Sustainable Coffee Production

Article · June 2017

DOI: 10.1093/acrefore/9780199389414.013.224

1 author:

Sarada Krishnan
Denver Botanic Gardens

Oxford Research Encyclopedia of Environmental Science

Sustainable Coffee Production

Sarada Krishnan

Subject: Agriculture and the Environment Online Publication Date: Jun 2017
DOI: 10.1093/acrefore/9780199389414.013.224

Summary and Keywords

Coffee is an extremely important agricultural commodity, produced in about 80 tropical countries, with an estimated 125 million people depending on it for their livelihoods in Latin America, Africa, and Asia, with an annual production of about nine million tons of green beans. Consisting of at least 125 species, the genus *Coffea* L. (Rubiaceae, Ixoroideae, Coffeeae) is distributed in Africa, Madagascar, the Comoros Islands, the Mascarene Islands (La Réunion and Mauritius), tropical Asia, and Australia. Two species are economically important for the production of the beverage coffee, *C. arabica* L. (Arabica coffee) and *C. canephora* A. Froehner (robusta coffee). Higher beverage quality is associated with *C. arabica*. *Coffea arabic*a is a self-fertile tetraploid, which has resulted in very low genetic diversity of this significant crop. Coffee genetic resources are being lost at a rapid pace due to varied threats, such as human population pressures, leading to conversion of land to agriculture, deforestation, and land degradation; low coffee prices, leading to abandoning of coffee trees in forests and gardens and shifting of cultivation to other more remunerative crops; and climate change, leading to increased incidence of pests and diseases, higher incidence of drought, and unpredictable rainfall patterns. All these factors threaten livelihoods in many coffee-growing countries.

The economics of coffee production has changed in recent years, with prices on the international market declining and the cost of inputs increasing. At the same time, the demand for specialty coffee is at an all-time high. In order to make coffee production sustainable, attention should be paid to improving the quality of coffee by engaging in sustainable, environmentally friendly cultivation practices, which ultimately can claim higher net returns.

Keywords: coffee, coffee berry borer, coffee leaf rust, coffee berry disease, sustainability, coffee value chain, coffee genetic resources, climate change

Introduction

Botany and Origin

The first botanical description of the coffee tree was in 1713, under the name of *Jasminum arabicanum*, by Antoine de Jussieu, who studied a single plant grown at the botanic garden of Amsterdam. The species was later classified under the genus *Coffea* as *Coffea arabica* by Linnaeus in 1737 (Charrier & Berthaud, 1985). Since then, many other *Coffea* species have been discovered and described through extensive taxonomic work; more recently, through molecular studies, the genus *Psilanthus* has been subsumed into *Coffea* (Charrier & Berthaud, 1985; Davis et al., 2011; Wintgens, 2009).

A tropical woody genus, *Coffea* belongs to the Rubiaceae family. The primary center of origin of *C. arabica* is the highlands of southwestern Ethiopia and the Boma plateau of South Sudan, with wild populations also reported in Mount Marsabit in Kenya (Meyer, 1965; Thomas, 1942). *C. canephora* has a much wider distribution, from West to East Africa in Ghana, Guinea, Guinea Bissau, Cote d'Ivoire, Liberia, Nigeria, Cabinda, Cameroon, Congo, Central African Republic, Democratic Republic of Congo, Gabon, Sudan, South Sudan, Tanzania, and Uganda and to the south to Angola (Davis et al., 2006).

Coffea arabica is an allotetraploid ($2n = 4x = 44$) that originated from two different diploid ($2n = 2x = 22$) wild ancestors, *C. canephora* and *C. eugenioides* S. Moore or ecotypes related to these two species (Lashermes et al., 1999). Due to the nature of its origin, reproductive biology, and evolution, and due to the narrow gene pool from which it spread around the world, Arabica coffee has very low genetic diversity (Anthony et al., 2002; Lashermes et al., 1999; Vega et al., 2008). It is self-compatible and mostly reproduces by self-fertilization, which occurs in about 90% of the flowers (Fazuoli et al., 2000).

The Arabica coffee tree is a small tree with the potential in the wild to reach 9 to 12 meters in height, growing at an altitude of 1,300 to 2,000 meters above sea level. From seed germination to first fruit production, the coffee plant takes about three years, when it reaches full maturity. The fruit of coffee is known as a cherry and the seed inside is known as the bean. The fruit is comprised of the epicarp (skin), mesocarp (pulp), endocarp (parchment), integument (silverskin), endosperm (bean), and embryo. The tree has an open branching system with a main vertical (orthotropic) stem from which arise primary plagiotropic branches from "head of series" buds. From primary branches arise secondary branches, followed by tertiary and quaternary branches. The four to six serial buds generate either flowers or orthotropic suckers. The leaves are opposite, dark green, shiny, and waxed. The flower consists of white, five-lobed corolla, a calyx, five stamens, and the pistil. The ovary at the base of the corolla consists of two ovules, which when fertilized become two coffee beans (Wintgens, 2009).

History

The history of coffee consumption begins in Ethiopia, where the local people have been drinking coffee for many centuries. From its center of origin in Ethiopia, coffee made its way to Yemen, possibly around the 6th century, with the first record of consumption as a beverage by practitioners of Sufism around 1450. From Yemen, coffee spread to Cairo, Damascus, and Istanbul, leading to the birth of the coffeehouse. Following this, coffeehouses opened in Europe, the first one in Venice in 1645 and in Oxford in 1650. The first coffeehouse in the United States opened in Boston in 1689. The tradition of coffeehouses as meeting places where news, political debate, and ideas are exchanged still continues (Vega, 2008). The opening of the first "Peet's Coffee & Tea" shop in San Francisco in 1966 was probably one of the significant changes in coffee consumption, causing the expansion of the specialty coffee industry in the United States. This was followed by the opening of the first Starbucks store in Pike's Place in Seattle in 1971. In 1974, Erna Knutsen coined the phrase "specialty coffee" to describe the high-end, green coffees of limited quantities she sold to small roasters; the coffees were sourced from specific geographic microclimates and had unique flavor profiles. The growth of the specialty coffee industry led to the formation of the Specialty Coffee Association of America (SCAA) in 1982. Today, SCAA is the largest coffee trade organization, with nearly 2,500 company members (SCAA, 2016). In the early stages of the specialty coffee industry development, there was a lack of definition of what specialty coffee was and how to quantify it. In 2009, the SCAA published revised quality standards for specialty coffee. To qualify as specialty, the coffee had to meet a minimum cupping score of 80 out of a 100-point scoring system (Steiman, 2013).

Cultivation of coffee was started by the Dutch East India Company in Java using seeds obtained from Mocha in Yemen in the 1690s. From Java, plants were taken to the Amsterdam Botanical Garden in 1706, from which a plant was taken to France in 1713; this plant was used by Antoine de Jussieu in first describing coffee. In 1720, one plant made its way from France to the French colony of Martinique in the Caribbean. From Martinique, coffee spread throughout the Caribbean islands: Haiti (1725), Guadeloupe (1726), Jamaica (1730), Cuba (1748), and Puerto Rico (1755). Around the same time, the Dutch introduced plants from Amsterdam to their South American colony in Suriname (in 1718); from there, coffee was introduced to French Guiana in 1719 and Brazil in 1727. This was the basis of the "Typica" genetic line of coffee. The "Bourbon" genetic line originated from coffee trees introduced from Mocha in Yemen to Bourbon (Reunion) Islands in 1715 and 1718 (Anthony et al., 2002; Vega, 2008). The French later introduced coffee cultivation in Ceylon (Sri Lanka) in 1740 and Ceylon become a major producer of coffee. In 1869, Ceylon's thriving coffee industry was devastated by a fungal disease, the coffee leaf rust (*Hemileia vastatrix*), leading to the replacement of coffee by tea in Ceylon by the 1900s (Damania, 2003).

In an effort to prevent the loss of coffee genetic resources and to enlarge the genetic base of coffee for future crop improvement, several international institutions, such as the United Nations Food and Agriculture Organization (FAO) and others, have initiated many collecting missions to various African countries since the 1960s. The emphasis has been on collecting *C. arabica* germplasm because of its economic importance, but a number of noncultivated species were also collected (as cited in Engelmann et al., 2007; Krishnan, 2013; Vega et al., 2008). In addition to these international collecting missions, local researchers within origin countries have performed their own collecting missions, such as in Ethiopia (Labouisse et al., 2008), Madagascar, and Cote d'Ivoire. *Coffea* field gene banks were established in several countries as a result of the collecting missions; the gene banks hold accessions from the collecting missions as well as cultivated plants selected in plantations and breeding centers. The 1998 FAO report, *State of the World's Plant Genetic Resources*, documented 21,087 coffee accessions conserved worldwide (Anthony et al., 2007). The FAO World Information and Early Warning System (WIEWS) Coffea *Germplasm Report* (2009–2011) is the most comprehensive inventory of coffee germplasm held in living collections. In 2009, Dulloo et al. did an inventory of limited gene banks, reporting 41,915 accessions in field gene bank collections worldwide. In 2016, the Global Crop Diversity Trust, in partnership with World Coffee Research, led the development of the Global Conservation Strategy for Coffee Genetic Resources, which was scheduled for completion in early 2017.

Economics

Worldwide, an estimated 125 million people are dependent on coffee for their livelihoods (Osorio, 2002), with more than 50 countries producing and exporting coffee, almost all in the developing world (Lewin et al., 2004; NCA, 2017). Like any commodity trade, the coffee trade has been characterized by boom and bust cycles since the 1880s, mainly due to an imbalance of supply and demand. In the early 20th century, attempts to stabilize coffee prices rested on efforts of individual countries, especially Brazil. Through the "valorization" scheme of 1905–1908, Brazil bought and stored large amounts of coffee and administered a tax policy imposing new levies on coffee hectarage that was aimed at driving production down and prices up (Thurston, 2013A). In the 1930s, when the coffee market collapsed, Brazil, the largest producer, responded by burning coffee or dumping it into the ocean. In the following decades, the price of coffee has alternately soared and dived, with the market hitting the lowest at 40 cents per pound in New York, while farmers' production costs amounted to about 70 cents a pound. This has led to poverty and food insecurity in countries where the majority of coffee producers are subsistence farmers (Osorio, 2002; Thurston, 2013B).

Significant transformation of the world coffee market occurred since the latter half of the 20th century. During the period between 1965 and 1989, the coffee market was regulated, with relatively high price levels, because upward and downward trends were corrected through the implementation of export quotas. The free-market period, which began in 1990, had two subperiods of significantly low price levels, 1989 to 1993 and 1999 to 2004, the latter being the longest period of low prices ever recorded (ICO, 2014). Coffee production is generally characterized by considerable instability, with a large crop one year followed by a smaller crop the next. In the world coffee market, as is the case for many commodities, price volatility is a major concern for all stakeholders. In exporting countries, price volatility leads to instability in producer incomes and uncertainty of export earnings and tax revenues. In importing countries, price volatility affects profit margins for roasters, traders, and stockholders (ICO, 2014). All these factors make the coffee crop less attractive throughout the supply chain, especially to growers, who will seek other, more remunerative crops to replace coffee. Despite these challenges, world coffee production has grown steadily since the 1960s, although it will be difficult to maintain this trend due to the continued rise in production costs, problems related to climate change, and the higher incidence of pests and diseases (ICO, 2014).

To illustrate the global scale of coffee production and consumption, Tables 1 and 2 give the figures for the total world coffee production, export, and consumption from 2006 to 2015 and the statistics for the top ten coffee producers of the world for 2015, respectively. Coffee production, export, and consumption have steadily increased since 2006 (Table 1). The top ten producers account for about 88% of total global coffee production and exports. Among the top ten producers, Brazil, Vietnam, and Colombia together produce and export almost 60% of the global total (Table 2).

Table 1. Total World Coffee Production, Export, and Consumption from 2006 to 2015

Crop Year	**Quantity (in 1,000 60-kg bags)**		
	Production	**Export**	**Consumption (Importing Countries)**
2006	128,728	91,745	75,093
2007	119,996	96,302	75,964
2008	129,566	97,599	75,715
2009	123,276	96,242	74,211
2010	134,246	97,067	76,552
2011	140,617	104,435	76,447
2012	144,960	110,914	76,949
2013	146,506	110,501	79,467
2014	142,278	114,766	80,627
2015	143,306	112,722	81,188

Note: *Production statistics for 2006/07–2015/16.

Source: ICO (2016).

Table 2. World’s Top Ten Coffee Producers—Production, Export and Proportions of World Production and Export During 2015

Country	Production (1,000 60-kg bags)	Percent of World Production	Exports (1,000 60-kg bags)	Percent of World Exports
Brazil	43,235	30.17	28,478	30.53
Vietnam	27,500	19.19	19,125	20.50
Colombia	13,500	9.42	10,031	10.75
Indonesia	12,317	8.60	4,847	5.20
Ethiopia	6,700	4.68	2,514	2.70
India	5,833	4.07	5,006	5.37
Honduras	5,750	4.01	4,746	5.09
Uganda	4,755	3.32	2,817	3.02
Guatemala	3,400	2.37	2,432	2.61
Peru	3,300	2.30	2,280	2.44

Total World Production & Export	143,306	88.17	93,275	88.21

Note: *Export statistics are for the period October 2015 to July 2016.

Source: ICO (2016).

Sixty-five percent of the world's coffee is consumed by just 17% of the world's population (Lewin et al., 2004). This provides tremendous opportunity for market expansion through promotion of coffee consumption in both producing and consuming countries. Table 3 provides statistics on imports by the top ten leading importing countries. The top ten countries account for about 81% of total imports, with the United States importing almost a quarter of the total imports, followed by Germany at 18%.

Table 3. World's Top Ten Coffee Importers During 2013, the Latest Year with Complete Statistics

Country	**Imports (1,000 60-kg bags)**	**Percent of Global Imports**
United States	27,016	23.14
Germany	21,174	18.13
Italy	8,823	7.56
Japan	8,381	7.18
France	6,713	5.75
Belgium	5,502	4.71
Spain	5,137	4.40
Russian Federation	4,410	3.78
United Kingdom	4,206	3.60
Netherlands	3,407	2.92
Total World Imports	116,773	81.17

Source: ICO (2016).

Brazil continues to be the world's largest coffee producer, and due to use of mechanized harvesting, it has achieved much higher productivity than with hand-picking (Thurston, 2013A). Colombia, which used to be the second largest producer, has been replaced by Vietnam, a producer of robusta coffee, and Ethiopia's production has been surpassed by Indonesia's (Table 2). In nearly all coffee-exporting countries, dependence on coffee as the main foreign export earner has fallen, although coffee is still extremely important in the economy of many countries. A major concern throughout the coffee industry is the small percentage of the total value of coffee realized by the producers and producing countries. A 2006 report estimated that exporting countries earned only 7% of the total market value of coffee. In addition to the cost of production incurred by the producing countries, which include cost of fertilizers, pesticides, transportation, etc., the increase in the value of coffee also comes from costs incurred by the consuming countries, such as advertising, wages, rents, insurance, utilities, transportation, etc. (Thurston, 2013A). Like all other agricultural commodities, coffee has an uncertain market future. Price volatility, dictated by supply and demand, and climate events affect the economics of the coffee trade.

Crop Production

Production

Coffee-producing areas are located in latitudes between 22º N and 26º S. The environmental factors affecting coffee growth and productivity are temperature, water availability, intensity of sunshine, wind, soil type, and land topography (Descroix & Snoeck, 2009). Optimal temperatures for growing Arabica coffee are 18ºC during the night and 22ºC during the day, although tolerated extremes extend from 15ºC up to 30º C. Robusta coffee can tolerate slightly higher temperatures, with optimal temperatures between 22 and 28ºC (Descroix & Snoeck, 2009). Water availability, in the form of rainfall and atmospheric humidity, affects growth of coffee. Most coffee-growing regions are typically rain-fed, since land topography is not conducive to installation of irrigation systems. For Arabica growth, annual rainfall of 1,400 to 2,000 mm is favorable, and for robusta, it is 2,000 to 2,500 mm. Rainfall below 800 to 1,000 mm for Arabica and 1,200 mm for robusta can result in poor productivity (Descroix & Snoeck, 2009). The best relative humidity for robusta is 70% to 75% and for Arabica it is around 60%. Natural or artificial shade is provided to coffee plants in cultivation to recreate their original forest environment, although sunlight-tolerant varieties have been developed for increased productivity. However, shade still remains useful, especially to mitigate the effects of extreme high and low temperatures (Descroix & Snoeck, 2009). Strong winds affect the growth of coffee, with significant damage caused by cyclones. Regions frequently impacted by cyclones include Madagascar, the Philippines, the Caribbean, Vietnam, and Hawaii. The best soils for coffee growing include alluvial and colluvial soils with texture, as in volcanic formations, and good drainage. Soil depth of at least 2 m is required for taproot growth and development (Descroix & Snoeck, 2009). Although flat lands or slightly rolling hills are best suited for coffee growing, they are not always available in many coffee-growing regions due to the natural topography of the land. Flat areas allow for mechanization. On steep slopes, mechanization is difficult and production becomes costlier since conservation measures need to be implemented to prevent soil erosion (Descroix & Snoeck, 2009).

A coffee plant starts producing flowers 3 to 4 years after planting, with full productivity achieved in 5 to 7 years. Productivity starts diminishing after about 20 years, although with proper handling, the trees can bear fruit for about 50 years or so. The time elapse between flowering and maturation of coffee berries varies depending on variety, climatic conditions, agricultural practices, etc. Typically, Arabica coffee takes about 6 to 9 months and robusta coffee takes about 9 to 11 months (Wintgens, 2009). Inputs like fertilizer and pesticides maximize coffee productivity.

A characteristic of coffee production is the biennial pattern of fruit bearing by the trees, with high yield in alternate years. In high-bearing years, in order to support their heavy fruit production, the trees sacrifice new growth production. The following year this is compensated for by reduced fruit bearing. The biennial bearing phenomenon is more common in unshaded production systems with deficient management. In well-managed systems with adequate fertilization and proper pruning, biennial bearing is less pronounced (Wintgens, 2009).

Once coffee berries are harvested, they are processed by one of two methods: the wet method or the dry method. Processing converts the coffee cherries to green beans, which is what is ultimately roasted, ground, and consumed. The wet process is more time, resource, and labor intensive. The cherries are sorted by immersion in water. The bad cherries float to the top and are discarded. Those that sink are the good, ripe cherries, which are further processed by pulping (removal of pulp) and drying. In the dry method, the cherries are directly dried, either naturally in sunshine or using mechanical dryers. Once the coffee is dried, through a process called hulling, the outer parchment layer (and the dried pulp in the case of dry-processed coffee) is removed. Polishing, which is an optional processing method, removes the silverskin, the layer beneath the parchment layer. The green beans are then color sorted and graded for size. The ideal moisture content of dried green beans is about 12%. Drying to below a 9% moisture content can result in shrunken, distorted beans.

Major Pests and Diseases

Coffee Berry Borer—*Hypothenemus hampei* (Ferrari)

The coffee berry borer, *Hypothenemus hampei* (Coleoptera: Curculionidae: Scolytinae), an insect endemic to Africa, is the most serious pest of coffee in many of the major coffee-producing countries in the world (Vega et al., 2009, 2012). It was accidentally introduced into Brazil in 1913, after which it invaded coffee plantations throughout South and Central America, Mexico, and the Caribbean (Infante et al., 2012). The coffee berry borer has been transported around the world, most probably through seeds containing the borer. Very few coffee-producing countries are still free of it. Its presence in Hawaii was confirmed in 2010; Papua New Guinea and Nepal still remain free of the pest (CABI, 2016).

The adult female borers cut a characteristic hole (Figure 1) at the blossom end of large green berries about eight weeks after flowering, and then they deposit their eggs in internal galleries. The larvae, upon hatching, feed on the seed. A single berry may be infested with up to 20 larvae. Many infested immature berries fall off the trees. Yield and quality of marketable product are significantly reduced; in heavy infestations, borers have been known to attack 100% of berries. The insect remains inside the berry most of its life, making it difficult to control (CABI, 2016; Crowe, 2009; Vega et al., 2009, 2012).

Click to view larger

Figure 1. Coffee berries infested by coffee berry borer with visible entry holes.

Photo courtesy of Sarada Krishnan.

There is no simple and cheap method of controlling this insect. Cultural control measures are recommended, with chemical control used as a supplement to cultural measures. Cultural measures that can be adopted to reduce infestations include: reducing heavy shade, keeping the coffee bush open by pruning, picking coffee at least once a week during the main harvest season, stripping the trees of any remnant berries once harvesting is done, ensuring that no berries are left on the ground, and destroying all infested berries by burning (Crowe, 2009).

Coffee Leaf Miner—*Leucoptera coffeella* Guérin-Meneville

The coffee leaf miner, *Leucoptera coffeella* (Lepidoptera: Lyonetiidae), is a moth whose larvae feed inside the leaf tissue and consume the palisade parenchyma. In Brazil, the leaf miner is one of the most serious pests on *Coffea arabica*. It is an introduced pest from Africa, and crop losses of up to 50% are possible. Twenty species of leaf miners of the genus *Leucoptera* have been described, and they infest 65 host species. Four species of *Leucoptera* are known to infest *Coffea* species: *L. coffeella, L. meyricki* Ghesq.*, L. coma* Ghesq., and *L. caffeina* Wash. (Filho, 2006; Filho et al., 1999). In eastern Africa from Ethiopia to South Africa, *L. caffeina* and *L. meyricki* are major pests of Arabica coffee. Both these species have also been recorded as attacking the indigenous wild coffee, *C. eugenioides* and other shrubs in the Rubiaceae family (Crowe, 2009).

The coffee leaf miner, *L. coffeella*, was first introduced to Brazil around 1851, probably on nursery stock imported from the Antilles and Bourbon Island. It is a monophagous pest that attacks only coffee plants (as cited in Filho, 2006). Infested coffee has large, irregular, brown spots on the upper surface of the leaf, which reduces the leaf's photosynthetic area. Rubbing or exposing the spots reveals fresh mines and small whitish caterpillars (Figure 2). Mined leaves shed prematurely. Loss in productivity is mainly due to leaf loss. Chemical control of the pest, although effective, increases cost of production and has associated environmental risks. Coffee cultivars with resistance to the pest have been and continue to be developed through classic breeding and molecular selection techniques. In Brazil, varieties resistant to *L. coffeella* have been developed using genes from *C. racemosa* (Filho, 2006; Filho et al., 1999).

Click to view larger

Figure 2. Coffee leaf miner larvae on *Coffea arabica* in South Sudan.

Photo courtesy of Sarada Krishnan.

Root-knot Nematodes—*Meloidogyne* spp.

Root-knot nematodes (*Meloidogyne* spp.) have become a major threat in all *C. arabica*-growing regions of the world (Noir et al., 2003). They are sedentary nematodes; the females settle into the rootlets of the coffee trees, causing distorted knots known as galls. Infected coffee trees do not necessarily die, but they are debilitated under normal growing conditions (Castillo et al., 2009). More than 15 species of *Meloidogyne* have been reported as pathogens of coffee, with different species causing different forms of damage to roots based on their respective interactions and associations with fungi. The most damaging species reported in Central America is *M. exigua* Goeldi (Bertrand et al., 2001, Castillo et al., 2009; Noir et al., 2003). In Guatemala, the most common species is *M. incognita* (Kofoid and White) Chitwood, which causes severe damage, often resulting in death of trees (Anzueto et al., 2001). In Central America, all cultivated varieties (such as Typica, Bourbon, Caturra, Catuai, Costa Rica 95, and IHCAFE90) are susceptible, with Costa Rica reporting an estimated drop in yield of 10% to 20% due to general weakening of the trees (Bertrand et al., 2001). In addition to their presence in South and Central American countries, various *Meloidogyne* spp. have also been documented in Africa and India, and two specifically in Kenya (Castillo et al., 2009).

From an economic viewpoint, nematodes are significant in Latin America because they limit coffee production. In many regions, the nematode problem is amplified by their association with fungi, leading to fungal infections of the plants, causing physiological alterations. The most common fungi are *Fusarium* spp. and *Rhizoctonia solani* Kuhn, both pathogenic in coffee during early stages of planting. Methods of control include disinfecting soil as a preventative measure, control of weedy hosts, pruning to strengthen root system, removal of dead plants, organic fertilization to stimulate root growth and improve nutrition, genetic resistance through breeding, grafting on resistant root stocks, chemical control, biological control, and use of antagonistic plants (Castillo et al., 2009). While standard Arabica cultivars are highly susceptible to *M exigua*, several accessions of *C. canephora* have exhibited a high level of resistance, including the interspecific hybrid —Timor Hybrid (as cited in Bertrand et al., 2001; Noir et al., 2003).

Coffee Leaf Rust—*Hemileia vastatrix* Berkeley and Broome

Coffee leaf rust caused by the obligate parasitic fungus *Hemileia vastatrix* causes considerable economic losses to coffee producers (Diola et al., 2011), especially with *C. arabica*, and is currently found in all coffee-growing regions of the world. First observed in 1861 near Lake Victoria, the fungus has now spread throughout coffee-growing countries, and it led to significant economic impact in Sri Lanka in 1868 (Silva et al., 2006). In India, coffee rust in susceptible *C. arabica* cultivars accounts for about 70% of crop losses (Prakash et al., 2004). The 2012/2013 outbreak of coffee rust in Central America resulted in more than 60% of the trees' exhibiting 80% defoliation in Mexico (Cressey, 2013). Crop devastation in Nicaragua, El Salvador, Guatemala, Dominican Republic, and Honduras was also reported, impacting over 1.08 million hectares (Cressey, 2013; ICO, 2013). According to the International Coffee Organization, the 2012/2013 outbreak of coffee rust in Central America was expected to cause crop losses of $500 million and to cost 374,000 jobs (ICO, 2013).

The first observable symptoms occur on the upper surface of the leaves as small, pale yellow spots. The spots gradually increase in diameter, and masses of orange uredospores are seen on the undersurfaces of the leaves (Figures 3 and 4). The centers of the spots eventually turn brown and dry, while the margins continue to produce uredospores and to expand. They eventually cover significant areas of the limb. The leaf rust results in loss of physiological activity, which causes the leaves to fall. Severe infection can cause branches to wither completely. Uredospores can be spread by both wind and rain, with splashing rain serving as an important means of local dispersal. Long-range dispersal is primarily by wind. Good cultural management is key in achieving control of the disease, although many factors dictate cultural methods, such as varieties grown, soil characteristics, amount and distribution of rainfall, etc. Chemical control using copper-based products is effective if applied at regular intervals as a preventative measure. A disadvantage of copper-based fungicide, in addition to cost, is that it accumulates in the soil and can reach levels toxic to plants and other organisms (Amerson, 2000; Muller et al., 2009).

Taking economics and minimization of chemical input for disease management into consideration, the most viable and effective option is the development and cultivation of tolerant coffee varieties. Hence, breeding for varieties resistant to coffee leaf rust has been one of the highest priorities in many countries (Prakash et al., 2004). Prakash et al. (2011) have successfully applied marker-assisted selection (MAS) to achieve durable leaf rust resistance. Using two sequence-characterized amplified regions (SCAR) markers closely linked to the rust- resistant *SH3* gene (Sat244 and BA-124-12K-f), they were able to distinguish the presence or absence of the *SH3* gene using the *C. arabica* cultivar S. 795, a cultivar derived from S.26, a spontaneous hybrid of *C. arabica* and *C. liberica*. The marker Sat244 was more efficient in distinguishing the homozygous and heterozygous status of the *SH3* gene. This study was the first report of the successful use of MAS for breeding for coffee leaf rust resistance.

Click to view larger

Figure 3. Underside of *Coffea arabica* leaves infected with coffee leaf rust.

Photo courtesy of Sarada Krishnan.

Click to view larger

Figure 4. Upper side of *Coffea arabica* leaves affected by coffee leaf rust.

Photo courtesy of Sarada Krishnan.

Coffee Berry Disease—*Colletotrichum kahawae* Bridge and Waller

Coffee berry disease (CBD) caused by the fungus *Colletotrichum kahawae* was first detected in Kenya in 1922 around Mt. Elgon, west of the Rift Valley. From Kenya, the disease spread rapidly, first to the Kivu district in the Democratic Republic of Congo, and then on to Uganda, Burundi, Rwanda, Tanzania, and Angola (Muller et al., 2009). Currently, the disease has been restricted to East, Central, and South African coffee growing countries (as cited in Hindorf & Omondi, 2011). It infects all stages of the crop, from flowers to ripe fruits and occasionally leaves, and may cause up to 70% or 80% crop losses if no control measures are adopted, with maximum crop losses occurring following infection of green berries, leading to formation of dark, sunken lesions (Figure 5) and premature dropping and mummification of the fruits (as cited in Silva et al., 2006). The annual economic impact of CBD to Arabica coffee production in Africa is estimated to be $300–$500 million, due to crop losses and cost of chemical control (van der Vossen & Walyaro, 2009). Although CBD is currently restricted to Africa, precautions to prevent introduction of the disease should be taken in other coffee-producing countries (Silva et al., 2006).

Control of the disease can be achieved through an integrated cultivation approach, with chemical control linked to improved cultivation practices and genetic control (Muller et al., 2009). It is reported that CBD resistance appears to be complete in *C. canephora* and partial in *C. arabica* (Silva et al., 2006). Breeding for CBD resistance in *C. arabica* was initiated in response to severe disease epidemics about 35 to 40 years ago in Kenya, Ethiopia, and Tanzania, with release of resistant cultivars to coffee growers since 1985 (van der Vossen & Walyaro, 2009). Under field and laboratory conditions, differences in resistance of coffee trees to CBD have been observed, with higher resistance in Geisha 10, Blue Mountain, K7, Rume Sudan, and progenies of Hibrido de Timor than in Harar and Bourbon in Kenya (Silva et al., 2006).

Click to view larger

Figure 5. Coffee fruits affected by coffee berry disease in Kenya.

Photo courtesy of Sarada Krishnan.

American Leaf Spot—*Mycena citricolor* (Berkeley & Curtis) Saccardo

American leaf spot, caused by the fungus *Mycena citricolor*, is predominantly prevalent in Latin America, specifically in Costa Rica and in the Caribbean. The disease also attacks a number of other plants in addition to coffee. In coffee, it affects all plant parts: stems, branches, leaves, and fruits (Muller et al., 2009). On coffee, subcircular brown spots are formed on leaves, which turn pale brown to straw-colored (Figure 6). The spots have a distinct margin, but with no halo. Mature spots become lighter and develop minute, yellow, hairlike gemmifers, mostly on the upper surface of the spots. The centers of older leaf spots may disintegrate, giving a shothole appearance. Similar spots may be produced on stalks and berries. The main effect is to cause leaf fall, with a consequent reduction in growth and yield of the coffee tree (Plantwise Technical Factsheet, 2015).

Control measures include use of copper-based fungicides alternating with use of modern triazoles with systemic effect. Practicing good cultural methods, such as weed control, pruning, and shade control, is necessary to prevent the disease and to reduce disease intensity. The economic impact of the disease has been relatively low, and hence very limited research has been done on developing resistance varieties (Muller et al., 2009).

Click to view larger

Figure 6. Coffea arabica leaves infected by American leaf spot in Jamaica.

Photo courtesy of Sarada Krishnan.

Coffee Wilt Disease—*Gibberella xylarioides* R. Heim & Saccas

Coffee wilt disease is a vascular fungal disease first detected in 1927 in the Central African Republic, where the disease spread and developed drastically over the next decade (Muller et al., 2009). The disease resulted in significant loss in production of robusta coffee in the 1990s in the Democratic Republic of Congo and Uganda, killing hundreds of trees (Hindorf & Omondi, 2011). First documentation of infection of *C. arabica* was in Ethiopia in 1958 (as cited in Hindorf & Omondi, 2011).

Symptoms include yellowing of leaves, which dry and fall, then branches die, which finally leads to withering and death of the entire tree within a few months. Plant death is caused by blockage of water and sap circulation due to colonization of the sap vessels by the fungal mycelium. Infection can set in any time from the cotyledon stage to maturity. Control of the disease through chemical treatment is not efficiently possible. Spread and contamination can be limited by applying a suitable antiseptic paste to cuts or wounds resulting from pruning, use of cultivation tools, and insect infestation, preventing entry of disease pathogen into sap vessels beneath the bark (Muller et al., 2009).

Sustainability and the Future

Environmental Sustainability

Due to increasing population pressures and accompanying deforestation and land degradation, natural forest ecosystems housing high levels of biodiversity are under serious threat in the centers of origin of various *Coffea* spp. in Africa (Kufa, 2010). In addition to being centers of origin, most African countries are also coffee producers (such as Angola, Burundi, Cameroon, Cote d'Ivoire, the Democratic Republic of Congo, Ethiopia, Kenya, Rwanda, Tanzania, Uganda, Zimbabwe, and others), and coffee has a central role in their national economies. Despite coffee's importance, coffee exports from Africa have steadily declined, leading to food insecurity among resource-poor, small-scale farmers. The reasons for the decline include market volatility, inadequate market access, inefficient policy frameworks, inadequate access to improved technologies and services, lack of incentives, and climate-associated risks. All of these factors have led to neglect of coffee farms or switching to subsistence farming to tackle food insecurity. Although coffee is predominantly grown in mixed-crop, agroforestry systems promoting conservation and organic farming, the demand for high-quality coffees resulted in increased costs of production and processing that are beyond the capacity of most coffee farmers in Africa. In addition, the coffee marketing system and sharing of benefits has to pass through a complex value chain, with the benefits rarely reaching poor communities in developing countries. Hence the practical contributions of fair trade and other sustainability initiatives have become questionable (Kufa, 2010).

Coffee production in an agroforestry system, a system involving production of coffee under the shade of diverse canopy species, has great conservation potential. Various coffee areas display a broad array of shade-management systems, ranging from no shade to intense shade. In the 1970s, there was a tremendous push in Central American countries toward less shaded or open-sun production systems, with the objective of increasing yields. The reduction or elimination of shade trees was accompanied by the introduction of agrochemical inputs, a campaign to combat the coffee leaf rust. This intensification system was promoted more in countries with strong governmental ministries and research institutions advocating modern practices for higher yields and reduction in complexity of traditionally managed systems, such as Costa Rica, Colombia, and Kenya. In countries where less technical assistance prevailed, growers continued to grow coffee in traditional systems utilizing shade. A consequence of intensification is the decline in biodiversity, whereas a coffee landscape managed with a diverse shade cover that mimics a natural forest will harbor birds and other wildlife. Advantages of utilizing a shaded system include providing viable habitat, enhancing biodiversity, sustaining biological control agents, such as birds and bats, and enhancing pollinators of the coffee itself (Rice, 2013).

Coffee as an agroforestry system providing ecosystem services for maintaining and restoring resilient biological and social systems is a very feasible option. Kufa (2010) recommended a call to action for embedding the agroforestry system of coffee production into climate agreements by providing compensation for the multiple ecological services yielded by adopting such a system in each country. Rice (2013) also recommended advocating shade-grown coffee to agricultural planners and policymakers in developing countries as an option for a positive correlation between conservation and the marketplace. There is an urgent need to mitigate the negative impacts of climate change on coffee production by maintaining quality environments through minimization of deforestation and forest degradation. Immediate measures are needed to identify, design, and implement conservation strategies to counter the threats arising from climate change to coffee ecology and production. To ensure success of environmental sustainability and biodiversity conservation, measures delivering incentives and equitable benefit sharing from the use of forest genetic resources and the ecosystem services, such as premium prices for quality coffees, should be addressed. This will lead to sustainable development of the coffee sector and enhance the well-being of resource-poor farmers in developing countries (Kufa, 2010). This process will require strong partnerships along the entire coffee value chain in both producing and consuming countries for coordination of sustainability initiatives for the future of the global coffee economy.

Coltro et al. (2006) conducted a life cycle assessment (LCA) of the environmental profile of green coffee production in Brazil. The study was done to understand detailed production inventory data (life cycle inventory—LCI) and to identify potential environmental impacts of tillage in order to generate ways to reduce impacts and to improve environmental sustainability. Results of the study showed that, for production of 1,000 kg of green coffee in Brazil, the inputs required were 11,400 kg of water, 94 kg of diesel, 270 kg of fertilizers and NPK, 900 kg of total fertilizers, 620 kg of correctives (such as limestone to correct soil acidity), and 10 kg of pesticides. The study provided important results for better correlation of agricultural practices and potential environmental impacts of coffee. Another LCA, conducted on a farm in Guatemala, showed that the bulk of the environmental impact of producing coffee was in transportation. When impacts due to other coffee processes, such as roasting and brewing, were compared, the farming of coffee was a small percentage of the overall impact (Salinas, 2008). Understanding the LCI of agricultural products is a fundamental step in understanding potential environmental impacts in order to establish the basis for product sustainability (Coltro et al., 2006). Environmental profiles differ with different agricultural practices, and they should not be generalized for different coffee-growing regions.

Sustainability of the Coffee Value Chain

Coffee is a truly global commodity, with the coffee value chain comprising a host of participants, from the producers to intermediary players to the final consumer. The breadth and intimacy among the various actors of the coffee supply chain make the sector one of critical importance for sustainable development at the local, regional, and global levels (IISD, 2003). The global coffee value chain has been transformed dramatically since the 1990s due to deregulation, evolving corporate strategies, and new consumption patterns (Ponte, 2004). Consumers are more discerning about the coffee products they choose for consumption, and they have numerous combinations to choose from with respect to sustainability (such as fair trade, organic, and shade grown) and specialty types (such as coffee variety, origin, brewing and grinding methods, packaging, and flavoring).

In the coffee industry, sustainability has become a hot topic. Sustainability developed within the North American specialty coffee industry, although Europe developed the first forms of sustainable coffee through the fair-trade movement (Ponte, 2004). Several initiatives have been created to address specific aspects of sustainability related to the coffee sector, addressing issues related to social, economic, and environmental problems. Several of the initiatives focus on providing a structure for implementing, administering, and monitoring social and environmental standards throughout the product chain, particularly at the production level (IISD, 2003). This has led to conferring of certification and labeling for easy identification and product choice by the consumer. Table 4 lists the different types of sustainability initiatives that have been implemented in the coffee sector (although the table is not all-inclusive).

Table 4. Description of Select Coffee Sustainability Systems

Initiative	Initiator	Key Characteristics	Geographic Coverage & Target Groups	Level of Stringency
Fair trade	Fair Trade Labeling Organizations International (FLO) and associated fair trade guarantee organizations	Focus on poverty alleviation; guaranteed minimum price paid to registered small-farmer organizations	Global; narrow target groups covering only small-scale producers	High; premium for social and economic aspects; third-party certification and monitoring of standards
Bird friendly	Smithsonian Migratory Bird Center (SMBC)	Preserve habitats of migratory songbirds, with minimum standards for vegetation cover and species diversity to obtain use of label; emphasis on songbirds and organic shade-grown coffee	Standards applied only to Latin American countries so far; targets are narrow, addressing only organic and shade-grown coffee producers	High; premium for environmental aspects; third-party certification

Organic	International Federation of Organic Agriculture Movements (IFOAM) and affiliated associations	Focus on environmental aspects and social justice; no synthetic chemicals, soil conservation, no GMOs, etc.	Global, but most organic coffee comes from Latin America, especially Mexico; all farms	High; accredited certification agencies monitor organic standards for production, processing, and handling
Eco-OK	Rainforest Alliance	Focus on biodiversity conservation, improving environmental and social conditions in tropical agriculture; emphasis on environmental protection, shade, basic labor and living conditions, and community relations	Latin American countries only; midrange, with big and medium-size estates of shade-grown coffee producers only, as well as some cooperatives	High; premium for environmental aspects; third-party certification

Utz Kapeh	Utz Kapeh Foundation (Ahold Coffee Company in cooperation with Guatemalan coffee suppliers)	Emphasis on creating transparency along the supply chain and rewarding responsible coffee producers using good agricultural practices; standards on environmental protection and management, and labor and living conditions	Mainly in Latin America, but growing in Asia and Africa; producers of all sizes and production types	Medium across all pillars of sustainability; third-party certification
Nespresso AAA Sustainable Quality	Nestle	Focus on sourcing high-quality sustainable coffee in a way that is respectful of the environment and farming communities	Narrow; high-quality Nespresso-only coffee growers	Medium across all pillars of sustainability; third-party verification

Starbucks C.A.F.E. (Coffee and Farmer Equity) Practices	Starbucks	Emphasis on high-quality coffee that is sustainably grown, with good social and environmental performance minimizing negative environmental impact	Narrow; high-quality Starbucks-only coffee growers	Medium across all pillars of sustainability; third-party verification
The Common Code for the Coffee Community (4C)	Multistakeholder (government/industry): Kraft Foods, Jacobs Kaffee, Nestle, German Development Agency (GTZ)	Provide a baseline standard, with opportunities for stepping up from the sustainability baseline to more demanding standards	Broad; producers of all sizes and production types	Low; baseline across all pillars of sustainability; third-party verification

Source: IISD (2003), Ponte (2004), and Reinecke et al. (2012).

Although these initiatives have the objective of being transparent and verifiable, the biggest challenges have been the growth in the number of initiatives and the lack of cooperation between initiatives, which pose a threat to their ability to meet standards on a broad scale (IISD, 2003) and create confusion among consumers. In addition, institutional and project-based initiatives launched by industry, NGOs, and governments add to the confusion and are limited in their ability to address macroeconomic problems and lack consistency across initiatives. Hence, clear, transparent, and flexible sustainability criteria need to be established with a multistakeholder mechanism for establishing and administering the implementation at the international level. This will ensure a trade-neutral path toward sustainable development within the coffee sector and better collaboration and coordination between existing initiatives, thereby improving the adoption rate of sustainable practices throughout the sector. Through integration of economic sustainability with social and environmental sustainability, there is a need and an opportunity to improve coffee-sector sustainability through the adoption of multilateral, multistakeholder, market-based approaches (IISD, 2003).

Drawing from the existing initiatives, the International Institute for Sustainable Development has identified five principles for sustainable development, providing a broad foundation for an integrated approach within the coffee sector (IISD, 2003):

- Principle 1: Fair price/wage to producers that covers production, living, and environmental costs within a competitive framework with a measured degree of stability.
- Principle 2: Maintain employment relationships in accordance with core International Labor Organization (ILO) conventions and local law.
- Principle 3: Implement environmentally sustainable production practices.
- Principle 4: Enhanced access to credit and opportunities for diversification for producers.
- Principle 5: Enhanced access to trade information and trade channels for producers.

The Future

Coffee genetic resources are under threat due to loss of the forest ecosystems housing these valuable gene pools (Gole et al., 2002). Some of the threats contributing to the erosion of coffee genetic diversity include human population pressures, volatile coffee markets, and global climate change. Conservation of coffee germplasm as seeds is not a viable option due to the recalcitrant/intermediate storage behavior of seeds (Dulloo et al., 1998; Ellis et al., 1990). Hence, coffee is conserved in field gene banks (Engelmann et al., 2007). Conservation of coffee genetic resources should take into account complementary methods of *in situ* (in their natural habitat) and other *ex situ* (outside their natural habitat) conservation methods. Krishnan (2013) articulated the urgent need to develop a comprehensive strategy for the conservation of coffee genetic resources through a thorough evaluation of existing germplasm.

In the coming decades, climate change will have a huge impact on coffee production, especially *C. arabica*, which is a climate-sensitive species. Noticeable effects of climate change, such as a hotter climate and less and more erratic precipitation, have already been documented in coffee-producing regions. In recent years, droughts have become more frequent in coffee regions and they are expected to increase in severity during the 21st century. The changes in temperature and rainfall will lead to a decrease in areas suitable for coffee cultivation, moving the crop up the altitudinal gradient, and will lead to increased incidences of pests and diseases, expanding the altitudinal range in which pests and diseases can survive. Direct impacts of climate change will result in stressed growth of coffee trees, limited flowering and berry development, poor yield, and poor quality of the coffee beans. Severe outbreaks and spread of diseases (such as leaf rust, coffee berry disease, wilt, leaf blight), insects (coffee berry borer, leaf miners, scales), and nematodes will be experienced—the coffee leaf rust epidemic of Central America in 2012/2013 being an example.

The imminent danger of the effects of climate change warrants the conservation of coffee ecosystems through reduction of deforestation and forest degradation (Kufa, 2010). Using locality analysis and bioclimatic modeling of indigenous Arabica coffee via distribution data, Davis et al. (2012) predicted a 65% to almost 100% reduction in the number of bioclimatically suitable localities by the year 2080. When an area analysis was used, the reduction in suitable bioclimatic space ranged from 38% to 90% by 2080.

In Central America, since 2000, the area affected by coffee berry borer has gradually increased (Laderach et al., 2010). In certain areas, in addition to drought, severe hurricanes will most likely become more frequent (Schroth et al., 2009). Schroth et al. (2009) identified a comprehensive strategy that will sustain biodiversity, ecosystem services, and livelihoods in the face of climate change. The strategy includes promotion of biodiversity-friendly coffee-growing and coffee-processing practices, incentives for forest conservation and restoration, diversification of revenue sources, integrated fire management, market expansion to develop a demand for sustainably produced coffee, crop insurance programs for smallholder farmers, and strengthening capacity for adaptive resource management. Developing adaptation strategies will be critical in sustaining the coffee economy and livelihoods in many countries. The key to this lies in utilizing the varied coffee genetic resources in order to develop varieties with drought stress tolerances and pest and disease resistances.

In 2016, World Coffee Research and the Global Crop Diversity Trust spearheaded the development of the Global Conservation Strategy for Coffee Genetic Resources. World Coffee Research (WCR) is a collaborative, not-for-profit 501(c)5 research organization with the mission to grow, protect, and enhance supplies of quality coffee while improving the livelihoods of the families who produce it. The program is funded and driven by the global coffee industry, guided by producers, and executed by coffee scientists around the world. The Global Crop Diversity Trust (The Crop Trust) is an international organization working to safeguard crop diversity, forever. The Crop Trust is an essential funding element of the United Nation's International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), an agreement that includes 135 countries.

Through engagement of multinational stakeholders engaged in various aspects of coffee production, processing, breeding, conservation, and research, the global strategy aims to ensure the conservation and use of coffee genetic resources for a positive, sustainable future of the crop and for those dependent on coffee for a livelihood. The strategy will act as a framework for bringing together stakeholders at all levels—local, regional, national, and global—in building awareness, capacity, and engagement in conserving the genetic diversity and use of coffee genetic resources for the long term.

Suggested Readings

Engelmann, F., Dulloo, M. E., Astorga, C., Dussert, S., & Anthony, F. (Eds.). (2007). Complementary strategies for *ex situ* conservation of coffee (*Coffea arabica* L.) genetic resources. A case study in CATIE, Costa Rica. *Topical Reviews in Agricultural Biodiversity*. Rome: Bioversity International.

Thurston, R. W., Morris, J., & Steiman, S. (Eds.). (2013). *Coffee: A comprehensive guide to the bean, the beverage, and the industry*. Lanham, MD: Rowman & Littlefield.

Wintgens, J. N. (Ed.). (2009). *Coffee: Growing, processing, sustainable production—A guidebook for growers, processors, traders, and researchers* (2d ed.). Weinheim: Wiley-VCH.

References

Amerson, P. A. (2000). **Coffee rust**. *The Plant Health Instructor*.

Anthony, F., Combes, M. C., Astorga, C., Bertrand, B., Graziosi, G., & Lashermes, P. (2002). The origin of cultivated *Coffea arabica* L. varieties revealed by AFLP and SSR markers. *Theoretical and Applied Genetics*, *104*, 894–900.

Anthony, F., Dussert, S., & Dulloo, E. (2007). Coffee genetic resources. In F. Engelmann, M. E. Dulloo, C. Astorga, S. Dussert, & F. Anthony (Eds.), *Conserving coffee genetic resources: Complementary strategies for* ex situ *conservation of coffee (*Coffea arabica *L.) genetic resources. A case study in CATIE, Costa Rica* (pp. 12–22). Rome: Bioversity International.

Anzueto, F., Bertrand, B., Sarah, J. L., Eskes, A. B., & Decazy, B. (2001). Resistance to *Meloidogyne incognita* in Ethiopian *Coffea arabica* accessions. *Euphytica*, *118*, 1–8.

Bertrand, B., Anthony, F., & Lashermes, P. (2001). Breeding for resistance to *Meloidogyne exigua* in *Coffea arabica* by introgression of resistance genes of *Coffea canephora*. *Plant Pathology*, *50*, 637–643.

CABI. (2016). Coffee berry borer datasheet. *Invasive Species Compendium*. Retrieved from **http://www.cabi.org/isc/datasheet/51521**.

Castillo, P. G., Wintgens, J. N., & Kimenju, J. W. (2009). Nematodes in coffee. In J. N. Wintgens (Ed.), *Coffee: Growing, processing, sustainable production—A guidebook for growers, processors, traders, and researchers* (2d ed., pp. 478–494). Weinheim: Wiley-VCH.

Charrier, A., & Berthaud, J. (1985). Botanical classification of coffee. In M. N. Clifford & K. C. Willson (Eds.), *Coffee: Botany, biochemistry and production of beans and beverage* (pp. 13–47). Westport, CT: Avi.

Coltro, L., Moural, A. L., Oliveira, P. A. P. L. V., Baddini, J. P. O. A., & Kletecke, R. M. (2006). Environmental profile of Brazilian green coffee. *International Journal of Life Cycle Assessment*, *11*(1), 16–21.

Cressey, D. (2013). Coffee rust gains foothold. *Nature*, *494*, 587.

Crowe, T. J. (2009). Coffee pests in Africa. In J. N. Wintgens (Ed.), *Coffee: Growing, processing, sustainable production—A guidebook for growers, processors, traders, and researchers* (2d ed., pp. 425–477). Weinheim: Wiley-VCH.

Damania, A. B. (2003). The early history and spread of coffee. *Asian Agri-History*, *7*(1), 67–74.

Davis, A. P., Gole, T. W., Baena, S., & Moat, J. (2012). **The impact of climate change on indigenous Arabica coffee (*Coffea arabica*): Predicting future trends and identifying priorities**. *PLoS ONE 7*(11), e47981.

Davis, A. P., Govaerts, R., Bridson, D. M., & Stoffelen, P. (2006). An annotated taxonomic conspectus of the genus *Coffea* (Rubiaceae). *Botanical Journal of the Linnean Society*, *152*, 465–512.

Davis, A. P., Tosh, J., Ruch, N., & Fay, M. F. (2011). Growing coffee—*Psilanthus* (Rubiaceae) subsumed on the basis of molecular and morphological data: Implications for the size, morphology, distribution and evolutionary history of *Coffea*. *Botanical Journal of the Linnean Society*, *167*, 357–377.

Descroix, F., & Snoeck, J. (2009). Environmental factors suitable for coffee cultivation. In J. N. Wintgens (Ed.), *Coffee: Growing, processing, sustainable production—A guidebook for growers, processors, traders, and researchers* (2d ed., pp. 168–181). Weinheim: Wiley-VCH.

Diola, V., de Brito, G. G., Caixeta, E. T., Maciel-Zambolim, E., Sakiyama, N. S., & Loureiro, M. E. (2011). **High-density genetic mapping for coffee leaf rust resistance**. *Tree Genetics and Genomes*, *7*(6), 1199–1208.

Dulloo, M. E., Guarino, L., Engelmann, F., Maxted, N., Newbury, J. H., Attere, F., & Ford-Lloyd, B.V. (1998). Complementary conservation strategies for the genus *Coffea*: A case study of Mascarene *Coffea* species. *Genetic Resources and Crop Evolution*, *45*, 565–579.

Dulloo, M. E., Ebert, A.W., Dussert, S., Gotor, E., Astorga, C., Vasquez, N., … Snook, L. (2009). Cost efficiency of cryopreservation as a long-term conservation method for coffee genetic resources. *Crop Science*, *49*, 2123–2138.

Ellis, R. E., Hone, T., & Roberts, E. H. (1990). An intermediate category of seed storage behavior? I. Coffee. *Journal of Experimental Botany*, *41*, 1167–1174.

Engelmann, F., Dulloo, M. E., Astorga, C., Dussert, S., & Anthony, F. (Eds.). (2007). Complementary strategies for *ex situ* conservation of coffee (*Coffea arabica* L.) genetic resources. A case study in CATIE, Costa Rica. *Topical Reviews in Agricultural Biodiversity*. Rome: Bioversity International.

FAO World Information and Early Warning System (WIEWS). (2009–2011). Coffea *germplasm report*. Retrieved from **http://www.fao.org/wiews-archive/germplasm:query.htm**.

Fazuoli, L. C., Maluf, M. P., Filho, O. G., Filho, H. M., & Silvarolla, M. B. (2000). Breeding and biotechnology of coffee. In T. Sera, C. R. Soccol, A. Pandey, & S. Roussos (Eds.). *Coffee biotechnology and quality* (pp. 27–45). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Filho, O. G. (2006). Coffee leaf miner resistance. *Brazilian Journal of Plant Physiology*, *18*(1), 109–117.

Filho, O. G., Silvarolla, M. B., & Eskes, A. B. (1999). Expression and mode of inheritance of resistance in coffee to leaf miner *Perileucoptera coffeella*. *Euphytica*, *105*, 7–15.

Gole, T. W., Denich, M., Teketay, D., & Vlek, P. L. G. (2002). Human impacts on *Coffea arabica* gene pool in Ethiopia and the need for its in situ conservation. In J. M. M. Engels, V. R. Rao, A. H. D. Brown, & M. T. Jackson (Eds.), *Managing plant genetic diversity* (pp. 237–247). New York: CABI.

Hindorf, H., & Omondi, C. O. (2011). A review of three major fungal diseases of *Coffea arabica* L. in the rainforests of Ethiopia and progress in breeding for resistance in Kenya. *Journal of Advanced Research*, *2*, 109–120.

ICO (International Coffee Organization). (2013). *Report on the outbreak of coffee leaf rust in Central America and action plan to combat the pest*. London: International Coffee Organization.

ICO (International Coffee Organization). (2014). *World coffee trade (1963–2013): A review of the markets, challenges and opportunities facing the sector*. ICC 111–5 Rev. 1. Retrieved from **http://www.ico.org/news/icc-111-5-r1e-world-coffee-outlook.pdf**.

ICO (International Coffee Organization). (2016). *International Coffee Organization trade statistics*. Retrieved from **http://www.ico.org/monthly_coffee_trade_stats.asp**.

IISD (International Institute for Sustainable Development). (2003). *Sustainability in the coffee sector: Exploring opportunities for international cooperation*. Retrieved from **https://www.iisd.org/pdf/2003/sci_coffee_background.pdf**.

Infante, F., Perez, J., & Vega, F. E. (2012). Redirect research to control coffee pest. *Nature*, *489*, 502.

Krishnan, S. (2013). **Current status of coffee genetic resources and implications for conservation**. *CAB Reviews*, *8*(16), 1–9.

Kufa, T. (2010, February). *Environmental sustainability and coffee diversity in Africa*. Paper presented at the World Coffee Conference, International Coffee Organization, Guatemala City.

Labouisse, J-P., Bellachew, B., Kotecha, S., & Bertrans, B. (2008). Current status of coffee *(Coffea arabica* L.) genetic resources in Ethiopia: Implications for conservation. *Genetic Resources and Crop Evolution*, *55*, 1079–1093.

Laderach, P., Haggar, J., Lau, C., Eitzinger, A., Ovalle, O., Baca, M., … Lundy, M. (2010). *Mesoamerican coffee: Building a climate change adaptation strategy*. CIAT Policy Brief no. 2. Cali, Colombia: Centro Internacional de Agricultura Tropical (CIAT).

Lashermes, P., Combes, M.-C., Robert, J., Trouslot, P., D'Hont, A., Anthony, F., & Charrier, A. (1999). Molecular characterization and origin of the *Coffea arabica* L. genome. *Molecular and General Genetics*, *261*, 259–266.

Lewin, B., Giovannucci, D., & Varangis, P. (2004). *Coffee market: New paradigms in global supply and demand*. Agriculture and Rural Development Discussion Paper 3. Washington, DC: World Bank, Agriculture and Rural Development Department.

Meyer, F. G. (1965). Notes on wild *Coffea arabica* from southwestern Ethiopia, with some historical considerations. *Economic Botany*, *19*, 136–151.

Muller, R. A., Berry, D., Avelina, J., & Bieysse, D. (2009). Coffee diseases. In J. N. Wintgens (Ed.), *Coffee: Growing, processing, sustainable production—A guidebook for growers, processors, traders, and researchers* (2d ed., pp. 495–549). Weinheim: Wiley-VCH.

Musoli, P., Cubry, P., Aluka, P., Billot, C., Dufour, M., De Bellis, T., … Leroy, T. (2009). Genetic differentiation of wild and cultivated populations: Diversity of *Coffea canephora* Pierre in Uganda. *Genome*, *52*, 634–646.

NCA (National Coffee Association). (2017). *Coffee around the world*. Retrieved from **http://www.ncausa.org/About-Coffee/Coffee-Around-the-World**.

Noir, S., Anthony, F., Bertrand, B., Combes, M. C., & Lashermes, P. (2003). Identification of a major gene (*Mex-1*) from *Coffea canephora* conferring resistance to *Meloidogyne exigua* in *Coffea arabica*. *Plant Pathology*, *52*, 97–103.

Osorio, N. (2002). *The global coffee crisis: A threat to sustainable development*. London: International Coffee Organization.

Plantwise Technical Factsheet. (2015). *American leaf spot of coffee* (Mycena citricolor). PLantwise KN owledge Bank. Retrieved from **http://www.plantwise.org/KnowledgeBank/Datasheet.aspx?dsid=35243**.

Ponte, S. (2004). *Standards and sustainability in the coffee sector: A global value chain approach*. United Nations Conference on Trade and Development and the International Institute for Sustainable Development. Retrieved from **http://www.iisd.org/pdf/2004/sci_coffee_standards.pdf**.

Prakash, N. S., Marques, D. V., Varzea, V. M. P., Silva, M. C., Combes, M. C., & Lashermes, P. (2004). Introgression molecular analysis of a leaf rust resistance gene from *Coffea liberica* into *C. arabica* L. *Theoretical and Applied Genetics*, *109*, 1311–1317.

Prakash, N. S., Muniswamy, B., Hanumantha, B. T., Sreenath, H. L., Sundaresha, K. D., Suresh, N., … Jayarama. (2011). Marker assisted selection and breeding for leaf rust resistance in coffee (*Coffea arabica* L.)—Some recent leads. *Indian Journal of Genetics and Plant Breeding*, *71*(2), 1–6.

Reinecke, J., Manning, S., & Von Hagen, O. (2012). The emergence of a standards market: Multiplicity of sustainability standards in the global coffee industry. *Organization Studies*, *33*(5/6), 789–812.

Rice, R. (2013). Culture, agriculture, and nature: Shade coffee farms and biodiversity. In R. W. Thurston, J. Morris, & S. Steiman (Eds.), *Coffee: A comprehensive guide to the bean, the beverage, and the industry* (pp. 41–51). Lanham, MD: Rowman & Littlefield.

Salinas, B. (2008). *Life cycle assessment of coffee production*. Retrieved from **http://bsalinas.com/wp-content/uploads/2009/10/paper.pdf**.

SCAA (Specialty Coffee Association of America). (2016). *History*. Retrieved from **http://www.scaa.org/?page=history**.

Schroth, G., Laderach, P., Dempewolf, J., Philpott, S., Haggar, J., Eakin, H., … Ramirez-Villegas, J. (2009). Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. *Mitigation and Adaptation Strategies for Global Change*, *14*, 605–625.

Silva, M. d. C., Varzea, V., Guerra-Guimaraes, L. Azinheira, H. G., Fernandez, D., Petitot, A-S., … Nicole, M. (2006). Coffee resistance to the main diseases: Leaf rust and coffee berry disease. *Brazilian Journal of Plant Physiology*, *18*, 119–147.

Steiman, S. (2013). What is specialty coffee? In R. W. Thurston, J. Morris, & S. Steiman (Eds.), *Coffee: A comprehensive guide to the bean, the beverage, and the industry* (pp. 102–105). Lanham, MD: Rowman & Littlefield.

Thomas, A. S. (1942). The wild Arabica coffee on the Boma Plateau, Anglo-Egyptian Sudan. *Empire Journal of Experimental Agriculture*, *10*, 207–212.

Thurston, R. W. (2013a). The global trade in coffee. In R. W. Thurston, J. Morris, & S. Steiman (Eds.), *Coffee: A comprehensive guide to the bean, the beverage, and the industry* (pp. 111–115). Lanham, MD: Rowman & Littlefield.

Thurston, R. W. (2013b). Introduction. In R. W. Thurston, J. Morris, & S. Steiman (Eds.), *Coffee: A comprehensive guide to the bean, the beverage, and the industry* (pp. 1–10). Lanham, MD: Rowman & Littlefield.

Van der Vossen, H. A. M., & Walyaro, D. J. (2009). Additional evidence for oligogenic inheritance of durable host resistance to coffee berry disease (*Colletotrichum kahawae*) in Arabica coffee (*Coffea arabica* L.). *Euphytica*, *165*, 105–111.

Vega, F. E. (2008). The rise of coffee. *American Scientist*, *96*, 138–145.

Vega, F. E., Davis, A. P., & Jaramillo, J. (2012). From forest to plantation? Obscure articles reveal alternate host plants for the coffee berry borer, *Hypothenemus hampei* (Coleoptera: Curculionidae). *Biological Journal of the Linnean Society*, *107*, 86–94.

Vega, F. E., Ebert, A. W., & Ming, R. (2008). Coffee germplasm resources, genomics, and breeding. In J. Janick (Ed.), *Plant Breeding Reviews* (Vol. 30, pp. 415–447). John Wiley & Sons, Inc.

Vega, F. E., Infante, F., Castillo, A., & Jaramillo, J. (2009). The coffee berry borer, *Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae): A short review, with recent findings and future research direction. *Terrestrial Arthropod Reviews*, *2*, 129–147.

Wintgens, J. N. (2009). The coffee plant. In J. N. Wintgens (Ed.), *Coffee: Growing, processing, sustainable production—A guidebook for growers, processors, traders, and researchers* (2d ed., pp. 3–24). Weinheim: Wiley-VCH.

Sarada Krishnan

Denver Botanic Gardens