnesota, Michigan, and Illinois (Figure 2).

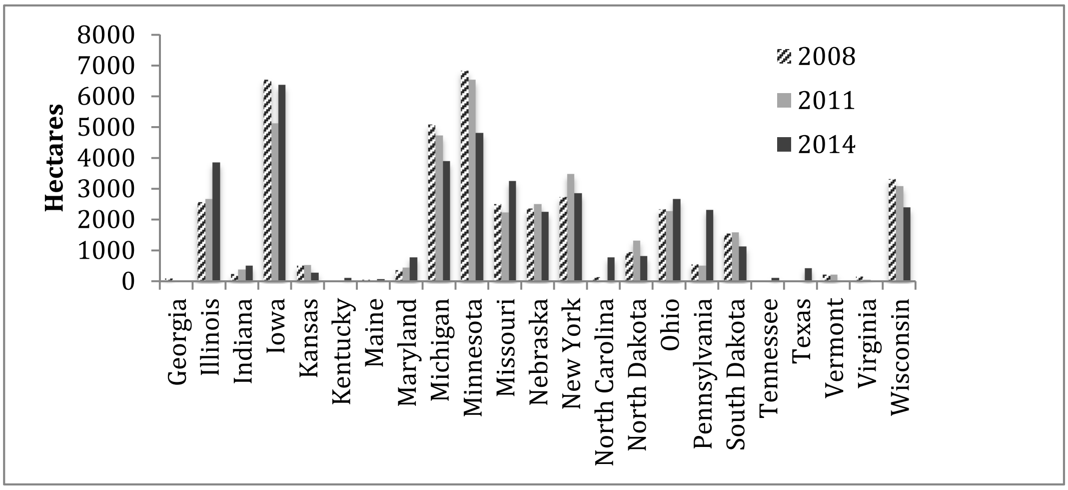


**Figure 2.** Production area harvested of organically produced soybean in the USA in 2008, 2011, and 2014 [3].

Most of the elevators that trade in organic soybeans are in these states, although the soybean seeds are stored on-farm until the contract is delivered. Organic soybeans are bought and sold as "premium beans" at a premium price compared to conventional soybeans, which comprise mostly transgenic soybean cultivars. Premium beans include non-GM clear and non-GM dark hilum soybeans, food and feed grade, respectively. Organic soybeans make up only a small portion of the premium beans for this market. The average per bushel prices for food grade and feed grade organic soybeans for the third quarter 2015 were 28.98 USD and 23.79 USD, respectively [13], while conventional soybeans averaged 9.19 USD for the same period [17]. A July 2015 USDA ERS report shows prices down slightly from a peak in 2012 [4] (Figure 3).

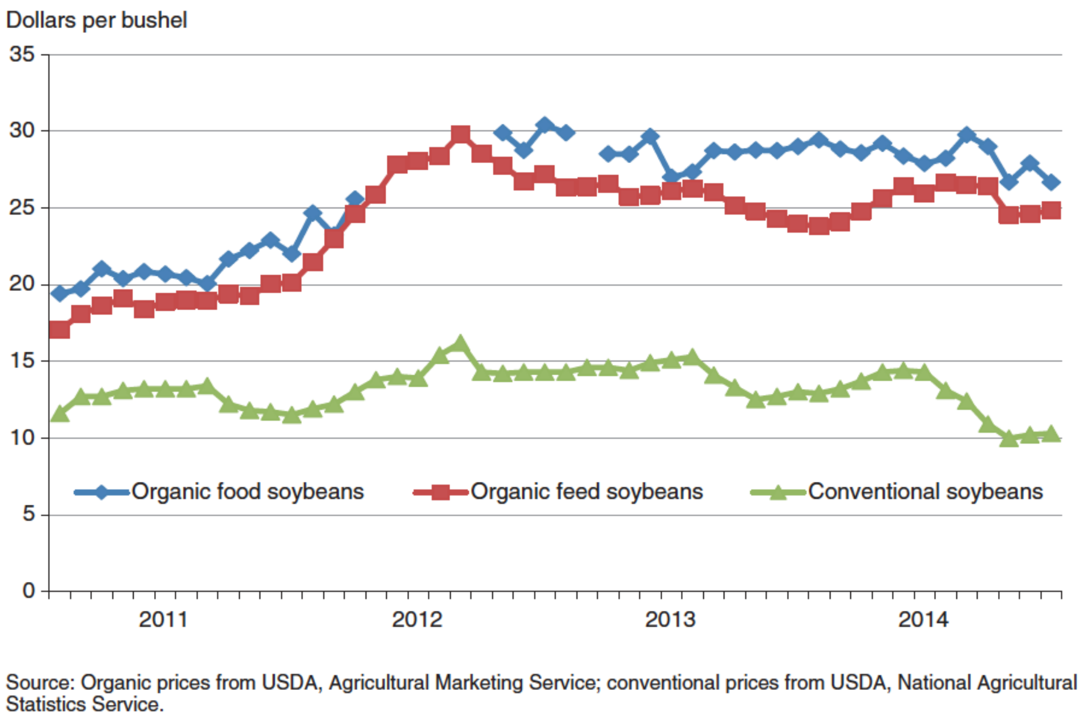


**Figure 3.** Prices in US dollars per bushel (27.22 kg) for soybean seed produced for organic food, organic feed, and non-organic (conventional) [4].

The report found costs for organically grown soybeans higher and yields lower than those for non-organic soybeans. However, the report concluded that these costs were offset, on average, by the price premium for organic soybeans [4].

## 3. Disease and Insect Pest Management Strategies in Organic Soybean Production

### 3.1. Overall Disease and Insect Pest Management Options for Organic and Non-Organic Production

Reducing the impact of pathogens and insect pests is a challenge in all agricultural production systems. Non-organic growers have tools to combat diseases and pests that differ from organic growers. Non-organic growers are able to use synthetic pesticides and transgenic cultivars, while many growers of organic soybeans use cultivars selected for specialty markets. These cultivars may not have the same agronomic traits found in the modern, grain-type cultivars that have benefitted from decades of breeding aimed at increasing yields and disease resistance [18,19].

To manage diseases and insect pests in an organic production system, growers often rely on integrated pest management (IPM) approaches. IPM is an ecologically based pest control strategy that relies heavily on scouting and greater awareness of the crop [20]. It incorporates biological control, cultural techniques, host resistance, and use of approved products to combat diseases and insect pests (Table 1).

**Table 1.** Examples of diseases and insect pests of organically grown soybean and their management in organic systems based on USDA organic production standards [1].

| Disease/pest [2] | Biological [3] | Cultural [4] | Resistance [5] | Pesticides [6] |
|---|---|---|---|---|
| Sclerotinia stem rot | Yes | Yes | No | Yes |
| Seedborne/seedling | Yes | Yes | Yes | Yes |
| Soybean aphid | Yes | Yes | Yes | Yes |
| Soybean cyst nematode | Yes | Yes | Yes | Yes |
| Soybean rust | No | Yes | No | Yes |
| Stink bugs | No | Yes | No | Yes |
| Sudden death syndrome | No | Yes | No | No |

[1] The USDA National Organic Program is a regulatory program housed within the USDA Agricultural Marketing Service that is responsible for developing national standards for organically produced agricultural products [21]; [2] This is not an exhaustive list of diseases and insect pests, but a list of pests that could be problematic in organic production fields; [3] These include commercial products that use biological control agents for pathogen and pest control; [4] These include techniques such as amendments, crop rotations, fertility management, tillage techniques, plant population densities, row spacing and row direction, time of planting, and others; [5] These include commercial cultivars, including grain-type non-genetically modified, which could be used in certified organic production; [6] These include commercial products that could be used in certified organic production according to USDA standards [21].

The Organic Materials Review Institute (OMRI), a nonprofit organization, provides organic certifiers, growers, manufacturers, and suppliers with an independent review of products intended for use in certified organic production, handling, and processing [22] and aids users in determining compliance with the USDA National Organic Standards. In some systems, monitoring of pathogens, insect pests, and environmental variables are used to develop models to assist with management decisions. Data or literature specifically on using IPM models for producing organically grown soybean are limited, but there are many methods available, some of which are reviewed later in this section.

### 3.2. Biological

#### 3.2.1. Biological Control, Biopesticides, and Soil Suppression

Biocontrol agents can be used to directly suppress plant pathogens or to stimulate host defense systems, making the plant hosts less susceptible to disease. The performance of a biocontrol product can vary somewhat more than the performance of a synthetic chemical based pesticide product, because the active ingredient is a living organism whose growth and activity is subject to environmental factors. However, when used properly and under the right conditions, biocontrol products can be very effective.

While specific biological control agents are currently being studied, and some organisms are being developed into commercial products, another aspect of biological control, called general suppression, also shows promise for managing soybean diseases, especially soilborne diseases. General suppression makes use of the fact that soils are habitats for many microorganisms, including fungi, bacteria, and nematodes, most of which are not pathogenic on plants and, in fact, are beneficial to plant growth in many ways, including that they can parasitize, compete with, or otherwise suppress plant pathogens. It has been shown that many soilborne plant diseases are more severe when sterilized soils are reinfested with plant pathogens as compared to when the pathogens are added to non-sterilized field soils [23].

Several biocontrol agents have been evaluated for their usefulness to control diseases of soybeans, with varying levels of success. The most effective strains of some of these organisms are now commercial products. The fungus *Trichoderma viride* has been developed into biocontrol products to be used against soybean pathogens including *Fusarium oxysporum* and *Pythium arrhenomanes* [24], and several species of the bacterial genus *Bacillus* have been shown to suppress the soybean cyst nematode. A specific strain *B. pumilus* GB34, has been developed as a commercial product. A few fungal biocontrol agents have been evaluated for their ability to control Sclerotinia stem rot including *Sporodesmium sclerotivorum* [25] and *Coniothyrium minitans* [26]; the latter is now a commercial product (Contans® WG, Bayer CropScience, Monheim am Rhein, Germany).

Microbial control of insects occurs naturally by bacteria, fungi, oomycetes, nematodes, and viruses. There are over 50 commercialized products that fit into the biopesticides category [27] and these are commonly used in some crops for controlling pest arthropods. Several strains of the bacterium *Bacillus thuringiensis* have been used as biological insecticides. This bacterium produces a number of chemicals that are toxic to certain insects, but not toxic to humans, other mammals and birds. Different strains of the bacterium produce different versions of the Bt toxin, which are effective against different ranges of insect pests. BT products are available commercially under several product names including Dipel®, Javelin®, Thuricide®, Worm Attack®, Caterpillar Killer®, Bactospeine®, and SOK-Bt®. Bt is recommended for management of green clover worm and Mexican bean beetle in soybeans [28].

#### 3.2.2. Beneficial Insects

There are many beneficial insects that reduce certain insect pest populations and the crop damage they cause. These insects are categorized into either predators (insects that directly feed on pests) or parasitoids (insects that colonize and feed internally on their host). Beneficial insects can either be released into fields directly or they can be attracted to the area with certain flowering plants. The flower choice depends on what time in the season a producer would need to attract a particular beneficial insect [29]. These are a few common insects that benefit and protect soybean production fields.

- **Assassin bugs** (Hemiptera: Reduviidae) are generalist predators found in most production systems. They feed on caterpillar eggs and larvae as well as other plant feeders [30,31].
- **Big-eyed bugs** (*Geocoris* spp.) are one of the most abundant predators. They colonize young soybean plants and remain throughout the season. Big-eyed bugs feed on aphids, whiteflies, mites, and caterpillar eggs and larvae. In the absence of insects, big-eyed bugs sustain populations by feeding on plants but cause little to no damage [31].
- **Spined soldier bugs** (*Podisus maculaventris*) are predatory stink bugs that can be confused with the plant-feeding brown stink bug. They are generalist predators and feed most commonly on leaf beetle larvae and also on soybean loopers. Spined solider bugs are large enough to feed on adult caterpillars [30,31].

- **Lady beetles** (Coleoptera: Coccinellidae) or ladybugs are the most familiar beneficial insect, and this group encompasses hundreds of different species. They are voracious predators and both larvae and adults preferentially feed on aphids, but will also consume mites and whiteflies [31].
- **Lacewings** (Neuroptera: Chrysopoidea), like lady beetles, are voracious predators. They feed on aphids, whiteflies, moths, and small caterpillars [31].
- **Aphid parasitoid** (*Lysiphlebus testaceipes*), also referred to as the aphid wasp, is a parasitic insect that lays its eggs inside the abdomen of an aphid. As the eggs hatch, the larvae feed on and kill the aphid. The adults will then leave the "aphid mummy" and go to a new host to "sting" and lay its eggs into it. These parasitic wasps may also spread the spores of *Neozygites fresenii*, the aphid fungus, which also colonizes and kills aphids [31].
- **Stink bug parasitoid** (*Trichopoda pennipes*) is a large fly, slightly larger than a housefly. These flies will lay their eggs on the backs of stink bugs. When the larvae emerge, they bore into their host and feed internally. There are also egg parasitoids in the Scelionidae family that will lay their eggs in stink bug egg masses [31].

### *3.3. Cultural Practices Used in Disease and Insect Pest Management in Organic Soybean Production*

The effect of cultural practices on disease and insect pest management should be carefully considered in all production systems, and may be most critical in organic production. A short list of cultural practices that especially impact disease and pest management include crop rotation schedules, fertility management, methods of tillage, plant population densities, row spacing and row direction, and time of planting.

#### 3.3.1. Amendments and Cover Crops

Organic matter in the soil is important, as it serves as a reservoir for nutrients and water, adds benefits to soil texture, and increases water infiltration into the soil. One way to increase organic matter in the soil is by planting cover crops between the plantings of main production crops. In temperate regions, cover crops are often planted in the fall, after the harvest of the production crop, and allowed to grow in the fall and following spring, when the cover crop is either incorporated into the soil or cut back prior to planting the next production crop. Some cover crops, such as cereal rye, are winter hardy and grow in the fall and the spring. Others, such as tillage radishes may be winter killed in regions with very cold winter climates. There are many benefits to planting cover crops, including the prevention of soil erosion, scavenging of nitrogen (to reduce nitrogen leaching and runoff), suppression of weed and insect pests, and the reduction of some plant diseases. Cereal rye and some other fall-seeded cover crops have been shown to reduce the severity of Rhizoctonia root rot and soybean cyst nematode affecting soybean crops when soybean is planted shortly after the incorporation of the cover crop in the spring. Results have not been consistent over time or across locations, but the practice does show promise as an alternative method of disease management.

It also has been demonstrated in several cropping systems that additions of organic material, such as composted plants and green manures, can increase the disease suppressive characteristics of soils in some circumstances [23,32–34]. This is not a simple situation, where the addition of any organic material to a soil will result in the suppression of any and all plant diseases. The success of disease suppression due to the addition of organic material depends on the pathogen(s) present, the amount and quality (carbon to nitrogen ratio) of the organic material, the time of incorporation, soil moisture and temperature levels after incorporation, and the properties of the soil. In fact, it has been shown that additions of organic material can suppress some diseases but increase the severity of others in some situations. In general, however, addition of organic material increases the diversity and activity of the community of microorganisms in the soil, and this often provides increased levels of suppression of soilborne plant diseases.

#### 3.3.2. Crop Rotations

Of the cultural strategies and techniques used to manage diseases and insect pests, crop rotation is very important for some pathogens and pests [35]. A typical crop rotation sequence in the Midwestern USA includes alternating plantings of corn and soybeans from year to year. Crop rotation can be used most effectively to manage pathogens and pests that (i) overwinter or survive when soybeans are not present in the field; (ii) survive for only a limited time in the field without the presence of a susceptible host; (iii) do not have an efficient means of long distance dispersal; and (iv) are not widely prevalent in the area. Planting soybean crops in the same location several years in a row can lead to a buildup of soybean dependent types of pathogens and pests in the field. Planting a non-host crop for one or more years between soybean plantings may lower the occurrence of the pathogens or pests present in the field.

Some pathogen and pest populations decline rapidly after a one-year rotation away from soybean, while others can survive for several years without the susceptible host being present. In this case, longer rotations (e.g., soybean, corn, wheat, alfalfa) are required to keep these pathogens or pests at an acceptably low level. For pathogens and pests that survive as saprophytes in the soil or on other host plants in the absence of soybeans, rotations may be ineffective. Likewise, there are other pathogens and pests that do not survive in the field at all and are reintroduced to the field every year, whether prevalent in a nearby geographic area or neighboring fields or introduced into the area from distant endemic areas via wind currents. Using rotations to manage pests in such cases will have little impact on the disease or pest development in the field. Examples of diseases that can be effectively managed using crop rotation include bacterial blight, soybean cyst nematode, and stem canker. These pathogens do not have a competitive saprophytic phase, have a fairly narrow host range, and do not have an efficient means of long distance dispersal. Examples of diseases for which rotation has little or no impact include sudden death syndrome, caused by a pathogen that survives in soil in the absence of a soybean crop; soybean rust, caused by a pathogen that produces spores that can be dispersed hundreds of miles by wind; and soybean mosaic, caused by a virus that does not survive in dead tissue but that is transmitted from live plants by several species of aphids.

#### 3.3.3. Tillage Practices

Tillage methods can also affect the survival and availability of pathogens and insect pests as many of them survive on infested crop debris on the soil surface. Incorporating plant debris into the soil buries the infested plant tissue, making it more difficult for the pathogens and pests to spread via splashing rain or wind currents. Once buried in the soil, microorganisms in the soil decompose the plant debris, and the pathogen dies when its food source is no longer available. Conservation tillage practices have been widely adopted to reduce soil erosion; however, the increased amount of crop debris left on the soil surface into the planting season has in some cases increased the incidence and severity of some soybean diseases and pests.

#### 3.3.4. Planting Dates and Densities

Adjusting the time of planting or selecting soybean cultivars of differing maturities may allow producers to avoid or minimize the time either when the host is most susceptible or when the pathogen or pest is most active. For example, the pathogen that causes sudden death syndrome (*Fusarium virguliforme*) infects young soybean seedlings, and the disease is often more severe on soybeans planted early in the season when soil conditions are cool and moist [36]. Planting later, when soils have warmed, may result in a lower incidence and severity of this disease. Other seedling diseases, such as Phytophthora root and stem rot, Pythium damping off, and Rhizoctonia root rot, are also usually more severe when soybean seeds are planted early into cool, moist soils, and delaying planting can minimize the development of these diseases as well [37].

High planting densities and narrow row spacing result in denser plant canopies and higher levels of humidity within the canopy. This can lead to increased levels of foliar diseases that are favored by moist conditions. For example, brown spot, caused by *Septoria glycines*, can start moving up the canopy earlier on soybeans planted in narrow rows [38]. High plant populations can also make soybeans more susceptible to diseases such as charcoal rot and Sclerotinia stem rot. Because soybeans adjust their canopy growth to fill existing space between plants and rows, lowering plant densities may not reduce the canopy density later in the season, but lower canopy densities earlier in the season may reduce or delay the development of some foliar diseases.

### *3.4. Host Resistance*

The soybean cultivars grown for organic production could theoretically be the same as those grown for grain production, which are generally high-yielding cultivars with resistance to many diseases and pests [19]. However, many commercial grain-types are transgenic and are not permissible in organic production. Furthermore, most organic soybean production is for niche markets that require unique traits not targeted in commercial grain-type breeding programs. Breeding soybean cultivars specifically for niche markets in organic production is on the increase, but not specifically for disease and pest resistance. For this reason, there is great potential for further enhancement of niche market cultivars in terms of resistance to most diseases found in grain-type cultivars including resistance to aphids, cyst nematode, frog-eye leaf sport, Phytopthora root and stem rot, rust, and others where single resistance genes can be moved into selected cultivars by backcrossing.

### *3.5. Organic Certified Pesticides*

There is widespread belief that the use of pesticides is not allowed in the production of organically certified crops. While incorrect, it is true that in organic production systems the use of a pesticide is viewed as a last resort. The rules and regulations governing organic certification in the USA, developed by the National Organic Program Board, allow for the use of certain kinds of pesticides under certain conditions, and as stated "organic standards are designed to allow natural substances in organic farming while prohibiting synthetic substances" [21]. The National Organic Program Board maintains a list of substances and whether use in organic productions systems is approved or prohibited. Exemptions have been made to allow the use of some synthetic chemicals, such as mating-disruptive pheromones used to manage insect pests, and products such as baking soda. However, not all "natural" substances are approved for use. The use of natural toxins, such as strychnine and arsenic are prohibited in organic production [21]. Many of the pesticides in the allowed section of the National Organic Program Board list should be used only after other management strategies, such as preventative, mechanical, and physical, management practices have been implemented [22].

Pesticides or other substances approved to manage disease problems in organic systems include "mineral based" substances such as copper and sulfur based materials, hydrogen peroxide and hydrogen dioxide, potassium bicarbonate, neem oil and other plant extracts, and potassium silicate. One of the first "modern fungicides" to be developed was Bordeaux mixture, a mixture of copper sulfate ($CuSO_4$) and slaked lime [$Ca(OH)_2$]. This fungicide was first used in the management of an epidemic of downy mildew of grape in France in the late 1880s, and it is still used effectively today in the management of plant diseases caused by bacteria and fungi. This and other copper based fungicides/bactericides, such as copper hydroxide [$Cu(OH)_2$] a "fixed" or insoluble form of copper, are approved for use in organic production systems per the descriptions below, with some restrictions to prevent the buildup of copper in the soil.

- **Copper sulfate** application rates are limited to those which do not increase baseline soil test values for copper over a time frame agreed upon by the producer and accredited certifying agent. When used for plant disease control must be used in a manner that minimizes accumulation of copper in the soil; it may be used as an algicide, insecticide, or disease control if the requirements of article 205.206(e) are met.

- **Coppers—fixed** may be used for plant disease control if the other non-chemical management strategies have been implemented, must be used in a manner that minimizes copper accumulation in the soil, and shall not be used as herbicides.

While the use of foliar fungicides for the management of diseases in non-organic soybean production systems increased in recent years when soybean prices reached a level that allowed applications to be economically justified, most of the fungicides currently used to manage diseases such as frogeye leaf spot and soybean rust are not allowed in organic production systems. However, an evaluation of fungicides allowed for use in organic production for the management of soybean rust found that of those tested, products with copper compounds as the active ingredient, performed the best [39].

## 4. Biological Enhancement to Improve Plant Growth

### *4.1. Plant Growth Promoting Rhizobacteria*

Plant-growth promoting rhizobacteria (PGPR) are characterized by their ability to enhance plant health by increasing nutrient update, fixing nitrogen, suppressing disease, stimulating phytohormone production, and eliciting defense responses [40–42]. Overall, PGPR aid in keeping the plant healthy, allowing the plant to better withstand abiotic and biotic stresses.

Nitrogen is an essential nutrient for plant health and growth as it is required for synthesis of nucleic acid, proteins, and chlorophyll [41]. Although, 78% of the atmosphere is $N_2$ gas, plants can not directly utilize this form, and therefore, major industrial farms apply exogenous N in the form of anhydrous ammonia or as a nitrogen solution. Leguminous plants, such as soybean, have the ability to fix their own nitrogen by forming associations with PGPR. PGPR survive freely in the soil, but the symbiotic relationship with legumes is what activates their nitrogen-fixing properties. Symbiosis starts with the host plant recognition of specific PGPR via chemical signals. This will cause the rhizobia to migrate towards the root hairs and penetrate the plant cells, facilitated by plant nodulation or nod factors. Once in the cytoplasm, the rhizobia form structures called bacteroids and begin nitrogen fixation.

Many rhizobia suppress certain diseases directly by producing toxic metabolites or indirectly by stimulating host defense responses [41]. PGPR have been shown to produce antibiotics, beta-1,3 glucanases, chitinases, cyanide, and siderophores, that inhibit growth of certain soil pathogens. For example, *R. japonicum* secretes rhizobitoxine, a toxin shown to inhibit infection of *Macrophomina phaseolina,* a soil-borne pathogen that causes charcoal rot in soybean [43].

PGPR can also suppress disease indirectly by promoting plant health, stimulating symbiosis with fungal mutualists, and by eliciting a defense response referred to as induced systemic resistance [40,44]. Activation of induced systemic resistance increases responsiveness of both the jasmonic acid and ethylene-defense pathways by a phenomenon referred to as priming [45,46]. *Bacillus* spp., *Pseudomonas* spp., and *Rhizobium* spp. have all exhibited the ability to elicit a resistance response in hosts [41].

Although not specifically organic-based, there has been a significant amount of research done on the positive impacts of PGPR on soybean [47–49]. Rhizobacteria help to increase nutrient uptake and elicit defense responses in plants, which makes these microbes a valuable amendment for organic producers as a way to promote health and potentially protect plants from diseases and pests. There are a large number of organically certified products containing different PGPR strains [22].

### *4.2. Mycorrhizal Associations*

The phylum Glomeromycota is composed of arbuscular mycorrhizal (AM) fungi, an ancient group of fungi that are believed to have helped plants first move onto land [50]. With over 200 species, AM fungi are ubiquitous and survive in a broad range of environments and form mutualistic associations with approximately 80% of all land plants including soybean. They contribute many benefits to the associated plant including enhanced nutrient uptake, drought tolerance, and disease and pest resistance. AM fungi are obligate biotrophs and persist in the soil as spores until they detect a host through exogenous signaling. This will stimulate germination and hyphal growth, resulting in the formation of a symbiotic connection with roots of the plant host. The extra radical hyphae will extend past the root system to obtain immobile nutrients, particularly phosphorus, in exchange for carbon from the plant [50,51].

Interest in AM fungi has increased in recent years. Their positive impact on crop production includes suppression of certain diseases by outcompeting pathogens for root tissue and stimulating host defense responses. To establish a symbiotic relationship, AM fungi interact with the plant to alter some specific plant defense pathways including the salicylic acid-dependent and the jasmonic acid/ethylene-dependent pathways to establish successful associations with roots [51]. The altering of these defense pathways often makes mycorrhizal plants more resistant to necrotrophic pathogens and chewing insects, but may make the plants more susceptible to biotrophic pathogens [51]. Mycorrhizal induced resistance has been shown to reduce disease severity in roots and also in shoots of colonized plants [51]. However, the effect of AM fungi is highly dependent on the host-pathogen-AM fungi interaction.

Overall, AM fungi are considered to be beneficial to soybean production, by increasing growth, nutrient uptake, and yield, especially when co-inoculated with PGPR [52,53]. Although there is little data on the effect of AM fungi in certified organic soybean fields, there are commercial OMRI-certified mycorrhizal inoculants labeled for use on soybeans [22].

## 5. Major Diseases and Insect Pests of Organically Grown Soybean

### *5.1. Diseases and Insect Pests in Organic and Non-Organic Production Fields*

There is little distinction among the major diseases and pests found in organically grown *versus* non-organically grown soybean, although there are differences in occurrence and severity of disease and the size of pest populations and corresponding management strategies. This section outlines methods used in organic systems to control threatening diseases and insect pests.

### *5.2. Seed Production Fields, Seed Staining, and Seed Treatments*

Obtaining high quality seed, uniform in size and appearance, is a main concern for producers of food grade soybeans. Producers will not receive the highest premiums for seed that is discolored for any reason. Seed can become stained by grass, leaves or dirt during harvest, or become discolored due to pathogens or pests (Figure 4).

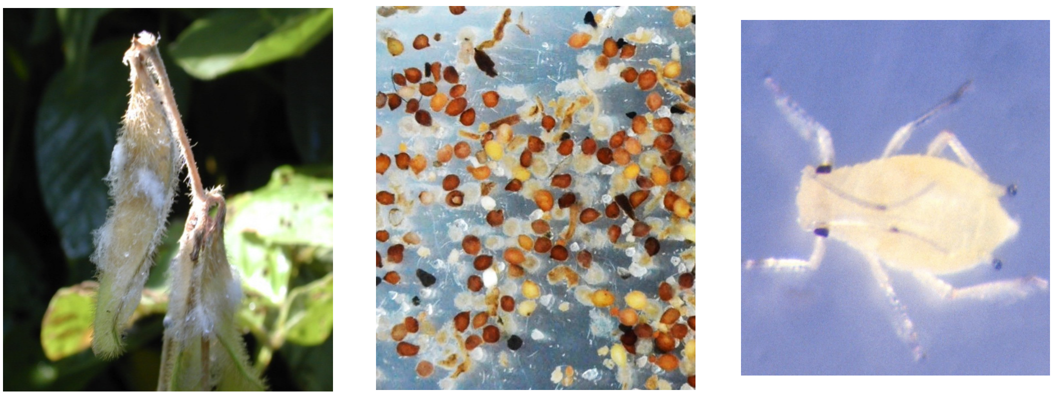

**Figure 4.** *Cont.*

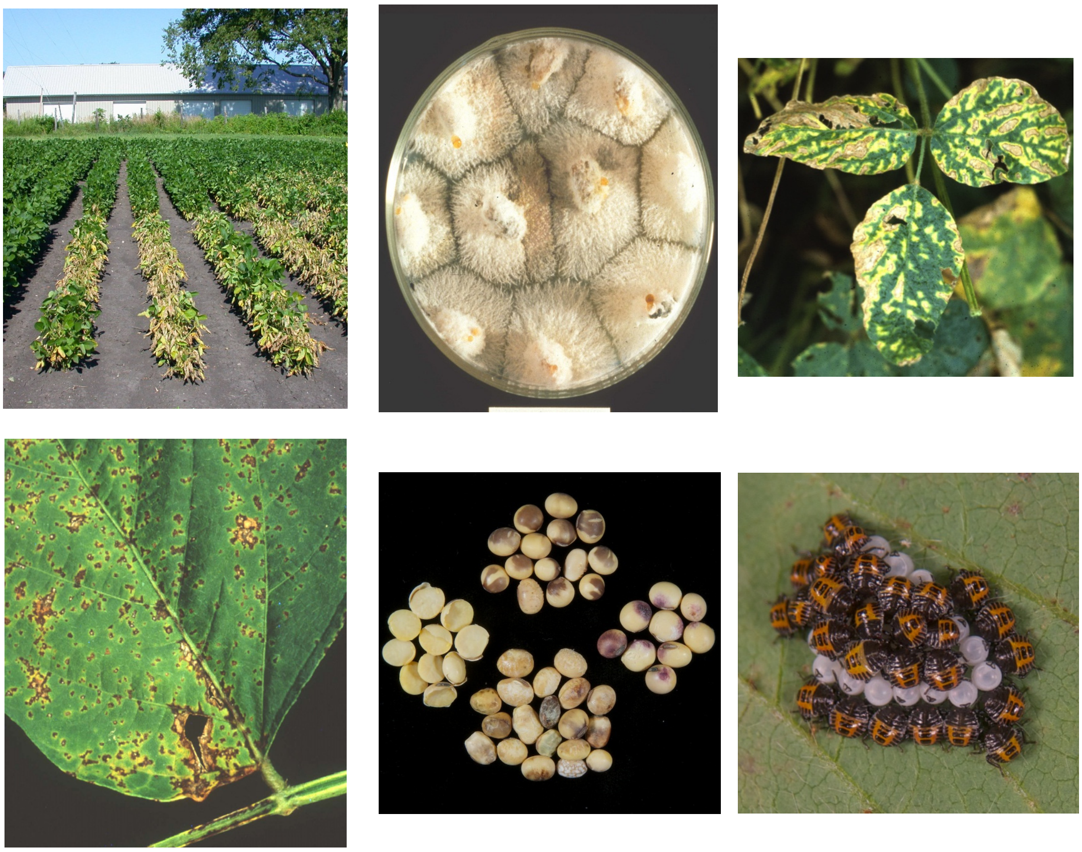

**Figure 4.** Examples of soybean diseases and insect pests found in organically produced soybean. Top right from left to right: Sclerotinia stem rot, soybean cyst nematode, and the soybean aphid. Middle right to left: Phytophthora root and stem rot, Phomopsis seed decay, and sudden death syndrome. Bottom right to left: soybean rust, seed abnormalities, and marmorated stink bug nymphs.

*Bean pod mottle virus* (BPMV) and *Soybean mosaic virus* (SMV) are viral pathogens that cause dark blotches on seed coats [54]. BPMV is transmitted by *Cerotoma trifurcate*, the bean leaf beetle; SMV is transmitted by the soybean aphid as well as other aphids [55]. Purple stain, caused by fungal pathogen *Cercospora kukuchii*, is another common cause of seed discoloration [56]. Besides staining, there are some fungi that cause Phomopsis seed decay, which can result in shriveled light-weight seed. Control methods for these issues focus on vector control, but overall the most effective method is sorting and removing stained seeds [57].

Upon arrival at the elevator, seeds are run through a cleaning process to remove large foreign field material. The seeds move through conveyors to remove small seeds, splits, discolored seed, and then sorted by size. Sorting at the elevators is essential to aggregate high quality uniform seed lots of seed for buyers who value uniform seeds for their processing. It is also highly effective at achieving high quality, pathogen-free seed stock for seed fields by removing seed stained or shriveled by disease and also by removing sclerotia carried on any field material.

Seed used in organic production for the food grade organic or feed grade organic soybean markets must originate from certified organic fields. In most non-organic soybean production, seeds are coated with fungicides that provide some protection against seedborne diseases and pre- and post-emergence damping off (Figure 4), and synthetic fungicides are applied late in the reproductive stages of the crop to protect against seedborne pathogens. In organic seed production fields, use of an organically approved seed coatings treatment to prevent diseases is not the default. Alhough several products are available [58,59]. In organic seed production fields, control methods may include delaying planting to avoid cool wet soil conditions or may focus on vector control. However, currently the most effective method is sorting and removing stained seeds before planting.

### *5.3. Sclerotinia Stem Rot*

Sclerotinia stem rot (SSR) is caused by the fungal pathogen, *Sclerotinia sclerotiorum*, which is a highly destructive pathogen that threatens many crops (Figure 4). The fungus survives in the soil in the form of sclerotia, its overwintering structure. During cool and moist conditions, the sclerotia germinate to produce structures called apothecia. These apothecia forcibly eject spores that will land on soybean plants and germinate on dehiscing petals and infect the stems of plants [60]. The disease is difficult to control. In non-organic soybean production application of fungicides and partial resistance are used to lower the impact of the disease. Although there is little information on the effectiveness of control in organically grown soybean, the longer crop rotation cycles found in many organic-based systems may contribute to further degradation of sclerotia in the soil than occurs in a corn-soybean rotation found in non-organic systems [61,62].

### *5.4. Soybean Aphid*

*Aphis glycines* Matsumura (Hemiptera: Aphididae), the soybean aphid, has been a major concern in North America since its arrival in 2000 [63] (Figure 4). Soybean aphids feed on the above-ground plant parts, reducing photosynthate production and yield. The soybean aphid can also indirectly reduce yield by transmitting certain viruses [63]. Management of the soybean aphid is achieved mainly by selecting resistant cultivars and by applying synthetic insecticides [64]. When host resistance is not a viable option, organic producers have options to release natural enemies, such as parasitic wasps or ladybeetles, or they can use an organic-certified insecticide containing pyrethrum.

### *5.5. Soybean Cyst Nematode*

*Heterodera glycines*, the soybean cyst nematode, is ubiquitous in most soybean producing regions and is one of the most important diseases in the USA [65] (Figure 4). The nematode feeds on the soybean roots resulting in stunted plants with reduced yields. The main methods of combatting this nematode is through crop rotation and host resistance [61]. In addition, the diversity of cropping and amendments used in organic production systems may result in reduced issues with soybean cyst nematode compared to a regular corn-soybean rotation system.

### *5.6. Sudden Death Syndrome*

Sudden death syndrome (SDS) is caused by the soilborne fungal pathogen *Fusarium virguliforme* and is identifiable mid to late season by distinctive interveinal chlorosis and necrosis foliar symptoms and, in severe cases, defoliation (Figure 4). SDS is often more severe when cooler and wetter conditions occur during some part of the growing season [66]. Management of SDS is primarily through cultural practices and the use of host resistance. Planting later to avoid cool, wet conditions, using deep tillage before or after the season, and selecting cultivars with partial resistance may reduce the severity of SDS [67].

### *5.7. Soybean Rust*

Soybean rust is a foliar disease caused by the fungal pathogen, *Phakopsora pachyrhizi* (Figure 4). The disease is more prevalent in subtropical and tropical regions, but has become a regular concern in the southern USA [68]. The fungus is an obligate biotroph and will form haustoria in plant tissues to remove photosynthates from leaves. The disease is commonly managed with the application of fungicides. Although sources of resistance are known, resistant cultivars are not yet commercially available in the USA [68]. For management in an organic system, there are a number of studies that have shown that fungicides, including copper-based fungicides, can effectively reduce the severity of this disease [69]. Planting organic fields in isolation, or using early planting dates or earlier maturing cultivars may also be partially effective at reducing the impact of rust [70].

### *5.8. Stink Bugs*

Stink bugs (Hemiptera: Pentatomidae) are shield-shaped insects that feed on the pods of soybean directly reducing yields and potentially resulting in visible seed damage (Figure 4). Historically, stink bugs have been a common problem in the southern USA, but there are many different species and several of them have been reported to occur wherever soybeans are produced [71]. Management of stink bugs primarily occurs after thresholds are reached. Although threshold numbers vary by state and region, in general, if five to nine bugs are found in 25 sweeps, then action is recommended [71]. Pyrethroid insecticides may provide some control, but along with insecticide use planting earlier or planting earlier-maturing cultivars to avoid the population build-up later in the season [62].

## 6. Future of Organic Soybean Production

Production of organically grown crops worldwide has increased because of increased demand for organic food products and increased presence of organic products in mainstream retail food outlets. For organically grown soybean, it is likely that the cropping area will double or triple in the next few decades, both in the USA and internationally, to meet demand for increased human consumption and increased demand for organic animal products. Diseases and insect pests pose potential constraints to production that can be costly for growers. Many of the current management tactics for organic producers only partially alleviate the problem and may be costly to implement. One management approach that needs further attention is to improve breeding efforts for increasing disease and insect pest resistance, which ultimately will provide growers with higher yielding disease and pest resistant cultivars. Another area of management that can aid organic soybean growers is the continued improvement of organically approved biopesticides and other products that stimulate growth and plant defenses to pathogens and pests. Private industry has increased their research capacity in these areas, and will continue to push forward improved soybean cultivars and products for certified organic production fields. Public research institutions may provide service to the growers by evaluating effectiveness of available cultivars and products. Other concerns that can affect yield, such as weed problems and feeding damage by mammals, will also need to be addressed as production expands. Growers in the future may benefit from advanced technologies that could include robots on the ground and in the air to reduce the impact of not only diseases and insect pests, but other abiotic or biotic constraints. Computer-based precision will be especially advantageous for organic growers. In summary, the increase in production of organically grown soybean will be complimented with improvements in host genetics, more organically approved biopesticides, other products that stimulate plant growth and yield, and new technological innovations that increase overall efficiency and productivity. All of these will add value to organically grown soybean, and knowledge advances for improved organic soybean production may in turn prove to be beneficial to other organic crops and to non-organically grown soybean.

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## References

1. Food and Agricultural Organization. Available online: http://www.faostat.fao.org (accessed on 25 October 2015).
2. Willer, H.; Lernoud, J. *The World of Organic Agriculture. Statistics and Emerging Trends 2015*; FiBL-IFOAM Report; Research Institute of Organic Agriculture (FiBL), Frick, and IFOAM—Organics International: Bonn, Germnay, 2015.
3. USDA-National Agricultural Statistics Service. Available online: www.nass.usda.gov (accessed on 28 October 2015).

4. McBribe, W.; Greene, C.; Foreman, L.; Ali, M. The profit potential of certified organic field crop production. *USDA-Economic Research Service*; Report Number 188. USDA: Washington, DC, USA, 2015.
5. Raghuvanshi, R.; Bisht, K. Uses of soybean: Products and preperation. In *Soybean: Botany, Production, and Uses*; Singh, G., Ed.; CAB International: Wallingford, UK; Cambridge, MA, USA, 2010; pp. 276–279.
6. Soyfoods Association of North America. Available online: www.soyfoods.org (accessed on 25 October 2015).
7. SoyConnection. The United Soybean Board. Available online: www.soyconnection.com (accessed on 25 October 2015).
8. Shanmugasundaram, S.; Yan, M. Vegetable soybean. In *Soybean: Botany, Production, and Uses*; Singh, G., Ed.; CAB International: Wallingford, UK; Cambridge, MA, USA, 2010; pp. 276–279.
9. Bernick, K. Edamame Takes Root In U.S. 2009, Corn and Soybean Digest. Available online: http://cornandsoybeandigest.com/edamame-takes-root-us (accessed on 28 October 2015).
10. Shurtleff, W.; Aoyagi, A. *History of Edamame, Green Vegetable Soybeans, and Vegetable-Type Soybeans: Bibliography and Sourcebook*; Soyinfo Center: Lafayette, CA, USA, 2009.
11. Roseboro, K. Edamame Offers Good Non-Gmo Opportunities to US Farmers. Available online: www.nongmoreport.com/articles/april2012/edamame-non-gmo-us-farmers.php (accessed on 28 October 2015).
12. McBride, J. Snacking on Soy: Arkansas Grows Edamame Commercially. Available online: www.farmflavor.com/ us-ag/ arkansas/top-crops-arkansas/snacking-on-soy-arkansas-grows-edamame-commercially/ (accessed on 28 October 2015).
13. USDA-AMS. Oganic Grade and Feedstuffs Monthly/Quarterly. Available online: www.ams.usda.gov/mnreports/lsbnof.pdf (accessed on 28 October 2015).
14. Kesmodel, D. Seller of Spam to Buy Applegate Farms Amid Change in American Eating Habits. Available online: www.wsj.com/articles/hormel-to-buy-organic-meat-maker-1432671859 (accessed on 28 October 2015).
15. USDA-AMS. Weekly USDA Certified Organic Poultry and Eggs. Available online: www.ams.usda.gov/mnreports/pyworganic.pdf (accessed on 28 October 2015).
16. USDA-FAS. Global Agricultural Trade System. Available online: www.apps.fas.usda.gov/gats (accessed on 28 October 2015).
17. USDA-AMS. Custom report. Available online: http://www.ams.usda.gov (accessed on 28 October 2015).
18. Fox, C.; Cary, T.; Colgrove, A.; Nafziger, E.; Haudenshield, J.S.; Hartman, G.L.; Specht, J.; Diers, B.W. Estimating soybean genetic gain for yield in the northern united states—influence of cropping history. *Crop Sci.* **2013**, *53*, 2473–2482. [CrossRef]
19. Hartman, G.L.; Bowen, C.R.; Haudenshield, J.S.; Fox, C.; Cary, T.R.; Diers, B.W. Evaluation of disease and pest damage on soybean cultivars released from 1923 through 2008 under field conditions in central illinois. *Agron. J.* **2015**, *107*, 2373–2380. [CrossRef]
20. Flint, M.L.; Bosch, R.V.D. *Introduction to Integrated Pest Management*; Plenum Press: New York, NY, USA, 1981.
21. USDA-Agricultural Marketing Service. National Organic Standards Board. Available online: www.ams.usda.gov/rules-regulations/organic/nosb (accessed on 28 October 2015).
22. Organic Materials Review Institute. Available online: www.omri.org (accessed on 28 October 2015).
23. Marzano, S.L.; Villamil, M.M.; Wander, M.B.; Ugarte, C.M.; Wen, L.; Eastburn, D.M. Organic transition effects on soilborne diseases of soybean and populations of Pseudomonadaceae. *Agron. J.* **2015**, *107*, 1087–1097. [CrossRef]
24. John, R.P.; Tyagi, R.D.; Prévost, D.; Brar, S.K.; Pouleur, S.; Surampalli, R.Y. Mycoparasitic *trichoderma viride* as a biocontrol agent against *Fusarium oxysporum* f. sp. *adzuki* and *Pythium arrhenomanes* and as a growth promoter of soybean. *Crop Prot.* **2010**, *29*, 1452–1459.
25. Del Rio, L.E.; Martinson, C.A.; Yang, X.B. Biological control of sclerotinia stem rot of soybean with *Sporidesmium sclerotivorum*. *Plant Dis.* **2002**, *86*, 999–1004. [CrossRef]
26. Gerlagh, M.; Goossen, H.M.; Fokkema, N.J.; Vereijken, P.F.G. Long-term biosanitation by application of *Coniothyrium minitans* on *Sclerotinia sclerotiorum*-infected crops. *Phytopathology* **1999**, *89*, 141–147. [CrossRef] [PubMed]

27. Lacey, L.A.; Grzywacz, D.; Shapiro-Ilan, D.I.; Frutos, R.; Brownbridge, M.; Goettel, M.S. Insect pathogens as biological control agents: Back to the future. *J. Invertebr. Pathol.* **2015**, *132*, 1–41. [CrossRef] [PubMed]
28. Penn State Extenion. The Agronomy Guide. 2015. Available online: www.extension.psu.edu/agronomy-guide/pm/tables/table-2-4-17 (accessed on 28 October 2015).
29. Fiedler, A.; Tuell, J.; Isaacs, R.; Landis, D. Attracting beneficial insects with native flowering plants. *Mich. State Ext. Bull.* **2007**, E-2973. Available online: www.nativeplants.msu.edu/uploads/files/E2973.pdf (accessed on 28 October 2015).
30. Grantham, R.; Arnold, D.C. Beneficial insects. *Okla. State Ext.* **2013**, Epp-7307. Available online: www.Osufacts.Okstate.Edu/docushare/dsweb/get/document-8688/ (accessed on 28 October 2015).
31. Stewart, S.D.; Layton, B.; Catchot, A. Common beneficial arthropods found in field crops. *Univ. Tenn. Ext.* **2007**, W127. Available online: www.extension.org/mediawiki/files/0/00/W127-Beneficials.pdf (accessed on 28 October 2015).
32. Baysal, F.; Bebitez, M.; Kleinhenz, M.; Miller, S.A.; Gardener, B. Field management effects on damping-off and early season vigor of crops in a transitional organic cropping system. *Phytopathology* **2008**, *98*, 562–570. [CrossRef] [PubMed]
33. Baysal, F.; McSpadden-Gardener, B.; Cardina, J.; Kleinhenz, M.; Miller, S. Effect of field management practices on disease development, soil chemistry and yield in organic tomatoes. *Acta Hortic.* **2009**, *808*, 113–116. [CrossRef]
34. Stone, A.; Scheuerell, S.; Darby, H.; Magdoff, F.; Ray, R. Suppression of soilborne diseases in field agricultural systems: Organic matter management, cover cropping, and other cultural practices. *Soil Organic Matter Sustain. Agric.* **2004**, 131–177.
35. Curl, E. Control of plant disease by crop rotations. *Bot. Rev.* **1963**, *29*, 413–479. [CrossRef]
36. Scherm, H.; Yang, X. Development of sudden death syndrome of soybean in relation to soil temperature and soil water matric potential. *Phytopathology* **1996**, *86*, 642–649. [CrossRef]
37. Thomson, T.B.; Athow, K.L.; Laviolet, F.A. Effect of temperature on pathogenicity of *Pythium aphanidermatum*, *P. debaryanum*, and *P. ultimum* on soybean. *Phytopathology* **1971**, *61*, 933–935. [CrossRef]
38. Eastburn, D.; DeGennaro, M.; DeLucia, E.; Dermody, O.; McElrone, A. Elevated atmospheric carbon dioxide and ozone alter soybean diseases at soyface. *Glob. Chang. Biol.* **2010**, *16*, 320–330. [CrossRef]
39. Gevens, A.; Wright, D.; Blount, A.; Mizell, R.; Sprenkel, R.; Mackowiak, C.; Olson, S.; Smith, J.A.; Marois, J.; Datnoff, L. Alternatives for organic soybean production. *Using Foliar Fungicides to Manage Soybean Rust*; Dorance, A., Draper, M., Hershman, D., Eds.; USDA: Washington, DC, USA, 2007; pp. 81–82.
40. Lugtenberg, B.; Kamilova, F. Plant-growth-promoting rhizobacteria. In *Annual Review of Microbiology*; Annual Reviews: Palo Alto, CA, USA, 2009; Volume 63, pp. 541–556.
41. Gopalakrishnan, S.; Sathya, A.; Vijayabharathi, R.; Varshney, R.K.; Gowda, C.L.L.; Krishnamurthy, L. Plant growth promoting rhizobia: Challenges and opportunities. *3 Biotech* **2015**, *5*, 355–377. [CrossRef]
42. Rodriguez-Navarro, D.N.; Oliver, I.M.; Contreras, M.A.; Ruiz-Sainz, J.E. Soybean interactions with soil microbes, agronomical and molecular aspects. *Agron. Sustain. Dev.* **2011**, *31*, 173–190. [CrossRef]
43. Chakraborty, U.; Purkayastha, R. Role of rhizobitoxine in protecting soybean roots from macrophomina phaseolina infection. *Can. J. Microbiol.* **1984**, *30*, 285–289. [CrossRef] [PubMed]
44. Pieterse, C.M.J.; Van Wees, S.C.M. Induced disease resistance. In *Principles of Plant-Microbe Interactions: Microbes for Sustainable Agriculture*; Lugtenberg, B., Ed.; Springer International Publishing: Bethesda, MD, USA, 2015; pp. 123–134.
45. Conrath, U.; Pieterse, C.M.J.; Mauch-Mani, B. Priming in plant-pathogen interactions. *Trends Plant Sci.* **2002**, *7*, 210–216. [CrossRef]
46. Kazan, K.; Manners, J. Myc2: The master in action. *Mol. Plant* **2013**, *6*, 686–703. [CrossRef] [PubMed]
47. Bhattacharyya, P.N.; Jha, D.K. Plant growth-promoting rhizobacteria (PGPR): Emergence in agriculture. *World J. Microbiol. Biotechnol.* **2012**, *28*, 1327–1350. [CrossRef] [PubMed]
48. Nehra, V.; Choudhary, M. A review on plant growth promoting rhizobacteria acting as bioinoculants and their biological approach towards the production of sustainable agriculture. *J. Appl. Nat. Sci.* **2015**, *7*, 540–556.

49. Vessey, J.K. Plant growth promoting rhizobacteria as biofertilizers. *Plant Soil* **2003**, *255*, 571–586. [CrossRef]
50. Akhtar, M.S.; Siddiqui, Z.A.; Wiemken, A. Arbuscular mycorrhizal fungi and *rhizobium* to control plant fungal diseases. In *Alternative Faming Systems, Biotechnology, Drought Stress and Ecological Fertilisation*; Lichtfouse, E., Ed.; Springer: New York, NY, USA, 2011; Volume 6, pp. 263–292.
51. Jung, S.C.; Martinez-Medina, A.; Lopez-Raez, J.A.; Pozo, M.J. Mycorrhiza-induced resistance and priming of plant defenses. *J. Chem. Ecol.* **2012**, *38*, 651–664. [CrossRef] [PubMed]
52. Sharma, M.P.; Sharma, S.K.; Prasad, R.; Pal, K.K.; Dey, R. Application of arbuscular mycorrhizal fungi in production of annual oilseed crops. In *Mycorrhizal Fungi: Use in Sustainable Agriculture and Land Restoration*; Springer: Berlin, Germany, 2014; pp. 119–148.
53. Young, C.C.; Juang, T.C.; Guo, H.Y. The effect of inoculation with vesicular-arbuscular mycorrhizal fungi on soybean yield and mineral phosphorus utilization in subtropical-tropical soils. *Plant Soil* **1986**, *95*, 245–253. [CrossRef]
54. Hobbs, H.A.; Hartman, G.L.; Wang, Y.; Hill, C.B.; Bernard, R.L.; Pedersen, W.L.; Domier, L.L. Occurrence of seed coat mottling in soybean plants inoculated with *Bean pod mottle virus* and *Soybean mosaic virus*. *Plant Dis.* **2003**, *87*, 1333–1336. [CrossRef]
55. Hill, J.H. Soybean mosaic virus. In *Compendium of Soybean Diseases and Pests*, 5th ed.; Hartman, G.L., Rupe, J.C., Sikora, E.F., Domier, L.L., Davis, J.A., Steffey, K.L., Eds.; American Phytopathological Society: St. Paul, MN, USA, 2015; pp. 114–117.
56. Ward-Gauthier, N.; Schneider, R.; Chandra, A.; Silva, E.; Price, P.I.; Cai, G. Cercopsora leaf blight and purple seed stain. In *Compendium of Soybean Diseases and Pests*, 5th ed.; Hartman, G.L., Rupe, J.C., Sikora, E.F., Domier, L.L., Davis, J.A., Steffey, K.L., Eds.; American Phytopathological Society: St. Paul, MN, USA, 2015; pp. 37–41.
57. Francis, C.A. *Organic Farming: The Ecological System*; ASA-CSSA-SSSA: Madison, USA, 2009; Volume 54.
58. Blue River Hybrids. 1r Seed Treatment. Available online: www.blueriverorgseed.com (accessed on 25 October 2015).
59. AgriEnergy Resources. Available online: www.agrienergy.net (accessed on 25 October 2015).
60. Hartman, G.L.; Rupe, J.C.; Sikora, E.F.; Domier, L.L.; Davis, J.A.; Steffey, K.L. *Compendium of Soybean Diseases and Pests*, 5th ed.; APS Press. American Phytopathological Society: St. Paul, MN, USA, 2015.
61. Hartman, G.L.; West, E.; Herman, T. Crops that feed the world 2. Soybean-worldwide production, use, and constraints caused by pathogens and pests. *Food Secur.* **2011**, *3*, 5–17. [CrossRef]
62. Dunphy, J.; Place, G.; Dominic, R.; Reberg-Horton, C. Crop production and management—organic soybean. Available online: www.content.ces.ncsu.edu/chapter-5-crop-production-management-organic-soybeans/ (accessed on 25 October 2015).
63. Hartman, G.L.; Domier, L.L.; Wax, L.M.; Helm, C.G.; Onstad, D.W.; Shaw, J.T.; Solter, L.F.; Voegtlin, D.J.; D'Arcy, C.J.; Gray, M.E.; *et al*. Occurrence and distribution of *Aphis glycines* on soybeans in illinois in 2000 and its potential control. *Plant Health Prog.* **2001**. [CrossRef]
64. Ragsdale, D.W.; Voegtlin, D.J.; O'neil, R.J. Soybean aphid biology in north america. *Ann. Entomol. Soc. Am.* **2004**, *97*, 204–208. [CrossRef]
65. Niblack, T.L.; Riggs, R. Soybean cyst nematode. In *Compendium of Soybean Diseases and Pests*, 5th ed.; Hartman, G.L., Rupe, J.C., Sikora, E.F., Domier, L.L., Davis, J.A., Steffey, K.L., Eds.; American Phytopathological Society: St. Paul, MN, USA, 2015; pp. 100–103.
66. Hartman, G.L.; Leandro, L.F.S.; Rupe, J.C. Sudden death synrome. In *Compendium of Soybean Diseases and Pests*, 5th ed.; Hartman, G.L., Rupe, J.C., Sikora, E.F., Domier, L.L., Davis, J.A., Steffey, K.L., Eds.; American Phytopathological Society: St. Paul, MN, USA, 2015.
67. Hartman, G.L.; Chang, H.-X.; Leandro, L.F. Research advances and management of sudden death syndrome. *Crop Prot.* **2015**, *73*, 60–66. [CrossRef]
68. Kelly, H.; Dufault, N.; Walker, D.; Isard, S.; Schneider, R.; Giesler, L.; Wright, D.L.; Marios, J.J.; Hartman, G. From select agent to an established pathogen, the response to *phakopsora pachyrhizi* in north america. *Phytopathology* **2015**, *105*, 905–916. [CrossRef] [PubMed]
69. Miles, M.R.; Hartman, G.L.; Levy, C.; Morel, W. Current status of soybean rust control by fungicides. *Pestic. Outlook* **2003**, *14*, 197–200. [CrossRef]

70. Hartman, G.L.; Sikora, E.F.; Rupe, J.C. Rust. In *Compendium of Soybean Diseases and Pests*, 5th ed.; Hartman, G.L., Rupe, J.C., Sikora, E.F., Domier, L.L., Davis, J.A., Steffey, K.L., Eds.; American Phytopathological Society: St. Paul, MN, USA, 2015; pp. 56–59.
71. Greene, J.; Davis, J.A. Stink bugs. In *Compendium of Soybean Diseases and Pests*, 5th ed.; Hartman, G.L., Rupe, J.C., Sikora, E.F., Domier, L.L., Davis, J.A., Steffey, K.L., Eds.; American Phytopathological Society: St. Paul, MN, USA, 2015; pp. 146–149.