COFFEE (*COFFEA ARABICA*) FIELD TRIAL IN SOUTHERN CALIFORNIA

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Phillip Callahan

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AUTHOR: Phillip Callahan

DATE SUBMITTED: Spring 2024

Department of Plant Science.

Dr. Valerie Mellano
Thesis Committee Chair
Professor of Plant Science

Dr. Anna Soper
Associate Professor of Plant Science

Duncan McKee
Soil Lab Technician and Instructor
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ABSTRACT

Coffee is the world’s most valuable agricultural export commodity, second only to oil in international trade (International Coffee Organization (ICO), 2022), with an estimated 21 billion pounds of green coffee produced around the world each year on over 25 million acres. Global coffee consumption continues to increase at an annual rate of 3%. About 125 million people in more than 60 developing countries depend on coffee for their food security and livelihoods. In some countries rural employment in coffee production accounts for 80% of foreign trade earnings, and nearly 75% of global coffee production comes from small farms of less than five acres. The retail value of the coffee industry is estimated to be 90 billion US dollars per year and yet, remarkably, coffee remains an understudied crop, receiving very little funding for genetics and genomics research (International Coffee Genome Network (ICGN), 2018).

In this study established Coffea arabica plantings in three locations of Southern California were measured by height, width, and caliper from 2022-2023. The measurements were then complied by average per site and compared. It was found that the plants at higher elevation, with higher clay content in soils, and higher average temperatures showed to be on average 44 cm taller (Figure 4) than those grown at lower elevation. This study demonstrated that Coffea arabica can be established successfully in a range of locations in Southern California. This area could be successfully used for the cultivation of coffee plants specifically for research such as the preservation of endangered species and evaluation of climate ready cultivars. Aside from the suitability of Southern California for Coffea arabica growability, there are currently no known major insect or pathogen pests of the plant in the area, which could promote international research partnerships and collaborations without the hazard of novel pest introduction via export from Southern California.
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LITERATURE REVIEW

Coffee Origin

The genus *Coffea* was first described by Linnaeus in 1753 and consists of more than 100 species and seven intraspecific taxa, all occurring naturally in equatorial Africa and Madagascar. There are three commercially planted species of *Coffea* in order of production; they are *C. arabica* (arabica), *C. canephora* (robusta), and *C. liberica* (liberica) (Gaitàn et al., 2015; Teketay, 2012; Ukers, 1935). *C. arabica* is known commercially as arabica coffee whereas *C. canephora* is known as robusta. Nearly 100% of the cultivated plants belong to either arabica or robusta (Gaitàn et al., 2015). Of the 127.96 million globally produced bags of Coffee beans exported in 2022, arabica accounted for 62.26% with 79.67 million bags exported. The remaining 37.74% was robusta coffee beans with 48.29 million bags exported in the year of 2022 (International Coffee Organization What’s New, n.d.). Arabica was distributed from its native region nearly 200 years prior to the discovery and distribution of robusta (Teketay, 2012; Ukers, 1935). Plantings of arabica in Southeast Asia were ravaged by Coffee Leaf Rust epidemics that began in 1869. Resistance was found in liberica and robusta. Robusta had a better flavor profile compared to liberica and was more prolific, leading to an establishment of long term cultivation of robusta in Southeast Asia (Gaitàn et al., 2015; Teketay, 2012; Ukers, 1935). Arabica is cultivated modern day primarily in Central and South America in areas of high elevation unsuitable for robusta and liberica. Today, robusta is produced mainly in Central and West Africa, Southeast Asia, and Brazil (Gaitàn et al., 2015; Ky et al., 2001).

Most authorities agree that the coffee plant is indigenous to Abyssinia (Ethiopia modern day), and probably Arabia. (Ukers, 1935). All botanists, who have explored the forests on the southwestern highlands of Ethiopia, agree that Ethiopia is the center of diversity of arabica.
(Charrier & Berthaud, 1985). Yemen was the first country where arabica was taken for cultivation from Ethiopia, however it is unclear how or when the coffee was distributed. Yemen appears to be the secondary center of distribution from which coffee was introduced to other countries India (1600), Ceylon (1600-1696), Java (1690 and 1699), and Bourbon in (1715-1718), it was from these countries that coffee spread to the rest of the world by trade and conquest (Teketay, 2012).

Arabica was first introduced to the continent of South and Central America by the Dutch in 1718 when they began planting coffee from Amsterdam in Suriname. From Surinam it was introduced to Cayenne (in French Guiana) in 1727. From French Guiana it was introduced to Brazil in 1727 (Wellman, 1961). The spread of arabica coffee around the world was based on very limited number of trees, the seven berries taken by Baba Budan to India; the small shipment to Reunion; and the tree taken from Java to Amsterdam in 1706, together with its offspring in Paris which provided all the planting material for South and Central America. Consequently, the whole genetic base of the arabica coffee industry is very narrow. (Wrigley, 1988). This leads to increased vulnerability to damage resulting from insect and pathogen pests within arabica coffee plantings and less climactic resilience.

Robusta was discovered in the Congo in 1898 and occurs wild in the equatorial forest from West Africa to Lake Victoria. Robusta was first planted on a small scale in Uganda and elsewhere in Equatorial Africa by the Aborigines. (Gaitàn et al., 2015; Teketay, 2012). Upon its discovery by Europeans, it was taken up by a horticultural firm of Brussels known as L’Horticole Coloniaie and cultivated for the market (Ukers, 1935). The director of the firm sent 150 plants from Brussels to Java in 1900 where it proved to be resistant to Coffee Leaf Rust which had decimated arabica and liberica, as a result of this it was extensively planted. Robusta was
introduced to Singapore and Trinidad from the Kew Botanic Gardens of England and since 1900 robusta has been widely distributed throughout the tropics where it has successfully grown at lower elevations unsuited to arabica and where Coffee Leaf Rust is a serious problem (Teketay, 2012). Today, robusta is cultivated in the lowlands of West Africa, Indonesia, Vietnam, and Brazil (Ky et al., 2001).

Liberica was originally found near Monrovia in Liberia and spread by cultivation in West Africa. Specimens of liberica were collected as early as 1792 in Sierra Leone and it was widely distributed throughout the tropics from Kew and other gardens (Teketay, 2012). In Java it was planted as a replacement for arabica in 1873 which was decimated by Coffee Leaf Rust (Teketay, 2012). In 1919 there were 4,940 mature acres of liberica present in Java, a miniscule amount when compared to the 110,903 acres of robusta present on the island (Ukers, 1935). Robusta proved to be the most resistant variety to the Coffee Leaf Rust, leading to a reduction in successive Liberica plantings. Today it is cultivated in Malaysia and West Africa and is traded in small quantities (Gaitàn et al., 2015).

Arabica is preferred over all other species because of its superior quality. Arabica makes a flavorful, full-bodied coffee, sharp in taste with rather low caffeine content (Smith & Bardener, 1985). The average arabica plant is a large bush with dark green oval leaves and reaches a height of fourteen to twenty feet when fully grown. Lateral branches produce flowers, this fact is used in pruning the coffee tree by cutting back uprights, causing the laterals to become more productive. Growers generally keep their trees pruned down to about six feet (Teketay, 2012; Ukers, 1935). Optimal average temperatures for arabica are between 17.8 and 2.2 degrees Celsius. In systems where no form of irrigation is installed, annual rainfall must range between 1,400 and 2,000 mm. The fruits are oval and mature in seven to nine months, containing usually
two flat seeds (Gaitàn et al., 2015). Arabica flowers are self-fertile and mostly self-pollinating, about 90% of the flowers are pollinated by the time they open (Lobo, 2020). Arabica is the only tetraploid species in the genus. Arabica has an allopolyploid origin, derived from a naturally occurring, interspecific hybridization between *C. eugenioides* S. Moore and *C. canephora* and followed by polyploidization. Arabica would have continued to be the exclusive producer of all coffee in the world, as it had been for more than 150 years until the end of the 19th century when the coffee leaf rust (*Hemileia vastatrix* Berk. & Br.) epidemics decimated arabica plantings growing at lower altitudes in tropical zones concentrated in Southeast Asia (Smith & Bardener, 1985). Arabica still makes up for most of the world’s coffee production because the plantings in Central and South America were isolated from the coffee leaf rust outbreaks until 1970. By the time coffee leaf rust reached Central and South America modern fungicides in addition to breeding programs that had begun in the 1960s to develop disease-resistant varieties in anticipation of possible coffee leaf rust epidemics had made considerable progress and had varieties available at time of pathogen introduction in some countries (Smith & Bardener, 1985).

As a species, robusta exhibits high amounts of genetic diversity and is composed of two groups: the Congolese group and the Guinean group. The Congolese group is subdivided into five subgroups: SG1, SG2, B, C, and UW. Those of the SG1 subgroup are known as *C. canephora* var. *kouilou* (in Brazil, known as conilon coffee), and the others are known as *C. canephora* var. *robusta* (or Robusta coffee) (Asefa Bikila, 2017). Robusta is a robust shrub or tree capable of growing up to 10 meters tall. The plant is grown in altitudes up to 610 meters and is widely grown in West and Central Africa, throughout Southeast Asia, and some parts of Brazil. The fruits are round, take up to 11 months to mature and contain oval seeds smaller and heavier than those of arabica (Buck et al., 2021; Gaitàn et al., 2015). Robusta is self-sterile, and
its leaves are slightly thicker than those of arabica. This tree is very hardy and can bear blossoms even when it is less than a year old, it blossoms through the entire year. The yield for the first three years is negligible, the fourth-year crop is large (Teketay, 2012; Ukers, 1935). Robusta is diploid and has higher genetic diversity than arabica due to its origin, reproduction method and dissemination (Ferrão et al. 2015). Robusta exhibits high grain yield and low susceptibility to abiotic and biotic stresses (Ferrão et al. 2015). Robusta is better suited in areas of hotter temperatures than arabica with ideal temperatures ranging between 22.2 and 27.8 degrees Celsius (Gaitàn et al., 2015; Campuzano-Duque et al., 2021). Robusta is capable of producing between 1814 kilograms to 3629 kilograms per hectare annually with technological management compared to 1361 kilograms to 2722 kilograms per hectare annually when compared to arabica (Campuzano-Duque et al., 2021).

Liberica is the third commercial species, it grows as a large strong tree up to 18 meters high with large leathery leaves, fruits, and seeds. Liberica coffee is cultivated in Malaysia and West Africa, but only very small quantities are traded, since demand for its flavor profile is scarce (Gaitàn et al., 2015). Liberca can live up to 30 years (Smith & Bardener, 1985). Liberica thrives in lowland tropical areas. Coffee wilt disease (tracheomycosis) epidemics caused by Fusarium xylarioides eliminated the majority of liberica species in the field between 1940 and 1950 (Berthaud & Charrier, 1988).

The following varieties discussed are all forms of arabica coffee. The Geisha variety is an arabica that was first discovered in the forested mountains of western Ethiopia in the 1930s in the provinces of Maji and Goldija. It was first brought to Panama from Costa Rica in 1963 after journeying through Tanzania, Kenya and Costa Rica (Boot 2013). Displaying unique flavor profiles, larger bean size and other phenotypic differences from other arabica varieties, this
variety also exhibits resistance to coffee leaf rust (*Hemileia vastatrix* Berkeley and Broome) (Boot 2013). The recent epidemic outbreak of coffee leaf rust in Central America has led to crop devastation in numerous coffee producing Central American countries. Taking economics and minimization of chemical input into consideration, the most viable and effective option is the development and cultivation of tolerant varieties (Prakash et al. 2004). Geisha coffee can play an important role in future breeding programs for crop improvement to confer disease resistance and improve cup quality (Krishnan & Boot, 2014).

The Bourbon variety began when arabica was introduced to Réunion (Bourbon) island in 1715-1718. Over the course of these years the French attempted to introduce arabica plants from the port of Mocha in Yemen, by 1720 a small number of plants from the second and third introduction were successful. (Teketay 2012). These plants produced a good crop and were used to establish large plantations on Réunion (Bourbon) island. These plants and their progenies led to the creation of the Bourbon variety. Bourbon was first introduced into the Americas in 1860 to southern Brazil, near Campinas. From there it spread north to Central America (World Coffee Research 2020).

Bourbon Amarillo is native to Brazil and descended from *C. arabica* var Bourbon. Bourbon Amarillo is very susceptible to rust. Plants reach maturity at 10-12 years old and can reach an average height of 2.6 meters. The main flowering takes place from September to October in the conditions of São Paulo and maturation from March to May depending on location. The expected yield is 25 bags per hectare, the plants are considered of low vigor and cultivation is recommended for regions above 3,300 meters of altitude. Bourbon Amarillo is capable of being grown in areas of lower temperature when compared with Catuai cultivars.
Coffee brewed using Bourbon Amarillo beans is known for floral and honey notes (Romano et al., 2022).

Catuai is an arabica that was bred by the Instituto Agronômico (IAC) of Sao Paulo State in Campinas, Brazil. When compared to Bourbon, Catuai can be planted at nearly double the density leading to higher yields. Catuai is highly susceptible to coffee leaf rust, it was released in Brazil in 1972 and is primarily cultivated in Honduras, Costa Rica, and Guatemala. Catuai’s small structure allows it to be planted densely and harvested more efficiently, led in part to the intensification of full-sun coffee cultivation in Central America in the 1970s and 1980s (World Coffee Research).

Catuai Amarillo is a descendent of C. arabica var Catuai. It shares the same compact growth structure and is planted at high densities across Central and South America in addition to Hawaii (Gutiérrez & Meinzer, 1994). Catuai Amarillo is known for its yellow cherries and high-quality coffee beverage (World Coffee Research).

Caturra is a natural mutation of C. arabica var Bourbon that was first discovered on an estate in Minas Gerais, Brazil between 1915 and 1918. Caturra has a single-gene mutation that causes the plant to grow smaller this is referred to as dwarfism. Caturra led in part to the intensification of coffee cultivation through higher density planting, often in full sun that took place in South and Central America in the second half of the 20th century (World Coffee Research). Caturra grows best at between 1219 and 2012 meters above sea level in areas with around 3,000 mm of annual precipitation. The cherries ripen slowly, which can affect the plants’ yield when grown at particularly high altitudes. The higher the altitude, the slower the coffee cherries ripen which can result in the last part of the crop being unavailable during the harvesting window. Caturra is resistant to droughts, winds, and exposure to sunlight and can adapt to hot
temperatures. Caturra is very popular among producers since they can fit a great number of plants into each square meter of land. Their small size also makes it easier for workers to handpick ripe cherries (Lancashire, 2021).

Catimor T5175 is a dwarf variety of arabica that is a cross between *C. arabica* Timor Hybrid 832/1 and Caturra. Catimor T5175 is resistant to coffee leaf rust and has a high yield potential. In Honduras, additional selection of Catimor T5175 led to the creation of *C. arabica* IHCAFE-90 and *C. arabica* Lempira (World Coffee Research).

IHCAFE-90 is an arabica that can produce early ripening yields and requires high amounts of fertilization. It is a dwarf plant with bronze tipped leaves and is susceptible to coffee leaf rust and Ojo de Gallo at high elevations (Zambrano 2020).

Lempira is a dwarf variety of arabica (WCR, 2022 and a hybrid between Caturra and Timor; it produces high yields and thrives in warm temperatures and acidic soil. It is susceptible to Ojo de Gallo caused by the fungus *Mycena citricolor* and coffee leaf rust (Zambrano 2020).

Typica is an arabica variety that is a slow grower that has low productivity. Typica are tall plants with long internodes and low tolerance to wind. They are not usually recommended for planting but are useful in genetic development of new varieties (WCR, 2022).

**Coffee Cultivation**

The coffee tree yields from one to twelve pounds a year, depending on the individual tree and region. In some countries the whole year’s yield is less than 200 pounds per acre (Ukers, 1935). Ideal conditions for growing coffee consist of the correct soil, climate, rainfall, and altitude. Coffee is capable of being grown in many soil types; however the ideal soil is fertile, volcanic red earth or a deep, sandy loam (Food and Agriculture Organization of the United Nations (FAO), 2020;Ukers, 1935). The soil must have a minimum depth of one meter. The most
important component of soil required is soil structure which allows good drainage. This is because water logging reduces yield considerably and even results in the death of coffee trees themselves (Food and Agriculture Organization of the United Nations, n.d.; Teketay, 2012; Smith and Bardener, 1985). Roots will be able to grow freely in a soil with good structure and drainage. Heavy clay soils are undesirable because of slow drainage; clay-heavy soils will restrict root growth and very heavy clays will not be penetrated at all (Smith and Bardener, 1985). A high-water capacity is necessary so that sufficient available water can be stored to maintain evapotranspiration throughout the dry season. Deeper soils provide for a greater volume of root proliferation, in areas of lower rainfall and a long dry season a deep soil is essential, 3 meters deep is ideal (Smith and Bardener, 1985). Ideal coffee soil pH lies in the range between 5-6 (Food and Agriculture Organization of the United Nations, n.d.). A slightly acidic soil is preferred for coffee, arabica is less tolerant of acidic and alkaline soil pH than robusta and will exhibit reduced yields at higher rates outside of the ideal range of 5-6. Coffee’s ability to grow in a wide range of soils means that fertilizer application levels will vary over a wide range. The optimum for any site will have to be determined on that site with reference to local conditions (Smith and Bardener, 1985).

Coffee is not sensitive to day-length. Where other parameters are suitable for coffee in the tropics and subtropics there will be no problems arising from the variation in day-length (Smith and Bardener, 1985). For every rise of 1000 meters in altitude, there is a fall of about six degrees Celsius. Altitude relates to temperature, in equatorial areas arabica is a highland crop growing from 1,000 to 2,000 meters, with robusta growing from sea level to 700 meters (Smith and Bardener, 1985). High elevation improves the quality of the bean and potential cupping quality. This is due to a delay in ripening induced by cooler weather associated with higher
altitudes, the inherent characteristics of acidity, aroma and bold bean can develop fully. Bold bean is classified as being the size between a large and a medium sized bean, with its width/length ratio bigger than that of a large bean (Food and Agriculture Organization of the United Nations, n.d.). The effects of the changes from wet to dry seasons and vice versa are vital for flower initiation, flower dormancy breaking and vegetative growth induction. Water requirements of coffee will vary depending on variety, field conditions, and geographical conditions.

Total annual rainfall must generally range between 1,400 and 2,000 mm for arabica varieties and 2,000 and 2,200 mm for robusta (Gaitàn et al., 2015). Water requirements can be reduced by use of proper, well-established, shade trees, mulch and cover crops (Food and Agriculture Organization of the United Nations, n.d.). Coffee needs a dry, stress period with little or no rain to induce a uniform flowering. Without a stress period, flowering may extend over many months making harvesting more difficult (Food and Agriculture Organization of the United Nations, n.d.). Humidity and cloud coverage have a water conserving effect on coffee plantings and can both be critically important during the dry season. When humidity is high the loss of water by evapotranspiration is reduced. High humidity is especially important during the dry season because it decreases the stress on the coffee trees thereby extending the rainless period through which the plants will survive without damage. Cloud coverage intercepts sunlight and reduces its intensity leading to an increase in humidity and lowering of temperature both of which are favorable during long dry seasons. Cloud coverage can also contribute to soil moisture when it appears near the ground in the form of mist (Teketay, 2012). Wind may have different effects on the growth and yield of coffee. Strong wind is detrimental as it may break branches of coffee trees. It also increases evapotranspiration as a result of which it creates water stress in the
trees. Cold wind increases the effect of low temperature. Hot wind may cause wilting or even death of leaves of coffee trees. Both cold and hot wind can reduce growth and yield of coffee. These problems can be counteracted by providing windbreaks for the coffee trees (Teketay, 2012). The use of shade is controversial, in many coffee growing countries coffee is grown satisfactorily without shade. When coffee is grown under optimum conditions of soil and climate, with a high standard of cultural practices and adequate inputs, higher yields are obtained without shade (Teketay, 2012). Arabica is grown under a wide range of management types from traditional rustic systems where coffee bushes are planted under heavily thinned natural forest and few inputs are used, to specialized shade systems where shade trees and inputs are carefully managed, to intensive systems with high densities of coffee bushes, little or no shade, and heavy use of agrochemical inputs. (Perfecto et al. 2019). Where soil conditions are not so favorable, rainfall is excessive, temperatures are too high or too low and possibly where there is a prolonged season of many hours of bright sunlight as well as low standard of cultivation, it is advisable to use shade to sustain regular yields and prevent over-bearing. Coffee trees established without shade give higher yields than shaded coffee. Nevertheless, they have a tendency to over-bearing, die-back, biennial bearing, erosion, disease and short productive life (Teketay, 2012).

In many coffee-growing areas, pruning is a major part of cultivation. Pruning is an important part of the cultivation process, if left to their own devices coffee trees sometimes grow as high as forty feet, the strength being absorbed by the wood, with a consequent scanty production of fruit. To prevent this undesirable result, and to facilitate picking, the trees on the more modern plantations are pruned down to heights ranging from six to twelve feet (Ukers, 1935). All pruning systems can be grouped either as single-stem or multiple-stem systems. Trees
on either system require regular attention to meet the below objectives. Most of the coffee crop is grown on two-year-old plagiotropic stems or primaries and one important objective of pruning is to maximize the amount of such wood. Pruning is beneficial to coffee plants in a variety of ways. It shapes the tree to make best use of the space between trees, removes dead diseased and over-age wood. Arabica coffee does not shed over-age laterals naturally, but robusta does. It provides an environment within the tree which is conducive to maximum crop production but minimizes the spread of pests and diseases, pruning can have the crop formed where it can be harvested easily and cheaply, it enables sprays of fungicides and insecticides to reach all of the tree, and it minimizes biennial bearing and consequent risk of die-back. Variety, environmental conditions and other factors affect the measures necessary to establish and maintain particular systems. Low temperatures restrict branching for both arabica and robusta (Smith and Bardener, 1985). Pruning opens up the coffee canopy to allow light and wind movement into the tree. The increased light is important in inducing more flower buds. Photosynthesis is increased by leaves which were previously heavily shaded. Creating greater freedom for air to pass through the coffee plot and individual trees, dries out the leaves more quickly after rain or heavy dew, making conditions less favorable to the spread of certain diseases (Teketay 2012).

The phenology of the coffee plant refers to the physical and physiological developmental stages of the coffee plant throughout the year, this is often referred to as the crop cycle. Coffee, like all plants, responds to the changing environment in which it grows as influenced by the seasons. As seasons change, the coffee tree switches from vegetative to reproductive growth and as the plant grows, it flowers, sets fruit, matures the fruit and is ready for harvest and regrowth for the next cycle. The phenological cycle gives excellent indicators of when to fertilize, irrigate, withhold water, prune, take leaf and soil analyses, check for pests and diseases and apply
controls for them. Timing is very important when using these practices to optimize production from the coffee tree (Food and Agriculture Organization of the United Nations, n.d.). Flower bud dormancy is broken, or rather progressively decreased, during the period of no visible growth (usually 1-4 months) by continued experience of low chilling on the winter dormancy of buds of temperate trees. Water stress can occur in the buds even though the roots are well watered and the longer the period of water stress, the easier it becomes to stimulate the buds to regrow. Water stress appears to decrease endogenous ABA levels in the buds but it may have the following two effects: (a) a decrease in cell permeability to the water both in the buds and the tree roots, increasing hydraulic conductivity during periods of drought and (b) a build-up of conjugated or bound gibberellic acid (GA) in the flower buds. Water stress appears to be mandatory for normal flower development; if the buds do not experience this they develop abnormally or not at all. After several weeks of water stress the lower buds are no longer fully dormant, but they need a special stimulus before they will regrow. This stimulus has been defined as a sudden relief of water stress (or rehydration), in the buds themselves, and/or a sudden drop in temperature, of about 3.9 degrees Celsius per hour. In the field both signals are often provided together at the end of a dry season. Irrigation, mists, immersion in water or spraying the buds with water can all provide the stimulus for regrowth. Exogenously applied GA can replace the environmental stimulus. During the 3-4 days after the stimulus has been received, meiosis occurs, and there is an increase in almost two orders of magnitude in the levels of endogenous, active GA in the buds. This increase in GA levels occurs before the buds increase abruptly in fresh weight and is thought to overcome the inhibitory effects of ABA, which remains in the buds at the same levels as before (Smith & Bardener, 1985).
The coffee belt of the world lies between the Tropic of Cancer and the Tropic of Capricorn with nearly all principal coffee consuming countries to be found in the north temperate zone, between the tropic of cancer and the arctic circle (Food and Agriculture Organization of the United Nations, 2020; Ukers, 1935).

**Coffee Propagation**

Coffee propagation is commonly done by seed, but tissue culture is gaining popularity. Seed selection for commercial farming focuses on harvesting the best seeds possible which is achieved by collecting cherries from the center third of the plant where the most nutrients are concentrated (Lobo, 2022). The beans do not retain their vitality for any considerable length of time and if they are thoroughly dried or are kept for longer than three or four months, they are useless for propagation (Ukers, 1935). Seeds take around 45 to 60 days to germinate. Seeds can be successfully germinated in a sandy soil mixture consisting of peat moss, perlite and vermiculite, rocks and pebbles should be removed from germinating medium. Seed beds or trays must be always kept moist to avoid drying. Seeds should be ready for transplant after 90 days (Lobo, 2022). Trees raised from seed begin to blossom in about three years, but a good crop cannot be expected of them for the first five or six years (Ukers, 1935). The World Coffee Research is propagating plants using tissue culture, lots of the plants cultured are having growth structure issues and are growing spread out rather than upright (Lobo, 2022). The coffee tree can be propagated by using the upright branches as slips which after taking root will produce seed bearing laterals (Ukers, 1935). The propagation of the coffee plant by cutting has two distinct advantages over propagation by seed, in that it spares the expense of seed production, which is enormous and it also gives a method of hybridization, which if used, might lead not only to very interesting but also very profitable results (Ukers, 1935).
**Sustainable Coffee Production**

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 (Krishnan, 2017). 55% of coffee cups sold are perceived by consumers as specialty coffee (Lobo, 2022). Coffee shops are the fastest growing niche in the restaurant business, with a 7% annual growth rate. 90% of world coffee production occurs in developing countries but it is consumed in industrialized nations. Fair trade coffee, though a small portion of the market is popular, fair-trade commodities are worth $1.26 per pound vs $0.70 to $0.90 per pound for non-fair trade. The top five importing countries of coffee are France, Germany, Italy, Japan and the United States of America. These countries consumed about 51.5 million bags in 2013 (Lobo, 2022). Coffee provides 75% of American caffeine consumption. The United States of America is the single largest buyer with about ¼ of global coffee imports (Lobo, 2022).

In recent decades, agriculture has prioritized the implementation of increasing amounts of energy into production systems to increase crop yield. Currently, the amount of energy demanded by production processes for transformations has often been higher than its return, an unsustainable form of cultivation. In a context marked by high inputs and inefficiency of agricultural systems, organic farming is seen as a feasible, sustainable alternative. A study in 2015 was conducted comparing energy use of three growing systems of *C. arabica* in Espírito Santo in Brazil. The three systems were defined as conventional cultivation, cultivation with good agricultural practices, and organic farming. It was found that organic farming was the most sustainable system from an energetic input point of view. Cultivation with good practices presented the highest physical yields. The most significant energy cost of organic systems came
from machinery and equipment. Yet for conventional cultivation, it was the use of chemical fertilizers. For cultivation with good practices, the highest costs came both from chemical fertilizers and from activities such as coffee processing and post-harvest (De Muner et al., 2015). Climate change, rising temperatures, longer droughts, and excessive rainfall appear to threaten the sustainability of arabica coffee production. Arabica has historically had remarkable adaptation to a wide range of environments throughout the intertropical belt, despite its genetically narrow source population, this could be attributed to the allotetraploidy of its genome (Chen 2010). Arabica coffee production is still based to a large extent on traditional cultivars developed long after by line selection within the Typica and Bourbon source varieties or in offspring of crosses between them. Some of these traditional arabica cultivars are high yielding and have a reputation for producing outstanding cup quality under optimal conditions of climate, soil and crop management. However, almost all of them are highly susceptible to the major coffee diseases and pests, which makes them increasingly difficult to maintain for economic and ecological reasons in many coffee regions. These reasons include the cost of chemical control and pesticide pollution problems. Many organizations across the globe have worked on breeding arabica for disease resistance in combination with vigor, productivity and quality. Genetic variation has been increased by introgressive breeding with other species, such as C. liberica, C. canephora, C. eugenoides, C. stenophylla, and C. racemosa. Introggression of new progenitors in the breeding programs should increase genetic diversity among cultivars. In 2010 Setotaw et al. showed that the genetic base of 121 cultivars released in Brazil between 1939 and 2009 was defined by only 13 ancestors. The situation is the same for Latin America as a whole (85% of the world production of arabica coffee). The limited number of parental lines included in the early stages of arabica coffee breeding contributed to the rather narrow genetic base of arabica.
cultivars released in Latin America (van der Vossen et al., 2015). 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. Additionally, they are being lost due to climate change leading to increased incidence of pests and diseases, higher incidence of drought, and many unpredictable rainfall patterns. Low coffee prices are also leading to abandoning of coffee trees in forests and gardens of shifting cultivation to other more remunerative crops. All of these factors threaten livelihoods in many coffee growing countries (Krishnan, 2017). Advanced coffee variety development will benefit tremendously from networks of collaborating coffee research centers, to facilitate the sharing of resources both financial, genetic, and genomic. Technologies and the scientific information at the pre-breeding stages. There is a global effort gaining traction between coffee producing nations to create the next generation of sustainable coffee lines capable of meeting the rising demand and growing challenges brought forth by climate change (van der Vossen et al., 2015). 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 (Krishnan, 2017).

Specialty Coffee Market

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 (Krishnan, 2017). Specialty coffee has emerged from the coffee industry of the twentieth century, with a culture of developing a better appreciation of coffee through quality beans and improved brewing methods. Consumers have been shown to have positive perceptions of specialty coffee with a market demand for the product. The shift to
use artisanal products has led to specialty coffee, which can be described as coffee that is made by means of the current applied brewing principles using high quality coffee beans. High quality coffee beans are found through correct farming and harvesting methods which reduce defects and ensure peak ripeness. The coffee beans go through the quality standards set by graders which ensure the beans meet specialty standards. It is important for roasters to use the right roasting method to bring out the desired bean aromas, flavors and quality (Urwin et al., 2019). The U.S. specialty coffee market gained strength in the 1970s and the 1980s with the rise of the independent coffee roasters focused on quality and consumers willing to pay significant premiums for quality coffee. In 1982 some of these roasters created the Specialty Coffee Association of America (SCAA). The SCAA has devoted itself to setting standards for coffee quality, and some coffee farmers have been focusing their efforts on meeting or exceeding those standards. Some farmers have begun replanting their farms with coffee varieties favored by the specialty market, unfortunately some of these are susceptible to coffee leaf rust and other diseases and pests, which require higher inputs of chemical control under certain conditions. High quality coffees are usually processed by washing either on the farm or on a centralized mill. This process can consume a great deal of water, and the contaminated effluent from washing can present significant environmental problems (McCook, 2017). In the past 40 years, coffee consumption internationally has doubled from 3,810 million kilograms to 7,893 million kilograms in 2015 (Fairtrade Foundation, 2018). The International Specialty coffee shop market was forecasted in 2017 to reach $121 billion by 2021 (Fairtrade Foundation, 2018). Specialty coffee consumption recently increased in America from 13% to 36%. North America has the most established specialty coffee market.
Latin America Coffee Production

Over the last 20 years, Coffee farms and landscapes across Latin America have undergone rapid and profound biophysical changes in response to low coffee prices, changing climatic conditions and severe plant pathogen outbreaks (Harvey, 2021). Many coffee farms in Latin America were transitioned from shaded to low shade or open sun systems with high agrochemical inputs and densely planted coffee bushes in response to neoliberal policies, growing global demand for coffee, and the need to prevent the spread of coffee leaf rust (*Hemileia vastatrix*) (Rice, 1999). Coffee leaf rust has had an impact on Central American arabica plantings in recent years resulting in an estimated 515 million USD in losses (International Coffee Organization, 2014). Since 2014 coffee production has started to recover due to the implementation of management measures such as coffee plant renovation and increased use of fungicides; the disease continues to hamper production in the region (Harvey et al., 2021). Some of the greatest land use trends which are affecting the sustainability of coffee growing regions across Latin America are the widespread shift to disease-resistant cultivars, the conventional intensification of coffee management with greater planting densities, greater use of agrochemicals and less shade, the conversion of coffee to other agricultural land uses, the introduction of robusta, the expansion of coffee into forested areas, the urbanization of coffee landscapes, and the increase in the area of coffee produced under voluntary sustainability standards (Harvey, 2021). Millions of farmers, agricultural laborers, and other workers across Latin America are dependent on coffee production, purchasing, and processing for their livelihoods (Canet Brenes et al., 2016). Latin America is home to 5 of the 10 world’s largest producers of coffee. 32.16% coming from Brazil, 8.83% coming from Colombia, 5.27% coming from Honduras, 2.7% from Peru and 2.52% from Mexico (ICO, 2018).
California Coffee Production

Coffee plants adapt and grow well in frost-free microclimates in California from San Luis Obispo to San Diego County. Coffee plants are commonly grown as ornamentals by backyard growers and California Rare Fruit Growers, but there is no history of commercial coffee production anywhere in the continental US. Specialty coffee consumption and the demand for specialty coffees have increased dramatically in the US and the world over the past several years. This trend, combined with increased demand for high value, differentiated agricultural products (local or California grown) and declining profit margins for existing crops, has generated a strong interest in the production of specialty coffee among farmers in Southern California. However, research-based information on coffee propagation, growing, production or variety performance is needed for Southern California residents and growers interested in coffee as an ornamental plant or a commercial enterprise (UCANR, 2023). In September of 2021 University of California Corporate Extension Farm Advisor Ramiro Lobo gave a presentation titled “Coffee (Coffea spp.): A New Crop & House Plant for Southern California”. He discussed research conducted under the UCCE to date and included several project goals. These included the development and documentation of coffee production practices for small scale growers in Southern California. They also included the evaluation of coffee varieties/accessions for commercial production under organic and conventional systems. Lastly, the development of coffee growing information for home, backyard growers (indoor, potted).

Commercial production in California is concentrated in Santa Barbara, San Louis Obispo, and San Diego Counties. Coffee as a commercial crop is not yet viable due to high costs of startup. At this moment in time, the ornamental potential of coffee plants as a houseplant outweighs the practicality of it being grown successfully as a field crop (Lobo, 2022).
Historically California has been able to produce many different specialty crops and the future developments could lead to coffee being grown successfully on a commercial scale (Lobo, 2022). Coffee water stress is important to research as a management tool to cause plants to have a uniform large bloom (Lobo, 2022). Coffee plants must be protected from the cold during establishment. Plants are getting too crowded as a response to the environment and result in a plant with an excess of crowded inner branches and foliage leading to higher incidences of pest and disease problems. The variety trials will help researchers and citizen scientists to provide data as to which varieties of coffee grow the most uniformly in California’s climate. Pruning is one method of managing the overgrowth, however in the commercial setting it will be extremely expensive. Mealybugs and ants have been the biggest pest problems of California grown coffee (Lobo, 2022). At Cal Poly Pomona Argentine Ants are the worst pest of the coffee plants due to their prolific nature and protection of sucking insects such as aphids, scales, and mealybugs. At Cal Poly Pomona Cryptolaemus has been routinely released with success to control mealybug outbreaks (McKee, 2023). At the South Coast Research and Extension Center in Irvine, California a lath house with halftime light exposure is housing the shade trial being conducted by Ramiro Lobo. The plants are in a variety of containers ranging from 57-Liter pots to 19-Liter pots planted in Sunshine Number 2 (Sun Gro®) because it can hold moisture well without rotting. Coffee plants in containers should be growing in at least 57-Liter pots (Lobo 2022). Given the current demand, there is potential for commercial coffee production in California (Lobo, 2022). It has been proven that coffee plants adapt well to growing conditions in Southern California, but site selection and or protecting the plants during the establishment phase is critical to ensuring the crop survives climatic conditions. For California-grown coffee to be profitable it must be of the highest quality to sell at premium prices. Variety selection, cultural practices, processing
methods and post-harvest handling are important factors to keep in mind in addition to growing the plants. In California, costs can be reduced by processing naturally without any significant problems. Coffee can dry without any risk of it getting fermented because of the dry environment. This eliminates pulping and washing and can be environmentally friendly by not generating honey water, the byproduct of washing coffee which is a major contaminant to the environment (Lobo, 2022).

Coffee’s water usage is globally not an issue because most places where it is currently cultivated rely on rainfall primarily as the sole source of irrigation. However, in California’s dry climate irrigation will be required in order to produce a crop. Coffee takes 130 liters of water to create seven grams of roasted beans. Comparatively, almonds use 57 liters of water on average per seven grams. Almonds are already known for having a water-intensive reputation and water is a precious resource in California. For California coffee crops to be provided with the necessary volume of water they will require irrigation supplied from canals and other surface waterways which have sunk to some of their lowest levels on record, or groundwater aquifers, which are increasingly running dry and leaving some in the state without a drinking water supply (Campbell, 2021).

**Hawaiian Coffee Production**

In the United States coffee is successfully cultivated in Hawaii. Hawaii’s coffee industry is one of the most diverse and dynamic in the world. The current technologies and production practices span a range of producers from .4-hectare organic rainfed farms to 1,619-hectare, totally mechanized, irrigated plantations. Hawaii’s coffee production grew in recent years from under .45 million kilograms of green coffee bean in 1992 to 1.2 million kilograms in 2003, with a farmgate value of $23.5 million. The coffees grown include a hybrid of “Mokka” one of the
most primitive landraces from Africa; ‘Guatemalan’ (also called “Kona typica”), and early 19th
century Central American landrace of Coffea arabica “typica” and some of the most modern
semi dwarf cultivars from Brazil, including both ‘Red Catuai’ and ‘Yellow Catuai”. The Kona
region of Hawaii is ideal for coffee. The principal factor is the climate in the Kona region. Its
spring and summer rainfall pattern is more favorable for coffee growth than the winter rainfall
normally received by much of the state. When rainfall coincides with warm temperatures, the
conditions are optimum for plant growth and fruit development in coffee and many other fruit
crops. Furthermore, Kona’s cool, dry winter is conducive to maturing the coffee fruits
(“cherries”) and forming flower buds for the next crop. The Kona coffee belt lies in a narrow
zone in Kona approximately 32 kilometers long and 3.2 kilometers wide. This “lower humid
zone” runs almost parallel to the coastline. The temperature in this area is ideal. The heart of the
coffee belt is CTAHR’s Kona Research Station in Kainaliu (445-509 meters in elevation). The
annual average temperature is 20.6 degrees Celsius; the average minimum is 15.6 degrees
Celsius, and the average maximum is 26.6 degrees Celsius. The seasonal drop in temperature
occurs simultaneously with drought, causing the coffee trees to slow their growth and develop
flower buds. The coffee belt has an ideal amount and distribution of rainfall, such that coffee in
Kona usually has not been irrigated. When grown under the conditions in Kona fertilizer
applications increase gradually over the first 5 years of the coffee plant’s development. By the
fifth-year, fertilizer rates at 907 kilograms per .4 hectare can produce a target yield of 4,435
kilograms of cherry per .4 hectare (Bittenbender & Smith, 2008). In order to obtain good coffee
yields, weeds must be controlled regardless of the pruning system, degree of mechanization, or
fertilization program. If weeds are neglected, no amount of fertilizer will help. Methods of
controlling weeds include hand hoeing, string trimming, mowing, and spraying. Each of these
has benefits and drawbacks for example hand hoeing can be practiced in organic settings with no worry of contaminating crops. Spraying is the most cost effective however it can have adverse environmental and human health effects. Mulching, ground covers, and cover crops are good preventative methods of weed control (Bittenbender & Smith, 2008).

Coffee leaf rust, *Hemileia vastatrix* is the most widespread, serious coffee disease in the entire world (Bittenbender & Smith, 2008). Hawaii was free of this pathogen until 2020 when it was found on a farm in Maui County (Keith et al., 2022). In the United States, arabica, which is highly susceptible to coffee leaf rust, accounts for most plantings in Hawaii. Kona has grown arabica coffee commercially for over 170 years. (Bittenbender & Smith, 2008). The plantings on Kona and those of the other islands are currently endangered by a new introduction of the coffee leaf rust. Coffee leaf rust was first reported in October 2020 by a coffee grower in Maui County. Coffee leaf rust (*Hemileia vastatrix*) was confirmed to be present on arabica samples taken from the farm in Maui County (Keith et al., 2022). This new discovery threatens the 6,900 planted acres of arabica planted across the six islands by over 1,470 growers. *Arabica* in Hawaii has a raw crop value of $55.9 million (USDA, 2021).

**Climate Change**

For most coffee growing countries, coffee production is a powerful job creator and a major economic driver. Production of coffee in Africa, Latin America, and around the globe continues to decline due to biotic and abiotic stresses exacerbated by climate change (ICGN, 2018). Coffee has proven to be highly sensitive to climate change. Because coffee plantations have a lifespan of about thirty years, the likely effects of future climates are already a concern (Bunn et al., 2015). Predictions using machine learning algorithms to derive functions of climatic suitability suggests that higher temperatures may reduce yields of arabica. Impacts are highest at
low latitudes and low altitudes. Impacts at higher altitudes and higher latitudes are still negative but less pronounced. It has been predicted that an overall global loss of up to 50% of optimal areas for coffee by 2050 (Bunn et al., 2015). One of the greatest reductions in suitability belonged to Latin America with a projected minimization at 88% of area suitable for coffee production by 2050 (Imbach et al., 2017). Coffee consumption is predicted to double by 2050 as rising incomes and living standards are positively correlated with coffee consumption. Meeting the future demand for coffee will require double production by 2050 (ICGN, 2018). The key driver of projected shifts in bioclimatic suitability for coffee cultivation are temperature and precipitation variables. Global studies indicated temperatures were more important than annual and seasonal precipitation when determining suitability for coffee production (Bunn et al. 2015). One possibility of alleviating this issue is migrating coffee to higher latitudes (Zullo et al., 2011). In the past, robusta production has been suggested to in part replace the losses of arabica due to climate change. Robusta can tolerate higher temperatures and could replace heat stressed arabica in situations where the climate rises. This scenario may be occurring in some regions however robusta needs climates with little intra-seasonal variability, limiting it to low latitudes. The climate may not only become hotter, but also more variable, which may aggravate negative effects on robusta production. Globally both species appear to be equally affected by climate change.

It is possible that new varieties of coffee and management practices can be developed to help mitigate the effect of climate change. Actions must be taken in order to avoid total decimation of the coffee industry due to historical coffee producing regions becoming inhospitable for coffee cultivation. Although breeding programs exist worldwide and have historically been used to strengthen coffee varieties against a plethora of threats, the threat of
climate change is further aggravated by the long lead time of adaptation measures such as breeding for stress tolerance, which may take decades (Eskes and Leroy, 2008). Additionally, the current commercial varieties have a narrow genetic base (Anthony et al. 2001; Zhang et al., 2021). This places emphasis on the importance of continuing and expanding trial experiments and genetic breeding programs to get ahead of the potential risk climate change poses. In the past breeding for disease resistance in combination with selection for vigor, productivity and quality started in the early 1920s in India, but especially in the second half of the 20th century in response to coffee leaf rust and coffee berry disease. Today brings new challenges of limited access to additional genetic resources of arabica and breakdown of host resistance to coffee leaf rust, aggravating insect pest problems and the increasingly negative impact of climate change on arabica coffee production worldwide. International networking on coffee breeding will facilitate sharing of resources and scientific information, application of genomics-assisted selection technologies, and pre-breeding for specific characters. Breeding and multiplication of new cultivars well adapted to the local environment will continue to be carried out at national or regional levels (van der Vossen et al., 2015). The development of advanced genomic tools to accelerate linkage of genotypic and phenotypic diversity in coffee is a way to address critical issues such as adaptation of the crop to climate change and help in the transformation of coffee production on a global scale (ICGN, 2018). There are 22 pseudo-chromosomes split by sub-species that have been constructed for arabica; this assembly is the most contiguous and complete so far generated for this species with 91% of the genome anchored to chromosomes (Zimin, et al., 2018). An accurate chromosome scaffolded high quality genome reference assembly is crucial for advancing coffee genomics and climate change adaptation studies. The assemblies of *C. arabica* and *C. eugenioides* are being used to improve downstream analyses,
including gene annotation, synteny, comparative genomics and population genetics using natural and breeding populations being phenotype for climate change adaptation. The following countries have expressed strong interest in working with ICGN and ICO to improve conservation and characterization of the world coffee gene pool for varietal development in a world of changing farming systems and climate. France, Brazil, Colombia, Guatemala, Costa Rica, Mexico, Côte D’Ivoire, Ethiopia, Kenya, Malawi, India and Vietnam (ICGN, 2018). The USDA ARS is currently working with the Centre National de Recherche Agronomique (CNRA), Côte d’Ivoire at the Sustainable Perennial Crops Laboratory in Beltsville, MD. Currently the two entities are extracting DNA from leaf samples and fingerprinting them using SNP markers. This data will be used to analyze genetic diversity in gene bank holdings and used in genome-wide association studies to detect quantitative phenotypic traits. Genomic selection will be performed to establish associations between SNP markers and the phenotypes to incorporate genome-wide markers to assist germplasm evaluation. This project will assist CNRA in improving genetic integrity, reducing genetic redundancy, analyzing genetic diversity, evaluating horticultural traits and enhancing the use of the coffee germplasm, which are housed in CNRA’s living germplasm collections. Ultimately this project will contribute to more efficient management of coffee germplasms, sharing of accurate information among users, better use of germplasm for varietal development through the identification of horticultural traits, such as new sources of resistance and tolerance to biotic and abiotic stresses and quality attributes (USDA ARS, 2023). Sequencing of the coffee genome has been a major milestone to develop advanced genomic tools to accelerate the development of varieties resilient to climate change with enhanced use of the diversity present in non-cultivated Coffea germplasm (Góngora et al., 2018). Understanding the coffee genome will offer opportunities for enhancing breeding progress to increase crop quality.
and yield, as well as to protect the coffee crop from major losses caused by diseases, insect pests and abiotic stresses related to climatic changes (van der Vossen et al., 2015). World Coffee Research is an industry association that comprises over 200 companies in 27 countries. WCR aims to provide coffee producers with more resources to develop research and development so they can meet the growing global demand for coffee. Climate change is one of the main factors that caused WCR to form. With the increases in climate unpredictability, drought, rain, storms, heatwaves, frosts, changing patterns of pest and disease factors contribute to higher levels of risk in coffee supply. This makes coffee availability and quality to become unpredictable which is highly detrimental to coffee producing companies (WCR, 2022). Over the past twenty years Brazil, Vietnam, and Colombia have pulled way ahead of other coffee producing nations because of heavy investments in innovation on production systems and on varieties. Today, these three countries produce over 60% of the world’s coffee, this reduces the diversity of the global coffee supply and in turn its resilience. The WCR aims to help the other coffee producing countries by increasing their innovation with the aim of helping them to create higher yields and more resilient crops which will in turn make the global coffee supply chain more resilient to abiotic and biotic stresses exacerbated by changing climate predictions. The WCR sees strategic value in partnering with non-coffee producing countries for partnership and collaboration. Varieties are the fundamental building block of any productive agricultural system (WCR, 2022).

As a climate-sensitive perennial crop, coffee is likely to be highly susceptible to changes in climate. The negative impacts include declines in coffee yield, loss of coffee-optimal areas with significant impacts on major global coffee-producing countries and growth in the distribution of pest and disease that indirectly influence coffee production. However there have also been positive effects of climate change identified such as increases in coffee-producing
niche, particularly in areas at higher altitudes. Also increases in pollination services could benefit self-sterile species such as robusta. Elevated carbon concentration has the potential to lead to higher yields (Pham et al., 2019).

Coffee Leaf Rust

Coffee leaf rust is the most famous and probably most damaging coffee disease, producing average crop losses of 30% when no control measures are practiced but it is capable of causing complete yield loss when infestations are severe. As a leaf disease, coffee leaf rust reduces the photosynthetic capacity, which in turn affects the quality of the coffee, especially when the epidemic is early during bean formation and filling, resulting in high portions of empty and dry beans during the harvest. In addition, extreme defoliation changes the normal development of the plant over the years, which is observed later as declining yields. Because of the economic losses and the capacity of the pathogen to overcome resistance in cultivars, coffee leaf rust continues to pose a serious threat to the coffee industry worldwide (Gaitàn et al., 2015). The fungus affects the leaves of coffee plants of all ages. The distinct symptom is the formation of yellow-orange lesions on the lower surface of leaves. Gene-for-gene interactions between coffee and the coffee rust can result in complete resistance reactions. More than 35 physiological races of the pathogen have been identified at the Center for Coffee Rust Research (CIFC) in Portugal. Rain, wind, and worker activities are the main pathways for disseminating the disease inside the plant canopy and across coffee plots. Transportation of planting material or contaminated goods are important modes for long-distance movement of the disease. A coffee leaf rust epidemic consists of a succession of monocyclic processes, and disease development depends greatly on the initial inoculum level. Rainfall distribution and amount are fundamental for the germination, infective process, and dissemination of the pathogen. Peaks in rust progress
overlap rainy seasons. Coffee leaf rust develops well at 16 degrees Celsius to 27.8 degrees Celsius. Plantations located at higher altitudes usually do not need controls because conditions are too cool for epidemic development. On susceptible varieties, disease control must begin 16 months after field planting. For chemical control protective fungicides are available. Biological control of *H. vastatrix* is becoming a large field of research for the future because of the increased interest in the specialty coffee market, sustainable agriculture, and fungicide residue limits (Gaitàn et al., 2015).

**Coffee Berry Borer**

The coffee berry borer, *Hypothenemus hampei* is the most serious pest of coffee all around the world wherever coffee is grown. It spread via the coffee trade from Central Africa, which is believed to be the place of origin, across Africa, Asia, and Central and South America. The coffee berry borer is a small black beetle, 1.5 mm long. All the immature life stages take place inside the coffee berry. Coffee berries at different stages of development can be attacked by the coffee berry borer. The coffee berry borer is usually dispersed by migrant coffee pickers, who bring coffee for personal use along with them from previous jobs. Adult flight dispersal is also a method of transport because they can be moved by the wind for several hours over vast distances. The coffee berry borer prefers red berries and uses sight to find targets. Damage is caused by boring and depositing eggs into the berry. Larvae emerge and feed on the seed of the berry, destroying it. Severe infestations may result in heavy crop losses. Worldwide, the coffee berry borer causes an estimated USD $500 million in losses. The coffee berry borer is difficult to control by application of spray insecticides since much of its life cycle takes place within the coffee berry. Cultural control methods have a limited impact on managing this particular insect pest. An integrated pest management approach is the greatest strategy to reduce borer
populations to under the economic damage threshold. The recommended methods of pest management include insect monitoring, using good harvesting practices, avoiding the escape of borers from the processing area, releasing biological control agents into the field, and integrating cultural practices. Several parasitic wasps attack the coffee berry borer in addition to the parasitic fungus *Beauveria bassiana*. The fungus and parasitoids have been successfully mass produced in several countries in Latin America and India (Gaitàn et al., 2015).

**Coffee Berry Disease**

Coffee berry disease is confined to date to the African continent and is the major economic threat to the production of arabica coffee growing at altitudes of 1,000-2,000 meters. *Colletotrichum kahawae* attacks all stages of the crop, including flowers, leaves, unopened inflorescences, and ripe berries. Crop losses in arabica growing countries of Africa reach 20-30% but can exceed 80% in extremely wet years. This disease has two distinct symptoms on berries known as active and scab lesions. Active lesions appear as a dark brown, slightly sunken spot on the berry, these spots enlarge to encompass the whole berry. Scab lesions are normally pale in color and are only slightly sunken. Scab lesions have no detectable effect on yield. Management of coffee berry disease has been largely carried out using fungicides. Copper is frequently used because of its low cost and because it provides effective control of other major diseases, such as coffee leaf rust. Cultural practices, which are the most effective, reduce the favorable conditions for disease development. These practices include pruning methods to avoid overlapping crop cycles and minimizing microclimatic conditions optimal for the fungus (Gaitàn et al., 2015).
Coffee Research

Global productivity has stalled in part because coffee is one of the most under-researched and under-innovated crops in the world relative to its huge global economic value. In UPOV, the International Plant Variety Database, there are 6,640 varieties of strawberries registered with global strawberry production at $15.6 billion. In contrast, there are 111 coffee varieties registered with global coffee production at $200 billion, there is 59 times less innovation in coffee breeding than in strawberry, yet coffee is 12 times more valuable (WCR, 2022). Coffee’s variety development is especially one of the most under researched and under innovated aspects of the crop’s global cultivation. This shows a huge unmet need and a massive opportunity for research to test coffee varieties and develop breeding programs. Variety innovation can address multiple sustainability and business challenges at the same time. There are currently international multi location variety trials currently happening with preexisting varieties.
INTRODUCTION

Relevance of the Topic

Coffee plants adapt and grow well in frost-free microclimates in California from San Luis Obispo to San Diego County. Coffee plants are commonly grown as ornamentals by backyard growers and California Rare Fruit Growers. The most notable commercial coffee production company in Southern California is known as Frinj Coffee. Specialty coffee consumption and the demand for specialty coffees have increased dramatically in the US and the world over the past several years. This trend, combined with increased demand for high value, differentiated agricultural products (local or California grown) and declining profit margins for existing crops, has generated a strong interest in the production of specialty coffee among farmers in Southern California. However, research-based information on coffee propagation, growing, production and variety performance is needed for Southern California residents and growers interested in coffee as an ornamental plant or a commercial enterprise (UCANR 2023).

Currently, California does not have the same pest pressures that have historically decimated coffee producing regions of the world, lending it to be a possible source of clean genetic material for global dissemination. In addition to the possibility of coffee as becoming a suitable specialty crop for Southern California, it has potential to be produced in collaboration with research centers across the globe in hopes of finding new cultivars better suited to unideal climactic conditions, drought, and other issues predicted to come with climate change. Climate change is leading to increased incidence of coffee pests and diseases (Krishnan, 2017). It has been predicted that an overall global loss of up to 50% of optimal areas for coffee by 2050 (Bunn et al., 2015). One of the greatest reductions in suitability belonged to Latin America with a projected minimization at 88% of area suitable for coffee production by 2050 (Imbach et al., 2017). Coffee consumption is predicted to double by 2050 as rising incomes and living standards
are positively correlated with coffee consumption. Meeting the future demand for coffee will require double production by 2050 (ICGN, 2018). The International Plant Variety Database has 6,640 varieties of strawberries registered with global strawberry production at $15.6 billion. In contrast, there are 111 coffee varieties registered with global coffee production at $200 billion, there is 59 times less innovation in coffee breeding than in strawberry, yet coffee is a 12x more valuable crop (World Coffee Research (WCR), 2022.) With climate change predicted to negatively impact historically coffee producing regions of the world, is it possible to test existing and new varieties of coffee in Southern California’s already arid climate, and possibly prove that coffee is more adaptable than it has previously been perceived to be.

**Specific Scope of Interest**

This coffee research project serves to provide research-based information on coffee growth performance for Southern California residents and growers interested in coffee as an ornamental plant or a commercial enterprise. It is the first step to develop and document coffee production practices for small scale growers under Southern California. It aims to evaluate arabica coffee for commercial production, research systems and develop coffee growing information for home, backyard growers (indoor, potted). In addition to this it aims to show the suitability of Southern California as an environment to grow coffee for the preservation of endangered *Coffea* species, evaluate climate ready cultivars, and establish collaboration between coffee research entities in the continental United States. This project is the beginning of field evaluation of *C. arabica* as conducted within Southern California under direct supervision of researchers and hopefully this project shows the potential for Southern California to lend itself as a valuable area for further coffee research and global collaboration to take place.
MATERIALS AND METHODS

This project evaluated established plantings of *Coffea arabica* (arabica) across three different locations in Southern California: Pomona (34.063093, -117.818696), Whittier (33.976446, -118.027792), and Carlsbad (33.132184, -117.320490) by measuring and comparing plant height, width, and trunk thickness. In Pomona five replications of 16 pairs of arabica coffee plants (*Coffea arabica*) were planted during April 24 to May 2, 2019, and another five replications of the same pairs were planted on September 16, 2019, at Cal Poly Pomona. At initial planting there was a total of 320 coffee plants in the field at Cal Poly Pomona. In May of 2019 two replications of the same 16 pairs of arabica were planted at Whittier College in collaboration with the research partner Dr. Cinzia Fissore. This added up to a total of 64 individual coffee plants at Whittier College. The planting at Carlsbad took place in May of 2019 and consisted of five replications of the 16 pairs of arabica of a total of 160 coffee plants. The 16 pairs of arabica were consistent across all fields. Historical weather data was gathered via WeatherSpark.com.

The plants at all locations were measured three times from 2022-2023. The measurements obtained were plant height, plant canopy width at widest point, and trunk caliper. Plant canopy height was measured using a tape measure from the south facing side of each plant and was recorded from top of soil profile to top of plant canopy. Plant canopy width was measured on the south facing side of each plant and was recorded at the widest point of the plant. Trunk caliper was measured on the south side of each plant 31 millimeters above the soil surface. In the event of multiple trunks, the thickest trunk was measured. Plants at all locations were irrigated using a drip system and the watering schedule was adjusted based on climatic conditions. The management practices, soil conditions, and climate differed per location.
Whittier coffee plants were staked to ensure upright growth and full canopy development, this also provided some support from the wind. Whittier was surrounded by a four-foot-tall fence and had California native plants spread randomly in the plot. Organic fertilizer was deployed at all three locations during the experiment at different rates. At Pomona a single application of Spinosad on November 2nd, 2022, was made to control Argentine ant populations with little success. A comprehensive soil analysis was completed by WARD Laboratories, Inc. on February 2nd, 2023. The soil analysis provided pH, organic matter content, and clay content. The organic matter content was calculated using a process that consisted of weighing a soil sample, then burning the same sample to remove organic matter, and then reweighing to calculate the percent organic matter lost upon ignition of the soil. Four composite samples were taken per site using a small hand trowel, two of which were taken in the rows between plants and two taken directly under the canopy of plants. On Friday, September 30th data was collected at Whittier. On Monday, October 3rd, 2022, data was collected at Cal Poly Pomona. On Thursday October 6th, data was collected at Carlsbad Flower Fields. On January 18th, 2023, data was collected at Cal Poly Pomona. On January 26th, the 2023 data was collected at Carlsbad Flower Fields. On Friday January 27th data was collected at Whittier. On Thursday April 20th data was collected at Cal Poly Pomona. On Friday April 21st data was collected at Whittier College. On Thursday April 27th data was collected at Carlsbad Flower Fields.
RESULTS

The soil analyses provided by WARD Laboratories Inc. found that Pomona had the highest clay content at 49% (Figure 1). Whitter had 25% clay content while Carlsbad had 13% clay content (Figure 1). The soil pH at Pomona was 7.5, soil pH of Whittier was 7.6, and soil pH of Carlsbad was 6.9 (Figure 2). Soil ignition revealed that Whittier had the highest organic matter content with the total being 10% while Pomona had 4% organic matter and Carlsbad had 3% organic matter (Figure 3). Pomona had the highest elevation with 245 meters followed by Whittier with 129 meters and Carlsbad with 34 meters (Figure 4). The width of the plants stayed relatively consistent between seasons in both Pomona and Whittier, however steadily decreased in Carlsbad (Figure 5). The height of the plants stayed relatively consistent between seasons in both Pomona and Whittier however decreased during the winter in Carlsbad (Figure 6). The caliper of the plants stayed relatively consistent in all sites except for a slight decline observed in Whittier (Figure 7). Pomona and Whittier are warmer locations than Carlsbad, all three locations share lowest temperatures within one degree Celsius. The lowest temperature at Pomona and Carlsbad is 18 degrees Celsius and 19 degrees Celsius at Whittier (Figure 8). Most coffee plants at all locations survived during the period research was conducted, four plants died in Pomona, zero plants died in Whittier, and three plants died in Carlsbad. However, these plant deaths resulted from external circumstances: gophers in Pomona, and a faulty irrigation system in Carlsbad.
DISCUSSION

The coffee research history at Cal Poly Pomona began in the spring of 2017 with a planting that died during the winter of 2017-2018. This first planting at Cal Poly Pomona established that young coffee field transplants unprotected will most likely perish if exposed cold for extended periods of time. The second planting at Cal Poly Pomona is now four and a half years old and has demonstrated that coffee plants can be successfully established in Pomona, California. There was a slight difference in elevation between these two plantings, the latter being placed adjacent to Interstate 10 which may have provided more warm air circulation that allowed for the plants to establish better than the first planting. This is a tremendous example of the resilience and ability of C. arabica to adapt to climates different than that of its origin. In addition to the climate compared to historical regions of cultivation for the plants, they have also been subject to extreme weed competition in Pomona. The plants can overcome the weed pressures surrounding them in the field. Another compounding challenge for the current planting at Cal Poly Pomona is that they were planted in soils not ideal for coffee production. The average soil pH of the coffee plot in January 2023 was 7.5 which is slightly alkaline, which is problematic for coffee cultivation as the plants generally prefer a slightly acidic soil with an ideal pH range of 5-6 (FAO, 2020). The average organic matter content of the soil was measured to be 3.6% which is pretty good in the conventional agricultural sense but could be supplemented by introduction of compost, mulch, manures, etc. The average of clay in the soil was 49%, this means that the soil classification is “clay”. Although a small portion of clay in the soil is beneficial for cation exchange and water retention, a soil with this high-level clay could have inhibited the Pomona coffee plants from reaching their full potential. Clay soil can waterlog the plants, restrict root growth, become impermeable to water, and promote incidences of abiotic and
biotic stresses (Smith and Bardener, 1985). With the combination of clay content and high soil pH, there is the opportunity for soil amendments to take place to provide the coffee plants with a better nutritional program that would promote better growth, provide disease and insect resistance. In addition to the environmental conditions, there is an infestation of Argentine ants that have introduced aphids, mealybugs, and scale insects onto the plants in various levels changing with the seasons at Pomona. Despite all these compounding factors, most of the plants have survived, and have outperformed those of Carlsbad in every measurement taken. Pomona’s out performance of the plants in Carlsbad could be explained in part by higher elevation, higher organic matter in the soil, and higher average temperatures. If anything, the research being conducted at Cal Poly Pomona over the past four and a half years has proven that C. arabica is an extremely resilient crop to both abiotic and biotic stressors in the Pomona climate. One explanation for why the coffee plants at Cal Poly Pomona have been able to survive despite sub-optimal growing conditions is that there are yet no incidences of coffee leaf rust, coffee berry disease, or coffee borer in the region. These pests have historically decimated coffee growing regions and been exacerbated in biotic and abiotic stress conditions. The exclusion and prevention of these pests from entering the state of California is critical moving forward. With the higher regulations on shipping plant material worldwide and the international efforts of the WCR and ICO to make new resistant germplasms available there is a great deal of responsibility on establishments producing and receiving plant material to mitigate the spread of these diseases and pests through vigilance and attention to detail.

The plants at Whittier College outcompeted the other two plantings in every measurement taken. The greatest difference between Whittier College and the other two sites was the clay content of 13% and the organic matter content of 10%. The organic matter content
could have been higher because of additional soil amendment resulting from native California plants being present within the field thus adding to root mass and leaf matter in the field. It is interesting to note that the pH of the soil at Whittier was also the highest at 7.6. This is very strange because this pH is out of the ideal range of 5-6 for coffee (FAO, 2020). It is possible that of the three, clay content, organic matter, and soil pH, the conclusion can be made that soil organic matter has the greatest impact on arabica plant height, width, and caliper thickness. Dr. Cinzia Fissore of Whitter College has worked with professional coffee agronomists and spent a great deal of time and effort into the care of her coffee orchard. She also has California native plants interplanted with her field and uses an organic fertilizer regimen. Her plants showed the best structure in comparison to those of the other sites, this could have been in part due to staking of plants to establish strong trunks and stature. Whittier also had a four-foot-tall fence across all sides of the orchard that protected the trees from winds which could have also influenced the results. Of the three sites, Whittier proved to be the most successful in arabica coffee establishment and will hopefully produce significant yields in the coming years.

Carlsbad performed the poorest of the three locations in relation to the measurements taken. One of the major differences between Carlsbad and the other two inland locations was its proximity to the ocean and thus exposure to offshore winds. Wind can have detrimental effects on the growth of coffee; however, these effects can be mitigated by the implementation of windbreaks (Teketay, 2012). In addition to this Carlsbad also had the lowest clay content this could have resulted in the inability of the soil to properly reattain and provide nutrition for the coffee plants in levels conductive to vigorous growth. Carlsbad was the only commercial field planted and was in partnership with Mellano Flower Fields. The field managers at this site had a rigorous nutritional schedule and had weed mats that protected the coffee plants from
competition. Another explanation for the lower measurements observed in Carlsbad could result from the moderately lower elevation and temperatures.

Future coffee research in Southern California should focus on coffee bean production, alternative species cultivation, and climate resilience. The plantings at Pomona, Whittier, and Carlsbad are now capable of producing coffee beans which should be examined based on quantity and market value. If the plantings can produce a crop capable of turning a profit, then it may be possible to grow coffee commercially in Southern California. Robusta (Coffea canephora) may be better suited to Southern California because it has been reported to thrive at elevations from sea level to 700 meters (Smith and Bardener, 1985). It is also less sensitive to acidic and alkaline soil pH than arabica (Coffea arabica) (Smith and Bardener, 1985). There is potential for Southern California based research institutions to partner with World Coffee Research (WCR) and together evaluate climate ready cultivars of coffee. In the coming years coffee production will become increasingly difficult due to climate unpredictability, drought, rain, storms, heatwaves, frosts, changing patterns of pest and disease factors climate change (WCR, 2022). Southern California could partner with the WCR and other organizations to conduct research developing climate ready cultivars of coffee and disseminate them to the rest of the world.
CONCLUSION

Each of the three plantings are ongoing research trials that will continue to provide an interested audience with knowledge related to Southern California grown coffee. This research opens the door for other projects in the Southern California region. This project incorporated intercollegiate research collaboration and involved the private industry. Each one of the three evaluated sites has successful plantings of coffee that have survived the climatic conditions over the past four and a half years. Moving forward in the research, the plants are reaching five years of maturity and are capable of producing a significant crop; yield data may start to be recorded at Cal Poly Pomona in addition to the other sites listed above. The plantings have proven that C. arabica plants can survive in the Southern California climate. The next step in the research is to continue with the projects and collaborate as much as possible with those interested in coffee research, whether it be here locally in Southern California or on a global scale. This can be accomplished with proper site setup and irrigation management practices. For coffee plants to flower they need a period of dry, cool conditions ranging from 1-4 months (FAO, 2020; Gaitan et al., 2015). In the field, hoop houses can be used to keep the coffee plants dry during the winter months. This also has the added benefit of protecting the crops from frost and wind when they are most vulnerable in the cold months under drought conditions. Being able to keep the plants dry will also avoid unwanted irrigations that could waterlog the plants otherwise. Once the risk of frost has passed and the crops have had a 1–4-month period of dry cool condition flowering can be induced. Irrigation, mists, immersion in water or spraying the buds with water can all provide the stimulus for regrowth. Exogenously applied GA can also be used to break bud dormancy and promote flowering (Smith & Bardener, 1985). Growing coffee in this manner may be the way to make it commercially viable in California. By manipulating irrigation during the
winter months, and controlling the phenological cycles of the coffee plants, uniform flowering and fruit set could be obtained. If this uniformity is successful, then a standard harvesting schedule could be established for California. Being able to harvest coffee in this way would reduce the number one cost of farmers in California, labor. In addition to reduction in labor costs by a shorter more effective harvest interval, growing under water stress conditions will save another major cost for farmers, water. Not only is this possibly an economically viable option for growing coffee but also has ecological benefits as well. In addition to hoop houses, weed cloth should be used to reduce weed pressures, one of the major pests currently competing with the coffee plants at Cal Poly Pomona. Weed cloth is a permeable material, allowing for water and nutrients to penetrate it unlike other forms of weed control such as tarping or plastic. Weed cloth is also ecological friendly, and an organic form of management practice. Mulch should be placed over the weed cloth in order to promote water retention and increase the longevity of the cloth in the field. The mulch can be placed up to 4 inches from the base of the coffee trunks and will promote organic matter content in the soil and provide a slow release of nutrients to the plants. Drip irrigation can be used to reduce water and incidences of weed growth in the field. Insect pests are best controlled by preventing introduction to the specific site. This can be achieved by monitoring protocols and vigorous inspection of plant material before planting on site. We learned from the failed production in 2017 that young coffee plants are more likely to die when introduced to field conditions in which they are exposed to extended periods of extremely cool temperatures. Ramiro Lobo has had great success growing coffee plants in 57-Liter pots using sunshine number 2 mix (Sun Gro®). Growing plants in pots until they are one meter tall and possess a full canopy could result in greater survival rates when introduced to the field in mid-February. Pruning is essential in coffee growing to regulate nutrient balance and management, so
the plant does not exhaust itself with excessive vegetative growth. Pruning can also promote the growth of flower producing lateral branches. Annual pruning of the coffee plants will lead to a long-term sustainability and longevity of the plants in addition to reducing pest pressures exacerbated by a clustered canopy. A successive planting using the research conducted over the past four years using the knowledge we have gained, and sustainable farming practices has the potential to create a commercially viable coffee crop. If this method of growing coffee in California proves to be cost efficient and successful, then California could be a tremendous resource in partnership with the WCR and ICO for research plots. In growing coffee in this way, we will be mimicking the phenological cycles naturally occurring where coffee is grown in other parts of the world. Allowing California to test out new varieties produced from the WCR research trial laboratories and provide comparable yield goals to historically coffee producing countries. California is an ideal place to carry out coffee field trials mainly because we have no incidences of coffee leaf rust, coffee borer, or coffee berry disease. If the majority of research is conducted by universities and organizations such as the WCR and ICO then the disease introduction risk by the transportation of germplasm is greatly reduced. Because California is clean and coffee can be grown here, this region is ideal for testing experimental varieties of coffee in field trials in collaboration with entities such as the WCR and ICO. This will help disseminate information on a global scale and help to promote the diversity of the coffee industry by giving countries access to new disease resistant and climate tolerant varieties that will in turn make the world coffee supply more resilient.
FIGURES

Figure 1: Differences between Pomona, Whittier, and Carlsbad in Clay % within the soil profile, soil analysis conducted by WARD Laboratories, Inc. for soil samples taken on February 2nd, 2023.

![Clay Percentage in Soil](chart1)

Figure 2: Difference between Pomona, Whittier, and Carlsbad in soil pH, within the soil profile, soil analysis conducted by WARD Laboratories, Inc. for soil samples taken on February 2nd, 2023.

![Soil pH](chart2)
Figure 3: Percent of organic matter from soil sample lost upon ignition, soil analysis conducted by WARD Laboratories, Inc. for soil samples taken on February 2nd, 2023.

Figure 4: Differences in elevation(m) in Pomona, Whittier, and Carlsbad (obtained via Google Maps).
Figure 5: Average *C. arabica* width(cm) from September 2022 to April 2023.

Figure 6: Average *C. arabica* height(cm) from September 2022 to April 2023.
Figure 7: Average *C. arabica* trunk diameter (mm) from September 2022 to April 2023.

Figure 8: Historical weather data depicting average high and low temperatures of Pomona, Whittier, and Carlsbad in Degrees Celsius. via © WeatherSpark.com
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