UNIVERSITY OF ZAGREB
FACULTY OF AGRICULTURE

CLIMATE CHANGE RESILIENCE: THE CASE OF COFFEE GROWERS IN COSTA RICA

GRADUATE THESIS

Hannah Powlison Belković

Zagreb, September, 2020.

UNIVERSITY OF ZAGREB
FACULTY OF AGRICULTURE

Graduate study programme:
Environment, agriculture and resource management
(INTER-EnAgro)

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STUDENT STATEMENT

ABOUT ACADEMIC INTEGRITY

I, **Hannah Powlison Belković**, JMBAG 0178116881 , born on 22 July 1986 in Chestnut Hill, PA USA, declare that I have independently written the thesis entitled:

CLIMATE CHANGE RESILIENCE:
THE CASE OF COFFEE GROWERS IN COSTA RICA

With my signature, I guarantee:

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REPORT
ON EVALUATION AND GRADUATE THESIS DEFENSE

Graduate thesis written by **Hannah Powlison Belković**, JMBAG 0178116881, entitled

CLIMATE CHANGE RESILIENCE:
THE CASE OF COFFEE GROWERS IN COSTA RICA

Is defended and evaluated with the grade _______________, on _______________ .

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1. Prof. dr. sc. Mario Njavro mentor ____________________
2. Prof. dr. sc. Ramona Franić member ____________________
3. Prof. dr. sc. Gabriel Ondrašek member ____________________

Acknowledgements

In loving memory of David Powlison

1949-2019

And for Matija, my partner in life and coffee

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Summary

Of the graduate thesis written by Hannah Powlison Belković, entitled

CLIMATE CHANGE RESILIENCE:
THE CASE OF COFFEE GROWERS IN COSTA RICA

Coffee farmers in Costa Rica are vulnerable to a broad spectrum of climate risks, centered on the production risks associated with the cultivation of *Coffea arabica* due to its climate sensitivity. Climate changes such as shifts in the timing and intensity of precipitation, the increase of extreme temperatures, and the growing number of extreme weather events are threatening *C. arabica* cultivation and value chains. The impacts of climate change on coffee production systems in Costa Rica are numerous, including impacts on biodiversity, coffee yields, land use, pests and diseases, and management requirements of water, soil, and shade. Beyond production, there are climate risks associated with coffee processing systems, coffee farming communities, and the entire global coffee trade.

Boosting the climate resilience of coffee farmers to better manage these risks can include various adaptive techniques such as the diversification of income streams, the diversification of crops and other species in shaded coffee agroforestry systems, and the diversification of (resilient) coffee cultivars. These measures, in combination with several other farm characteristics, have been identified and evaluated based on their proposed contribution to farm-level climate resilience. The resulting Resilience Indicator Index was used to perform a theoretical case study analysis of four coffee farms in the Tarrazú region of central Costa Rica. It was concluded that, in addition to adaptive measures like improved shade and water management, income diversification, and the use of more climate-resilient coffee cultivars, a key component of climate resilience is related to the farmer's flexibility and willingness to innovate.

Keywords: coffee, climate change, global warming, *Coffea arabica,* Costa Rica, climate resilience, adaptation

1. Introduction

Climate change is a widely accepted reality that will have an ongoing and worsening impact on numerous sectors of the global economy as long as emissions of greenhouse gases (GHG) continue to rise. The agricultural sector is especially vulnerable to the effects of climate change due to its dependence on natural resources and favorable weather conditions (Romero 2005). Farmers cultivating *Coffea arabica*, the species which accounted for 58% of global coffee supply in 2018/19, are particularly threatened due to the plant's sensitivity to climate change (ICO 2019). According to the International Center for Tropical Agriculture (CIAT), 50% of coffee-producing agricultural land will be unsuitable for this crop by 2050 (Bunn et al 2014). These losses will be disastrous for the 25 million coffee farming families, primarily in East Africa and Central and South America, more than 70% of whom are smallholders farming less than 10 hectares (DaMatta et al 2007) with meager resources to bolster climate resilience.

Central America is one of the regions which is expected to be most affected by climate change as it is vulnerable to droughts, hurricanes and El Niño-southern oscillation (ENSO) weather events (Imbach et al 2017). Coffee farmers in Costa Rica are at especially high risk since, according to the World Bank Group (2020), this country has the 8th highest exposure to economic risks resulting from changing climate patterns. Furthermore, 77.9% of the population lives in areas which are at "high risk of multiple hazards, including floods and landslides, cyclones, storm surge, and sea level rise" (World Bank 2020). Costa Rica was an early adopter of policies relating to environmental protection and building resilience to climate change. In particular, they have been successful with reforestation, land conservation, and biodiversity preservation efforts, and most recently, have gained international attention for their commitment to net zero carbon emissions by 2050 (UN Environment 2019). Considering Costa Rica's position - both at-risk from climate change and as a global environmental leader - it seems valuable to examine their approach to improving farmers' climate resiliency as their efforts are likely to prove more broadly applicable in coffee-producing regions in order to ensure farmers' livelihoods and reduce disruptions to global supply chains.

Macro-level antidotes to climate-related challenges (in appropriate regions) will include drastic measures such as the movement of *C. arabica* coffee plantations to cooler elevations and latitudes, or even the abandonment of coffee farming altogether. Overall economic impacts of climate change will include unpredictable yields leading to strong price fluctuations; higher prices due to less area under cultivation; increased vulnerability to pests and diseases leading to rising production costs; and competition for arable land with other crops, especially food crops (Haggar and Schepp 2012).

This paper aims to examine the spectrum of climate impacts on coffee production in Costa Rica and to propose various adaptive techniques to build climate resilience, specifically those related to diversification - of coffee cultivars, of companion crops, plant species and agricultural techniques, and of on-farm income-generating activities. It is expected that farmers will be able to minimize climate risks by taking advantage of the ecological and economic benefits of diversification. Thus, the goal is to assess farm-level climate resilience and to discern whether any more broadly applicable theories may be drawn out of this analysis. Though this research is focused on the specific context of Central Pacific Costa Rica, the resulting evaluation could be applied in diverse coffee-growing regions in order to contribute to the livelihood preservation of coffee farming families worldwide despite the looming challenges which climate change presents.

2. Materials and methods

This paper will provide a literature review of climate change impacts on coffee production systems, as well as a more specific overview of the challenges faced by coffee farmers in Costa Rica. A case study comparison of four specific farms in the Tarrazú region of Central Pacific Costa Rica will enable a more detailed evaluation of climate resilience indicators and the economic and ecological value associated with on-farm diversification measures. Data will be collected from national and international coffee institutes and associations, from the international community of scientific coffee research, from personal farmer questionnaires, and (in some cases) follow-up interviews and/or in-person farm observation.

3. Review: Climate change impacts on coffee production systems

3.1. Coffee and climate change in context

3.1.1. The global coffee industry

The coffee production industry, which supports 25 million farming families globally (Vega et al 2003) is now and will continue to be dramatically affected by climate changes (Baca et al (2014), Bunn et al (2015), Jaramillo et al (2011), Haggar and Schepp (2012)). This is especially due to the extreme climate sensitivity of *Coffea arabica*, a species prized for its high quality and broad spectrum of desirable flavor profiles and accounting for roughly 60% of global production (ICO 2019a). *C. arabica* thrives in a narrow range of optimal conditions and is highly sensitive to changes in temperature and precipitation patterns (DaMatta 2006), as well as the increased pressure from pests and diseases which these changes cause.

Coffea species (primarily *C. arabica* and *C. canephora*) are one of the most valuable tropical export crops worldwide, with annual export value in 2017/18 reaching

$25 billion USD (ICO 2019a) and global production in 2018/19 of approximately 170 million bags[1] (ICO 2020a). Though native to Africa, *Coffea* species have been transported and grown around the world for centuries, and coffee exports provide an important source of foreign exchange and national income for many producing countries (FAO 2015). The entire industry is valued at more than $200 billion USD annually, with most value added in importing countries (Europe, North America, and - increasingly - emerging economies) and overall coffee consumption has been growing steadily at 2.2% annually (ICO 2019b). However, coffee prices have been trending downward since 2016 (ICO 2019b), with serious economic and social consequences in the 70+ tropical/equatorial countries where coffee is produced (FAO 2015) and many farmers struggling to cover their basic costs of production (ICO 2019b). Many smallholder farmers have specialized in coffee to the extent that their "dependency on cash crops and lack of economic diversity creates an increased vulnerability to coffee-price fluctuations and to climate change" (Frank et al 2010). This situation has brought a global spotlight onto the sustainability of the coffee industry as a whole.

3.1.2. *Climate change in Central America*

There are numerous scenarios for how climate changes will continue to materialize during the coming years - depending on anthropogenic GHG emissions, among other factors - and each coffee-growing region faces a unique array of possible changes in temperature, precipitation, and extreme weather events. All of these changes will have a significant impact on the quality and quantity of coffee production due to the fact that "climatic variability is the main factor responsible for the oscillations and variation of the coffee grain yield in the world" (Haggar and Schepp 2012).

In Central America, mean average annual temperatures are likely to increase anywhere from +1.6°C to +4.0°C by 2100 (Magrin et al 2014). Temperature extremes are also likely to increase, with more warm days and less cold nights (Magrin et al 2014). While there has been a trend toward decreasing annual rainfall in the region (–1 mm day–1 50 yr–1 during 1950–2008), there is some uncertainty in future regional projections (Magrin et al 2014). It seems that precipitation may increase or decrease depending on both the emissions scenario and the specific location, with general decreases likely across northern Central America, and possible increases in Costa Rica and Panama (Imbach et al 2012). Historical trends also seem to indicate less predictability in the timing of the rainy and dry seasons, which has a particular impact on agricultural producers (Eakin et al 2013).

In terms of extreme weather, the frequency and intensity of these events (storms, droughts and floods) in Central America has been steadily increasing over the last few

[1] The standard weight of a bag of green (unroasted) coffee is 60 kg.

decades. Between 2000-2009 there were 39 hurricanes in the Caribbean Basin which affected the region, compared to 15 in the 1980s and 9 in the 1990s (UNEP & ECLAC 2010). These events generated massive economic losses and impacted hundreds of thousands of people (Magrin et al 2014) in the region due to the fact that

> the character and severity of the impacts from climate extremes depend not only on the extremes themselves but also on exposure and vulnerability. These are influenced by a wide range of factors, including anthropogenic climate change, climate variability, and socioeconomic development (Magrin et al 2014).

Thus, in addition to mitigation efforts, it will be important for Central American societies to reduce the risks associated with these climate changes by minimizing their exposure across every sector and industry, to the extent possible.

3.1.3. *Mitigating climate change in the coffee sector*

While this paper will focus on adaptive measures to building climate resilience, a robust response to climate change must of course consist of both adaptation and mitigation measures, since without mitigation any ameliorative efforts will be tragically temporary. Current climate changes are having a significant impact on global agricultural systems and activities, “reducing the capacity of natural resources (biodiversity, soil and water) to sustain the food demand of the world’s increasing population” (FAO 2019). Simultaneously, the agricultural industry itself is a significant contributor to climate change, accounting for 10-12% of total anthropogenic GHG emissions (Smith et al 2007). The primary sources of GHG emissions from coffee production are N_20 resulting from mineral N fertilization, CH_4 from coffee processing wastewater, and CO_2 from drying coffee using electricity or burning firewood (NAMA 2020).

Mitigation in the coffee production sector should thus include reducing the use of mineral fertilizers and pesticides; enhancing carbon sequestration through soil and agroforestry management; reducing, recycling, and/or treating wastewater from processing; implementing sustainable drying solutions; and offsetting transport emissions. Mitigation also includes moving towards net positive values in forest cover by reducing deforestation and increasing reforestation efforts (GCR 2020). Furthermore, it is important to note that while the carbon footprint across the entire coffee supply chain is 4.98 kg CO_2e/kg green coffee from Costa Rica, just 1.93 kg CO_2e/kg green coffee is produced during farming and processing, and the other 3.05 kg CO_2e/kg green coffee is generated from processes within consuming countries (Killian et al 2013). Clearly, holistic efforts to reduce coffee’s total carbon footprint are thus a shared responsibility between producing and consuming countries.

3.1.4. *Coffee's climate requirements*

There are over 100 species within the *Coffea* genus, but just two of these currently dominate the global coffee market: *Coffea arabica* and *Coffea canephora* (Davis et al 2006). *Coffea arabica* is a perennial shrub which evolved in the partial shade of the understory in the highlands of Ethiopia (DaMatta et al 2008; Haggar and Schepp 2012). Suitable altitudes for *C. arabica* range from 1500 - 2800 m above sea level, where seasonal temperature variations are less pronounced (Haggar and Schepp 2012). The optimal air temperature range for *C. arabica* is between 14℃ and 28℃, with absolute values from 10℃ - 30℃ (FAO EcoCrop), and optimal annual precipitation is around 1200-1800 mm (Carr 2001). From germination to full fruiting maturity takes 3-5 years, and the cherry-like fruit can be various shades of red, yellow or pink depending on the cultivar. The outer skin and pulp are removed during processing in order to expose the inner endosperm (or 'bean' - referred to as green coffee), which is then dried, hulled, and roasted before consumption.

Coffea canephora (colloquially known as Robusta, the most common varietal of this species) evolved in warmer, wetter environments and at lower altitudes than *C. arabica*, most likely in the Congo River basin in Central Africa (Haggar and Schepp 2012). Robusta accounts for approximately 40% of coffee produced worldwide,[2] and while it is generally agreed to have an inferior flavor profile when compared with *C. arabica*, one assumed advantage of this species has been that it is better suited to climate change due to its ability to thrive in warmer temperatures and with higher precipitation rates (even exceeding 2000 mm/annum) (DaMatta et al 2007). However, recent research from Kath et al (2020) has shown that this species is not as heat resilient as was once believed. The researchers compiled ten years of yield, temperature and precipitation observations from 798 coffee farms across South East Asia and found the optimal mean range for Robusta production to be 16.2℃ - 24.1℃, which is significantly lower than the prior estimated range of 22℃ - 30℃ (Kath et al 2020).

3.2. Biodiversity

The warming climate will continue to have a pronounced and increasingly dramatic effect on biodiversity worldwide. There are reports that numerous plant species are being affected by the increases in global temperatures, changing the temporal and spatial patterns of growth and development, causing earlier flowering and shifts both upslope to higher altitudes and to latitudes farther away from the equator (Lovejoy 2008). Climate change is also predicted "to increase the rates of species

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[2] From 1988 until 2018 there was a federal ban on planting *C. canephora* in Costa Rica (Pretel 2018). As a result, no coffee of this species is currently harvested.

extinction” (Magrin et al 2014) around the world, initiating unprecedented upheaval in global ecosystems. There are three primary concerns regarding biodiversity and coffee production in the face of a changing climate: the biodiversity of coffee itself, the biodiversity of the specific farming systems where coffee is grown, and the potential losses of biodiversity as coffee production moves into previously uncultivated forest areas.

3.2.1. *Biodiversity of* Coffea *species*

The varieties of *Coffea* species that are most commonly grown for production worldwide have an alarmingly narrow base of genetic diversity. A 2012 study by Davis et al from the Kew Royal Botanic Gardens concluded that indigenous *C. arabica* (conserved in-situ in Ethiopia) was negatively impacted under all three emissions scenarios considered, with outcomes ranging from 65% reduction (best-case) to 100% reduction (worst-case) of bio climatically suitable locales by 2080. The loss of this living library of genetically diverse *Coffea* stock would further limit the possibilities for developing new, more climate-resilient varieties in the future (Koehler 2017). In response to this embedded crisis, World Coffee Research (WCR) implemented their International Multi-location Variety Trial, a long-term study of 31 coffee varieties planted across more than 40 test plots in 22 different countries (WCR 2020a), which will enable the development of more climate-resilient varieties which are designed to thrive in specific climate zones.

3.2.2. *Biodiversity of coffee farming systems*

Coffee in Central America (and elsewhere) is sometimes cultivated in diverse coffee agroforestry systems (CAS) as an understory crop in combination with larger shade tree species and sometimes ground cover crops (Cerda et al 2020). CAS are “widely regarded as environmentally sustainable and enabling for biodiversity conservation” (Hernandez-Aguilera & Rodewald 2019), particularly due to the birds who provide pest-control services, the range of flora, and the activity of various pollinators, the biodiversity of which increases coffee fruit-set (Vergara & Badano 2008). The innate biodiversity of such a system is a balancing act, with each participating species having its own set of essential biological requirements. Due to their variability, such systems have more efficient nutrient cycling, improved soil health, and increased carbon storage (Gomes et al 2020). Also, the microclimates which develop under shade reduce temperature extremes and risks of stress due to drought and damaging wind shear.

As producers have sought ways to increase production of the coffee fruit, many have opted for growing coffee as a monocrop in full sunlight, thus speeding the photosynthetic process, vegetative growth, and in turn fruit yield, but also decreasing the natural defenses of the CAS to various pests and diseases. A 2020 study by Cerda et al identified six types of CAS in Costa Rica which seemed to minimize yield losses while also providing valuable ecosystem services. They concluded that the “regulation of diseases and associated losses in agroforestry systems should be based on...the positive effects of plant biodiversity, adequate shade cover, good soil fertility, and minimal use of fungicides” (Cerda et al 2020).

3.2.3. *Biodiversity and land use changes*

There is concern that as temperatures warm coffee production will move to higher altitudes, possibly into areas of virgin forest, as currently suitable land for coffee production becomes less suitable. According to the IPCC “conversion of natural ecosystems is the main cause of biodiversity and ecosystem loss in [Central America], and is a driver of anthropogenic climate change” (Magrin et al 2014). A 2017 study by Moat et al used a modelling approach to estimate changes in land suitability for the cultivation of *C. arabica* in Ethiopia and found that while 39-59% of current growing areas may be rendered unsuitable, there could be simultaneously up to a 400% increase of suitable growing areas if coffee were to be relocated. Thus, it is likely that the competition between land use for forest conservation and coffee cultivation (not to mention urban development as the global population continues to grow) will become increasingly intense in the coming years, having a potentially negative effect on biodiversity in coffee-producing regions.

3.3. Coffee yield

There has been a scramble in recent decades to determine the impacts of climate change on future yield rates and quality of agricultural crops, and coffee is no exception. For coffee, “the relationships between the climatic parameters and the agricultural production are quite complex, because environmental factors affect the growth and the development of the plants under different forms during the phenological phases of the coffee crop” (Haggar and Schepp 2012). Due to steadily growing global demand for coffee (ICO 2020b), increasing yields has been a primary objective of many producers and supporting organizations (e.g. in-country extension services and international NGOs); the first stated goal of the FAO’s Climate Smart Agriculture program is to “sustainably increase agricultural productivity and incomes” (FAO 2019). While the impact of climate change on coffee yield encompasses a constellation of interrelated phenomena, the cornerstone of inquiry focuses on the exact phenological responses of the coffee plant to various climatic conditions.

As previously mentioned, both *C. arabica* and *C. canephora* are sensitive to temperature extremes. In *C. arabica*, temperatures above 23℃ can speed up processes of ripening and fruit maturation with a corresponding loss in bean density and cup quality (DaMatta 2007), and above 30℃ overall growth is severely slowed, and leaf yellowing, tumor growth or flower abortion may occur (Damatta and Ramalho 2006). At the other end of the spectrum, a mean annual air temperature below 18℃ limits vegetative growth, particularly where there is a risk of frost (i.e. at high altitudes) (Camargo 2010).

Regarding precipitation, for *C. arabica* rainfall amounts outside of the optimal range of 1200-1800 mm per annum can cause significant harm to the coffee crop (Carr 2001). Water stress during the vegetative growth phase is responsible for reduced rates of shoot extension, node development and individual leaf area (Carr 2001). Yet in preparation for flowering, 2-4 months of water stress are necessary to promote bud development during the quiescent growth phase (DaMatta et al 2007). In the 6-16 weeks following blossoming, the coffee fruits rapidly gain volume, meaning that final seed size is determined by water availability during this period (Carr 2001). Thus, it is evident that proper flowering and fruit set depends upon the right amounts of rainfall, but also - critically - the timing of the rainfall during the plant's reproductive cycle. Meanwhile, rainfall above the optimal range could cause soil erosion and root rot (e.g. in slow-draining soils with high clay content), as well as creating beneficial conditions for certain pests and diseases to thrive (e.g. *Hemileia vastatrix*) (Avelino et al 2015). When heavy rains fall during the traditional dry season[3] when the fruit is nearing full maturation, it can cause the cherry's outer skin to swell and split, speeding fermentation and compromising the quality of the seeds. Heavy rainfall during the harvest period can also damage ripe coffee cherries, reducing both yield and quality.

The impact of climate change on overall plant growth and development is not yet well understood, though it seems likely that the increased amount of CO_2 in the atmosphere could speed up photosynthetic processes and thus vegetative growth, boosting "the growth and vigor of the coffee plant" (Watts 2016). A 2019 study by DaMatta et al concluded that coffee may benefit more from the increase of atmospheric CO_2 than many other C3 plants due to the specific characteristics of its photosynthetic processes. Indeed, in their field experiments utilizing CO_2 'fertilization' coffee crop yields increased by 28%. Furthermore, the plants grown under both elevated CO_2 and under various temperature regimes also demonstrated a "higher metabolic/functional photosynthetic activity for all temperature treatments" (DaMatta et al 2019), which is promising. However according to Watts (2016) "there is no guarantee this 'fertilisation effect' will offset the risks imposed by a more hostile climate". It is clear that more research is needed in order to assess the effects of various future climatic parameters on coffee yield and quality, and that adaptive on-farm resilience-building strategies will be a key component of preparedness for climate change in any case.

[3] In Costa Rica the dry season is roughly December - April.

3.4. Land use

A 2015 study by Bunn et al reaffirmed previous evidence that, barring a dramatic reduction in GHG emissions, there will be a 50% reduction in the land suitable for *C. arabica* production by 2050. This was determined by mapping various coffee-producing climate zones and the ways in which they are expected to change in the coming years. According to this study, drier producing regions are especially at risk, with the highest losses expected in several high-yield areas like northern Minas Gerais state in Brazil, some parts of India, and Nicaragua. Of course, not all regions face such dramatic reductions in suitable land area, and some new regions will certainly emerge as suitable locations for *C. arabica* production in the future, which will help offset some of the expected losses in global yield. However, there is concern, as mentioned previously regarding biodiversity and land use, concerning barriers to the development of new suitable locales for coffee cultivation. Simply moving coffee farms to higher altitudes or further from the equator has limited viability due to a constellation of associated sociopolitical, economic, agronomic, and ecological challenges. According to Watts (2016) the

> geography of coffee is unlikely to be rearranged in a straightforward and orderly fashion. Instead, a warming world is a more erratic, less predictable one…[the] upslope movement of coffee plots could come at the expense of tropical rainforests, thus increasing GHG emissions and speeding up global warming.

In some parts of Central America, climate adaptation measures which address the entire ecosystem - rather than a single sector or interest group - are gaining traction. These include “the effective management and establishment of protected areas, conservation agreements, and community management of natural areas” (Magrin et al 2014). Costa Rica has been a leader in adapting these types of land use policies as the government has pursued a dedicated environmental agenda since the 1980s. This has included aggressive reforestation efforts - from just 21% land cover in 1987 to 50% in 2005 (Conservation International 2017); strict land use regulations (over 25% of the country is environmentally protected area)(OECD 2015); emphasis on preserving genetic biodiversity in plant and animal populations; and marine protection (Conservation International 2017). The country also pioneered a payments for environmental services (PES) program - one of the first of its kind in the world - which contributed to reforestation and biodiversity enhancement efforts (World Bank 2017). Ideally, these kinds of policies will offer incentives and support for coffee farmers to adopt agronomic best practices on their farms, thus both increasing their resilience to climate risks and contributing to mitigation efforts.

3.5. Water management

Water management in *C. arabica* cultivation in Central America is almost completely dependent on rainfall. Just 7% of total agricultural land in Central America is irrigated, which is dominated by rice and sugarcane production (Pomareda 2013). One challenge for irrigation is that coffee is often cultivated on steep hillsides since the higher elevations of these marginal lands meet the plant's requirements for relatively cooler, more stable temperatures in the tropics (Pomareda 2013; DaMatta 2007). Increased temperatures and growing irregularity in rainfall patterns may mean that irrigation becomes necessary in growing regions that previously relied solely on rainfall, particularly in young plantations. Identifying the most efficient irrigation technologies, water sources, and delivery systems for these locales will be key to maximizing the use of valuable freshwater resources.

As mentioned previously, the predictability of rainfall is one of the most significant challenges faced by coffee producers due to the particular water needs at different phases of plant development. There are several critical periods regarding water use in coffee growth, namely a long dry period prior to flowering, and sufficient rain during the rapid fruit expansion stage in order to ensure that berry growth is not limited (DaMatta et al 2007). When rains are heavy and distributed throughout the year, this can cause "scattered harvest and low yields" (DaMatta et al 2007).

According to the SCAA (2016), there are several techniques which comprise a 'water-smart' approach to coffee management, including contour planting, micro-terracing for each tree, soil management to prevent topsoil erosion, maintaining a vegetative soil cover and canopy, and efficient irrigation, as needed. A robust approach to pest and disease management is also necessary to prevent opportunistic outbreaks. Additionally, in anticipation of more irregular rainfall patterns, farmers might consider picking nearly-ripe cherries early (to prevent windfall or splitting from unseasonal rains) and investing in rain covers for drying patios at processing facilities. Finally, increased drought periods may require adaptations such as adjusting nitrogen fertilization regimes, Cova planting (2+ trees per planting station), increasing planting density, grafting onto cultivars with more resilient root stock, stumping trees every 5-7 years, mulching and weed control, shade management, and planting more drought-resistant cultivars (Rodriguez 1966, DaMatta & Ramalho 2006).

Climate change will also have an impact on how coffees are processed. Historically, coffee processing has been a very water-intensive process (Brando 2013). For a traditionally washed process coffee, up to 20 m^3 of water may be used to process 1 ton of coffee cherries, whereas even switching to a semi-washed technique could reduce water demand to 1 m^3 per ton of cherries (Calvert & Von Enden 2010). Yet in recent years many producers have begun implementing water conservation techniques such as producing more coffees with low-water processing styles,[4] recycling or reusing wastewater when possible (in the mill or as fertigation), treating wastewater before release into natural waterways, and using mechanical and/or gravity-powered transport mechanisms such as elevators or conveyors instead of water-dependent pipes and channels for moving coffee through the mill (Brando 2013). Such conservation techniques will likely become more common and even essential as increasing drought periods mount pressure on freshwater resources. Treatment of coffee processing wastewater is particularly key since this substance releases CH_4 into the atmosphere and has a high polluting potential of surface and groundwaters due to its chemical composition (Calvert & Von Enden 2010). Treatment techniques incorporating biogas capture would offset CO_2 emissions and increase farm-level energy independence.

3.6. Shade management

Cultivating coffee in the shade of taller companion trees can provide multiple benefits to the farming system including: lowering mean air temperatures (Siles et al 2010); reducing damaging temperature extremes, decreasing wind turbulence, increasing relative air humidity, increasing water use efficiency in the soil (DaMatta 2006); making a less-favorable environment for pests, diseases and weeds (Staver et al 2001); slowing fruit maturation which can increase final cup quality (DaMatta 2007); softening the impact of heavy rainfall on fruit (reducing drop) and soil (reducing erosion); promoting pollinator biodiversity and, depending on the companion species planted, can also improve nutrient cycling (e.g. leguminous species) and/or diversify the farm economy by providing additional products for sale or consumption. Significant potential drawbacks of shade-grown coffee are competition for water and nutrients and lower yields due to the diminished rate of growth. Yet some research has shown that adequate species selection (of both coffee cultivar and shade tree) and management - especially pruning and “judicious evaluation of planting density, soil type, water and thermal regimens” (DaMatta 2006) can minimize these challenges and boost the many benefits offered by shaded CAS (Siles et al 2010).

It seems that the benefits of shaded coffee cultivation are especially important in hot, dry climate zones (DaMatta 2006), and at lower altitudes. According to a study by Rahn et al (2018) comparing two East African sites (Mt. Elgon, Uganda and Mt. Kilimanjaro, Tanzania) coffee cultivation at low elevations (up to 1000 masl) currently benefits from 50% shade cover assuming soil water storage capacity is adequate, “enabling a 13.5% increase in coffee yield compared to unshaded systems.” Shade management will be increasingly important under future climate conditions as coffee grown at these lower elevations is projected to be most severely affected, with yield

[4] E.g. dry processed naturals, pulped naturals (honeys), and mechanically demucilaginated coffees

reductions of 18-32% due to temperature increase, drought stress and water competition “requiring careful selection of appropriate shade tree species or the adoption of other technologies like conservation measures or irrigation” (Rahn et al 2018).

Ongoing research is needed regarding the impact of shade in coffee cultivation due to the fact that these complex agroforestry systems must be designed on a hyper-local level. They should take into account optimum shade coverage, species selection and beneficial associations, the soil water regime, planting density and spatial arrangement, cultural management protocols, and “site-specific knowledge of the seasonal food web dynamics” (Staver et al 2001). A model developed by Hernandez-Aguilera and Rodewald (2019) sought to quantify the economic tradeoffs involved with the transition from full-sun to shade-grown coffee production, and found that farmers who convert 36-66% of production to shade-grown will optimize their coffee profits, accounting for the price premium available and various ecosystem services which shade provides the farm. Overall, shaded CAS are a “practical... means of buffering climatic fluctuations, thus rendering coffee cultivation less dependent on external inputs, such as supplemental fertilization and irrigation” (DaMatta 2006).

3.7. Soil management

Soil is an important carbon sink, and appropriate soil management, especially regarding nitrogen fertilization, is a key factor in maintaining the climate change mitigation potential of this valuable resource (Lugato et al 2018). Some land management techniques speed the release of carbon and nitrous oxide (N_2O) from the soil, thus contributing to global warming. Yet there are several ways whereby organic carbon sequestration can be enhanced in agricultural soils, and N_20 emissions balanced. According to Lugato et al (2018) “practices based on crop residue retention and lower soil disturbance tend not to increase N_2O emissions as long as carbon accumulation continues.” Coffee, as a perennial crop, is not prone to the same challenges as annual agricultural crops in this regard, yet soil conservation techniques to increase carbon sequestration, reduce erosion (especially on steep hillside plantations) and enhance soil quality remain important (OECD 2015). Furthermore, appropriate soil management is a relatively low-input method of reducing production risk, which is meaningful “especially for poor rural smallholders…[as] these methods diminish costly dependence on agrochemicals, reduce the impacts of drought, and encourage on-farm diversification for food security and income protection” (Varangis et al 2003).

Companion planting with *C. arabica* - whether for shade or as a groundcover - is an especially relevant tool with multiple benefits to the entire agrosystem including reducing soil erosion, increasing soil organic matter content, reducing damagingly high soil temperatures, increasing water storage capacity and soil humidity, contributing to soil nutrition (leguminous species), and potentially contributing to the diversity of the farm's overall production as a source of food and/or forage. A case study by a Coffee&Climate team found that interplanting young coffee transplants (< 2 years old) with *Brachiaria ruziziensis* and *Cajanus cajan* lowered maximum soil temperatures and overall environmental temperatures, increased soil humidity and beneficial soil organisms, decreased erosion, and - with appropriate pruning - contributed a significant amount of nitrogen-rich organic matter to the soil. Overall they found a significant yield increase in those plots which included the companion species (Coffee & Climate 2020).

3.8. Pests and diseases

The effects of climate change in coffee-producing regions are already being observed in the spatial and temporal distribution of certain pests and diseases which affect the coffee plant. In particular, changing temperature and precipitation regimes are contributing to outbreaks which often have disastrous results. Overall, "higher temperatures improve living conditions for pests and diseases, [which] increases pest attacks leading to the loss of quality of the coffee beans or even to the destruction of yield and plants" (Haggar and Schepp 2012). While some of these pests and diseases seem to be controllable with appropriate investments in resilient cultivars, strict management protocols, and high levels of pesticide use, most smallholder farmers (farming less than 7 ha) in Central America are unable to make these investments due to economic constraints (Avelino et al 2015). Furthermore, historically "the strategy of maximizing coffee production with pest control dominated by synthetic pesticides has not only increased yields substantially, but also production costs, pesticide resistance, and both human health and environmental risks" (Staver 2001). Heavy pesticide use also contributes to GHG emissions, and can compromise water and soil quality especially when used improperly.

Hypothenemus hampei (Coffee Berry Borer - CBB) and *Hemileia vastatrix* (Coffee Leaf Rust - CLR) are a common pest and disease (respectively) which negatively affect coffee producers. The ways in which these two species are influenced by climate change in the future will have a significant effect on coffee yields. An important initiative seeking to protect the future of *C. arabica* production is broad-based genetic research to find, develop, and distribute coffee cultivars which are resistant to certain pests and diseases, primarily CLR. There has been some success in these efforts, notably in the CLR-resistant Sarchimor varieties like Victoria 1, San Isidro 26 and others, which were developed at Hacienda Alsacia in Costa Rica by the Starbucks Coffee Agronomy Company (Rodriguez 2018). Unfortunately there has so far been negligible success using similar breeding methods to develop cultivars which are resistant to CBB (Mugo 2009), but more research to this end is certainly needed.

3.8.1. *Coffee Berry Borer*

CBB is a small beetle which feeds almost exclusively on the endosperm of plants in the *Coffea* family (Damon 2000), and causes roughly USD $500 million in losses and damages to global coffee crops per year (Jaramillo 2011). CBB spend a significant part of their life cycle deep within the coffee fruit, making them difficult to control by chemical methods (Baker et al 2002, Mugo 2009). Warming temperatures due to climate change have a significant influence on CBB populations. A model published by Jaramillo et al in 2009 predicted that “a 1–2℃ increase could lead to an increased number of generations, dispersion and damage [by CBB]; whereas a rise in temperature of 2℃ and above could lead to shifts in altitudinal and latitudinal distribution of the pest.” And a 2011 report by Jaramillo et al confirmed this prediction, as changes in the altitudinal range of CBB had already been noted in several coffee-producing regions.

There are a range of adaptive techniques for managing CBB outbreaks, including biological, mechanical, and chemical control methods. Plant diversification in coffee agrosystems is one of these tools. In a 2012 study by Avelino et al there was found to be a high correlation between landscape context and the spread of certain coffee pests and diseases across 29 coffee plots in Turrialba, Costa Rica. The researchers found that the incidence of CBB increased as the amount of coffee in the landscape increased, suggesting that “connected coffee plots favored coffee berry borer movements and improved its survival” (Avelino et al 2012). Considering planting density and companion planting with coffee, as discussed previously thus has the additional benefit of boosting farm resilience to yield losses caused by CBB infestations.

3.8.2. *Coffee Leaf Rust*

Coffee leaf rust (CLR) is a disease caused by the fungus *Hemileia vastatrix* which causes defoliation and can result in heavy yield losses, and affects *C. arabica* most strongly (Avelino et al 2015). There have been recent epidemics of this disease across Central and South American coffee-growing regions, notably in Costa Rica in 2012-2013 (Avelino et al 2015). In Central America that year yield losses from CLR outbreaks averaged 16% compared to the previous year’s harvest and in many cases stumping of entire plantations was required, meaning that these plots needed three years to return to productivity (Avelino et al 2015). CLR continues to be a looming threat to coffee farmers across Central America, and the impact of rising temperatures and changing rates of precipitation are of particular significance to CLR, since the epidemics in Central and South America from 2008-2013 “were enhanced by weather conditions consistent with climate change” (Avelino et al 2015), namely a reduction in the diurnal variability of temperature and changes in rainfall distribution.

Another factor that contributed to these outbreaks was the combination of low coffee prices on the C market[5] and rising input costs, which left many farmers (especially smallholders) without any profits from their crop, and thus unable to invest in appropriate adaptive and management techniques to prevent future losses from CLR. Some examples include planting more resilient coffee varieties, replanting older (and thus more vulnerable) plots, applying fungicides preventatively, applying adequate nutrition, considering plant density to reduce disease spread, supporting biodiversity and populations of natural predators, and planting/maintaining windbreaks to minimize CLR spread[6] (Avelino et al 2015, Rodriguez 1966, Rodriguez 2018). While it was accepted until recently that CLR would not thrive above 1100 masl, the spread of the disease during the recent epidemics in Central and South America did not seem to be slowed at higher altitudes (Avelino et al 2015).

3.9. Coffee processing systems

There are multiple steps in a coffee processing system, beginning after harvest and continuing until stable green coffee beans are ready for domestic consumption or export. Accordingly, there are several ways in which expected climate changes in Central America will impact this necessary chain of events.

First of all, harvest practices may need to be adjusted. Scattered rainfall patterns could cause the harvest period to lengthen. The unpredictability of rainfall requires great consideration from producers as to the timing of coffee harvests in order to minimize the potentially devastating impacts of heavy rainfall on tree-ripe fruit that is ready to be picked. Farmers may decide to pick fruit that is nearly ripe (producing lower quality beans), rather than risk massive damages to yield and bean quality in the event of unseasonal rainfall. After harvest, it is important for coffee cherries to be moved to drying surfaces (for dry process) or into tanks (for wet process) as quickly as possible to minimize damage to the fruit, which could increase undesired fermentation. Yet even for planned fermentation steps, higher temperatures will affect these protocols and speed the process. Drying, which takes place - at least in part - outside on cement patios or raised mesh drying tables (African beds), will also be affected by climate change, particularly unpredictable rainfall which may necessitate adaptations into greenhouses, other covered drying arrangements, or mechanical dryers. Finally, once the green coffee has been dried it is stored until it reaches the final humidity level (less than 12-13%) (Clarke 1985). At this final stage, increased heat and humidity could speed the

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[5] The C price is the benchmark for raw Arabica coffee futures.

[6] Avelino et al (2012) found significant correlation between the incidence of and the amount of open grassland, suggesting that “wind turbulence, produced by low-wind-resistance land uses such as pasture, favored removal of coffee leaf rust spore clusters from host surfaces, resulting in increased epidemics.”

loss of freshness, increase the incidence of certain pests in storage facilities, and increase the prevalence of certain species of ochratoxigenic fungi (Sousa et al 2019).

3.10. Coffee farming communities

As temperature extremes become more severe, the effect on human labor in the coffee plots will become more pronounced. Coffee is mostly hand-picked on the steep slopes where it grows in Costa Rica due to its scattered pattern of ripening, and also due to the mechanical challenges presented by the rugged landscape (Avelino et al 2015). On extremely hot days, coffee workers may need to take more breaks, pickers might only be able to pick at dawn and dusk hours, and take other precautions to ensure their physical health and well-being (ILO 2019). These adjustments could have an impact on coffee yields. Coffee pickers are usually migratory laborers, many of whom travel long distances (and often cross international borders) in order to work for several weeks during the coffee harvest, and they are among those most at risk due to climate changes impacts in the coffee industry. In Costa Rica most coffee pickers are seasonal migrants from neighboring Nicaragua and Panama. Climate change has a disproportionate negative impact on these types of workers as they are already more vulnerable to disruptions in the global supply chain.

It is well-established that the agricultural sector is particularly vulnerable to climate risks, particularly those associated with natural disasters resulting from weather and climate extremes. Globally, coffee farmers are often additionally vulnerable due to preexisting conditions of poverty; food insecurity; harsh environmental conditions; lack of governmental support, market access or agricultural inputs; and general lack of resilience to shocks. Compounding factors include an aging farmer population, farm abandonment due to commodity market fluctuations and urbanization, and competition for land use due to urban sprawl and population growth. In light of this constellation of challenges, a range of adaptive options must be considered in order to build the resilience of coffee farming communities.

According to Eakin et al (2011), existing farmers' organizations and cooperatives should be bolstered in order to increase farmers' adaptive capabilities when faced with environmental, climatic, and social shocks. Resilience can also be increased by boosting farmers' access to financial instruments such as credit and crop insurance. Farmers with access to credit are able to make timely agronomic investments even when coffee payments are delayed, or may be able to take on shipping expenses in direct trade relationships. Crop insurance policies are less common in Costa Rica and are "expensive and difficult to implement due to contract design, lack of information, moral hazard and high transaction costs" (Naranjo 2015). Furthermore, as the impacts of climate change increase in frequency and severity, there will be more demand for these types of financial support across many sectors in the same affected locales, which will put pressure on regionally-available resources. Finally, coffee farmers need better access to timely and accurate weather, market, and technological information (Eakin et al 2011) in order to make informed agronomic and business decisions.

3.11. The global coffee industry

While this paper focuses on crop-level, household-level and community-level impacts, climate change will likely cause massive disruptions to other segments of the international coffee supply chain as well. The domestic movement of green coffee from the farms/mills to dry milling/storage facilities and overseas shipment hubs must also be considered. The transport step in the coffee production chain is significant due to the fact that most coffee - roughly 92% in Costa Rica - is exported to markets in North America and Europe (Gerz & Avelino 2006; Gonzalez 2017). Thus the success of this industry is highly dependent on global transportation systems, particularly oceanic shipping lines. Weather-related disruptions in transport lines (whether overland or overseas) may become more frequent in proportion to increasing extreme weather events which result from climate change. GHG emissions resulting from truck and shipping transport steps are included in the carbon footprint for coffee (Killian et al 2013), and the consequences on local road and traffic conditions must also be considered.

It is apparent that climate change poses a variety of threats to the coffee industry, and the response is correspondingly diverse. There are dozens of projects, spearheaded by non-profit and for-profit organizations alike, which are seeking to find sustainable solutions to the global challenge of climate change and its effect on the coffee industry in particular. A promising trend in the specialty coffee[7] industry is the movement towards so-called ‘direct trade’ or relationship coffee, wherein roasters and green coffee buyers develop relationships with specific farmers and cooperatives and often commit to purchase lots from them year after year. Sometimes these arrangements include contracts or some element of prepayment, which can help to distribute risk more evenly across the supply chain (May et al 2004). The responsibility of green coffee buyers, roasters and consumers should include the absorption of more risk from the production end, as well as a commitment to support coffee farmers in their efforts to diversify.

Another instrument which could bolster the climate resilience of small coffee farmers is certification[8]. However, for farmers outside of a cooperative or who produce

[7] Specialty coffee is a gourmet product defined by the Specialty Coffee Association (SCA) as “coffee that is free of primary defects, has no [unripened beans], is properly sized and dried, presents in the cup free of faults and taints and has distinctive attributes” (Rhinehart 2017). Practically, this means that the coffee must pass certain grading and cupping tests, and that it is afforded a price premium.
[8] Including but not limited to: Organic, Fair Trade, Rainforest Alliance, UTZ, Bird Friendly, Carbon Neutral, Starbucks CAFÉ etc.

relatively small quantities, it is unfeasible to pay the fees and make the necessary investments in order to qualify for these certifications[9]. While this is a valuable tool for certain segments of the industry, the position of many smallholder coffee farmers is such that certifications are an unlikely - even if desirable - goal.

4. Coffee and climate change in Costa Rica

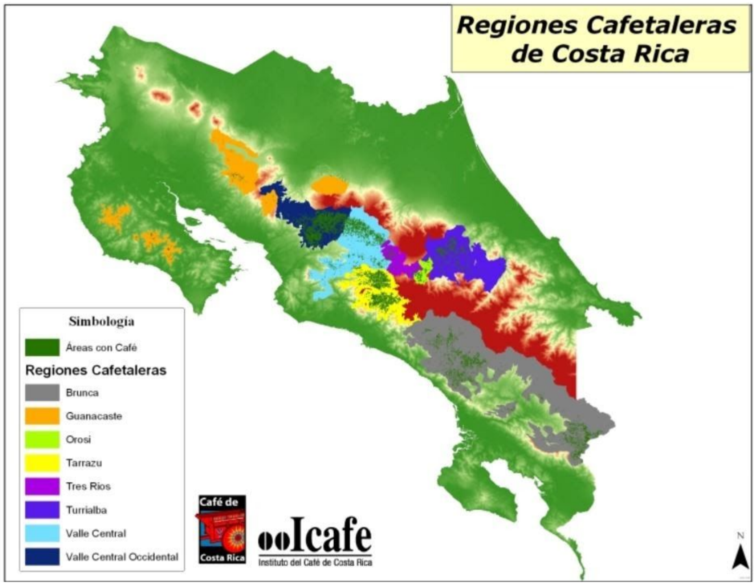
Costa Rica has a well-established tradition of coffee production, dating back to the end of the 18th century (Gerz & Avelino 2006). In 2018/19 Costa Rica produced 1,427,000 bags (ICO 2020a), and the previous year coffee exports had a trade value of $347 million USD, accounting for 2.68% of total exports (OEC 2018). Employment in the coffee industry has been declining in recent years, due in part to an aging farmer population: in 2017/18 there were 43,035 coffee producers identified in the country (Arroyo 2018), down from 55,247 producers in 2005/6 (Gonzalez 2017). According to a 2014 agricultural land survey performed by the National Institute of Statistics and Census, there are 26,527 coffee farms in the country comprising an area of 84,133 ha (Gonzalez 2017). The sensitivity of such an important crop to climate changes obviously poses a serious problem for the social and economic systems in Costa Rica.

Coffee production in Costa Rica is a valuable sector of the economy, as well as being closely tied to national identity. While coffee's share of GDP has fallen to less than 3% in recent years, it is a labor-intensive industry and employs up to 150,000 people during coffee harvest time (NAMA 2020a). Coffee was the first agricultural product to be given status as a Nationally Appropriate Mitigation Action (NAMA) as per the 2007 UN Climate Change Conference, implemented by the Costa Rican government in 2008 (NAMA 2020a). The government has committed to become carbon neutral by 2021 (NAMA 2020b). Coopedota, a 900 member farming cooperative in Tarrazú, has set an example by becoming the first carbon neutral coffee company, and other initiatives supporting low-carbon and carbon-neutrality in coffee production are gaining traction (NAMA 2019). It is promising that:

> due to a strong national tradition of environmental protection, sustainable development and – more recently – climate change mitigation, Costa Rican farmers are well versed in many of the linkages between agriculture and the environment and a number of agricultural practices are already adaptive. For instance, low external input agriculture, soil conservation and crop diversification are key tenets for many Costa Rican farmers…[and] some farmers have started experimenting with more resilient seed varieties." (OECD 2015)

[9] See Tellman et al 2011 for a discussion regarding barriers to Fair Trade certification in El Salvador, some of which apply to other certifications as well.

Figure A: Coffee-producing regions in Costa Rica
(Red indicates mountainous areas where coffee is not produced)



(ICAFE 2020)

In addition to carbon neutrality, the Costa Rican coffee sector is well-positioned to take advantage of the higher price points available in the niche specialty coffee market. The number of wet milling facilities in Costa Rica more than doubled between 2005/6 and 2015/16, increasing the 'traceability' and lot-by-lot processing which specialty coffee consumers value so highly (Gonzalez 2017). Known for its high quality *C. arabica*, there has also been discussion about the implementation of a Geographical Indication for Costa Rican coffee, possibly both as a national entity and divided into the 8 growing regions identified by ICAFE (e.g. Cafe de Tarrazú) (Santaram 2018).

5. Climate risks and resilience

All farmers face risks, whether these are related to business risks (production, market, or legal) or external financial risks (OECD 2020); identifying, analyzing and managing these risks and building resilience in response is thus an integral part of the agricultural sector. Parsing climate risks by type is helpful in order to "avoid the common fallacy of exclusively situating climate change impacts in agriculture at producer level" (Choudhary *et al* 2015). It is also important to consider the complex ways in which risk sources are interconnected, with multiple casualties in several directions. This is especially apparent in the current COVID-19 global pandemic, which has "reinforced that exogenous risks from outside the agriculture sphere can also cause substantial shocks to the sector, simultaneously impacting input markets, labour, logistics and consumer demand in unpredictable ways" (OECD 2020)[10].

Climate-related production risks can be direct, such as changes in temperature and precipitation patterns, or indirect, such as damages resulting from increased pest activity and expanded pest ranges. Market risks have to do with the volatility of the C price, which is affected by climate-related losses due to pests and diseases, losses due to unpredictable weather patterns and events, and higher concentrations of losses in the event of an unfavorable harvest due to increasing monoculture production. Other risk factors affecting price volatility are regional agricultural and trade policies, aging farmer populations, and reduced farm size or even farm abandonment. According to Leo Peskett of the Overseas Development Institute, under several IPCC climate scenarios (A1F1, A2, B1, B2) "global coffee production will fall, leading to significant price rises…[and while] some market actors surely will be able to benefit from rising prices...this will create a lot of climate change losers, among them small-scale farmers, whose livelihoods heavily rely on the income from coffee production" (Haggar and Schepp 2012).

Coffee farmers who are threatened by the myriad of climate change impacts to the sector would benefit from incorporating a holistic risk management approach into their business planning. This approach should ensure "that decisions are no longer made from a paradigm of *reactivity*, but from a '*resilience*' perspective" (OECD 2020, emphasis mine). Resilience is "the ability to prepare and plan for, absorb, recover from, and more successfully adapt and transform in response to adverse events" (OECD 2020). While there are several components of a resilience-focused risk management framework - including absorptive and transformative capacities (OECD 2014) - this paper focuses on adaptive strategies to manage risk on the farm level. According to the OECD (2020),

> [such] strategies... play a critical role in reducing risk exposure to catastrophic events, particularly over the long-term. For this reason, risk management frameworks should encourage farmers to develop entrepreneurial skills and their human capital more broadly, as well as promote or support the uptake of resilience-enhancing practices or technologies.

[10] For further analysis of the wide-ranging impact of the COVID-19 pandemic on the global coffee industry see the ICO report Impact of COVID-19 on the global coffee sector (June 2020).

6. Case study methodology

Case studies are a "research strategy which focuses on understanding the dynamics present within single settings," (Eisenhardt 1989) and typically utilize a synergistic combination of quantitative and qualitative data. This combination allows for a particularly rich, multilayered analysis of the subject at hand. Furthermore, using case studies to develop theory is an approach uniquely suited to new topic areas (Eisenhardt 1989). While there has been a considerable upswing of attention and research devoted to climate change and coffee production over the last few years, the enormity, urgency, complexity, and regional specificity of this topic demands further research. Accordingly, the 'roadmap for building theories from case study research' presented by Eisenhardt (1989) follows.

6.1. Sample selection

Following the definition of research questions, primary data was collected from four coffee farms in the Tarrazú region of central Costa Rica in the form of questionnaires. Tarrazú is one of the eight coffee-growing areas designated by the Costa Rican Coffee Institute (ICAFE). Farm selection was not random, but rather was based on established contacts resulting from trading relationships[11]. The fact that these relationships existed demonstrated the diversity in marketing channels already employed by these farm businesses, thus successfully '[focusing] efforts on theoretically useful cases" (Eisenhardt 1989). Initially, six farmers were contacted, and four were able to respond. The questionnaire was composed in English by the author with translation assistance into Spanish, and was e-mailed to participants. Upon completion, responses were translated from Spanish into English.

6.2. Data collection & recording

Two (sometimes three) main types of data will be utilized in order to triangulate the evidence and enrich the analysis. In general, data collection should be flexible - every effort was made not to 'force' data into a preconceived form. One strength of the case study approach when used for forming emerging theories is in its potential for the increased complexity of theoretical outcomes due to the multifaceted nature of the data collected and resulting relationships. The combination of hard and soft data will allow more robust descriptions of these relationships.

A. Quantitative data - Many questions in the questionnaire focused on acquiring data that is straightforward and measurable.

[11] The author is part owner of Cogito Coffee d.o.o., a coffee roasting company based in Zagreb, Croatia.

B. Qualitative data - Some questions were open to personal interpretation and experience, in order to facilitate further communication on particular hard-to-measure topics.
C. Observation - there are a few farms where either the author has been personally or from which the author has extensive video recordings taken by her partner. In these cases observational data may also be included in order to round out the complex picture of the farm itself.

6.3. Data analysis and reaching conclusions

The characteristics of each farm were entered into Table 1 (See Appendix A) in order to facilitate analysis within each case and also comparison among the four farms. This helped to synthesize the information and explore whether any unique patterns emerge, as well as reducing the possible tendency to force preconceived patterns of similarity or difference from case to case. Cross-case patterns were examined by selecting a category and looking for similarities and differences present.

Following data analysis, the initial resilience indicators were adjusted and sharpened when necessary. A case of evidence was accumulated for each indicator which effectively measured this construct. In particular the "'why' behind [certain] relationships" was sought in order to confirm and extend the resultant theories (Eisenhardt 1989). When it seemed that the emergent theory had been sufficiently saturated with available data, then closure was reached and hypotheses formulated. The preceding literature review served as a platform and robust context for the case study and the emergent theories which resulted from the analysis. The breadth and quality of this review served to enhance the "internal validity, generalizability and theoretical level of theory-building from...the research" (Eisenhardt 1989).

6.4. Challenges of a case study approach

Foremost among the difficulties of a case study approach was the difficulty of resisting conclusion-focused planning and thinking. Having visited some of these farms firsthand, it was important for the author to avoid building a framework that simply fit the previously-made observations. While, according to Eisenhardt (1989), "it is impossible to achieve this ideal of a clean theoretical slate", it should certainly be sought after. Another challenge which is unique to case study research is that each case is heavily weighted, so any missing responses, misunderstanding, or misinformation will dramatically skew results. Particular challenges faced during data collection also included:

- Time constraints due to work/stress - particularly during this period of the COVID-19 global pandemic. This factor was mentioned specifically by one respondent as a hindrance to timely completion of the questionnaire, so presumably this was an issue for other farmers as well.

- Access to e-mail and internet availability - one of the six farmers contacted was unable to respond because he had problems with their internet connection. Another had trouble using e-mail, but was eventually able to respond via Whatsapp.
- Biased selection - all of the farmers contacted sell part of their harvest through specialized marketing channels, as this is how the author came into contact with them. This affords higher prices than they would be able to sell for on the C market. Due to this fact, these farmers are not necessarily regionally representative in terms of their RI index score. They likely have additional resources of social, intellectual, and/or financial capital in comparison with other small to medium size coffee farms in the Tarrazú region.
- Translation of the questionnaire and farmer responses - Three individuals were involved with the translation process, all Costa Rican nationals and native Spanish speakers. Two of these have had personal contact with the farmers themselves and work in the coffee industry. Of course as with any translation there is the potential for misunderstanding and miscommunication, though since the nature of the questions was relatively objective, it seems unlikely that gross misunderstandings occurred during this step in the process.

See Appendix A: **Table 1 Characteristics of Case Study Farms**

7. Defining resilience indicators (RIs)

7.1. RI 1: Agricultural products for household consumption or sale

Reducing sole dependency on income from coffee sales is at the root of several RIs developed and examined in this research. This is due to the fact that while adaptive agricultural practices are important, the sensitivity of the crop on so many levels to such a variety of climate change impacts suggests that diffusion of the coffee-specific risks would be beneficial in building farmers' resilience capacity. Thus, the production of agricultural products for consumption or sale is a valuable tool which many smallholder coffee farmers already employ (SCAA 2013). Two studies from Central America have found that over 60% of smallholder coffee-producing households experience food insecurity at some point during the year (Bacon 2008; Mendez 2010), and climate risks will likely compound this difficult situation.

Most climate change impacts (drought, hurricanes, increased pest pressure) will affect other crops as well, so selection is key to avoid overlapping sensitivities when possible among the species produced. When cultivated within the coffee plots, low-competition species must be selected (for water, soil nutrients, and sunlight), while maximizing potential benefits (see previous sections 3.2.2 Biodiversity of coffee farming systems; 3.6 Shade management; and 3.7 Soil management). On parts of the farm where coffee is not grown, fruit and nut trees and garden vegetables and legumes can improve the year-round food security of the farming household or be sold for income. Furthermore, animal products such as milk, meat, and fiber from ruminants; eggs and meat from poultry; and honey from bees can reduce the household's dependence on seasonal crops both for consumption and as a source of income. Wood products such as timber for construction or fuel, prunings for fuel or forage, and resin can also contribute to the farm's income diversity. Ruminants and poultry also provide nutritionally-rich manure which can reduce the need for external fertilizer inputs. Most of these activities are compatible with existing farming activities, though barriers may include capital costs, and time and land use.

This RI was measured with questions regarding on-farm biodiversity, non-coffee crops produced, non-coffee related income sources, proportion of land used for these crops, and proportion of income derived from these crops. This RI was assigned a two point value, categorized as follows:

- 1 point was given for the production of food crops for household consumption
- 1 point was given for the production of non-coffee agricultural crops to diversify farm income

7.2. RI 2: Non-agricultural on-farm income

Besides agricultural production, there are other on-farm income sources which would contribute to income diversity, thus boosting climate resilience. Agrotourism, educational programs and research partnerships, or other trade crafts (e.g. carpentry) could be ways to add financial, social and intellectual capital and reduce vulnerability to climate risks.

This RI was measured by a question about non-coffee income sources and was assigned a two point value, for any non-agricultural on-farm activities which contribute to the farm's income.

7.3. RI 3: Coffee varieties

Growing a healthy mix of different coffee cultivars makes a coffee farm less vulnerable, particularly when those cultivars have demonstrated increased resilience to climatic stresses associated with climate change, and also resilience to heightened pressure from pests and diseases (See section 3.2.1 Biodiversity of *Coffea* species). In addition to cultivating a bouquet of various cultivars for production, farmers who are experimenting with new seed types on a smaller scale may find new varieties which are especially suited to the microclimates on their farm property.

This RI was measured by questions about the percentages of each coffee variety grown on the farms, how the farmers decide which varieties to grow, and whether they are experimenting with any new varieties. This RI was assigned a 3 point value, categorized as follows:

- 1 point given for 3 varieties under cultivation; no mention of experimentation
- 2 points given for 4-5 varieties under cultivation; no mention of experimentation
  OR
  3 varieties under cultivation; experimentation
- 3 points given for 4-5 varieties under cultivation; experimentation
- ½ point was reduced for the cultivation of more than 80% of any single variety

7.4. RI 4: Use of shade

Increasing the use of shade trees has multiple benefits for coffee farming systems (See sections 3.2.2 Biodiversity of coffee farming systems, and 3.6 Shade management). In particular, protection from temperature extremes, protection from wind shear in case of extreme weather events, and increasing humidity and water-holding capacity are all ways that coffee agroforestry systems provide increased resilience to climate change impacts. Additionally, this synergistic activity is a way of both adapting to and mitigating climate change by increasing carbon stocks in coffee plots (Rahn et al 2013).

This RI was measured with questions regarding land use on the farm property, soil management, biodiversity, and shade management. Within the specific questions about shade management, farmers were asked which species they grow, their priorities when planting shade species, and about differences they notice between plots with relatively more shade (>40%) and relatively less shade (<20%) in terms of: coffee production, overall plant health, prevalence of pests and diseases, and biodiversity. This RI was assigned a 3 point value, categorized as follows:

- 1 point given for some use of shade in coffee plots (10-20%)
- 2 points given for increased use of shade in coffee plots (20-40%)
- 3 points given for significant use of shade in coffee plots (more than 40%)

7.5. RI 5: Diversity of marketing channels

Farmers who only sell their coffee on the C market are more vulnerable to price risk. Accessing a range of marketing channels means that farmers have increased agency in defining prices themselves in direct negotiations with green coffee buyers, whether through direct trading relationships with roasting companies or via specialty coffee trading companies. Furthermore, they may have the possibility to distribute risks up the production chain by using various types of contracts and planned purchasing schemes. Also, by producing a brand of roasted coffee for domestic consumption, farmers are able to diversify their income and protect themselves from disruptions in global trade and transport (see section 3.11 The global coffee industry).

This RI was measured with questions regarding the percentage of coffee sold on the C market vs. on the specialty market; whether or not farmers produced a roasted coffee brand for the local market; and if so, what percentage of their income this accounted for. This RI was assigned a 3 point value, categorized as follows:

- Percentages of 1 point given according to the percentage of coffee sold on the specialty market
- 1 point given for having a roasted coffee brand
- ½ point given for 1-5% of income from roasted brand; ½ point given for 6-10% of income from roasted brand

7.6. RI 6: Control of coffee processing technology

Coffee farmers who are able to process their own coffee cherries to some extent are at an advantage in that they add value to their product and are able to sell directly (or nearly so) for export, rather than losing profit due to a chain of middlemen. There is a significant initial expense associated with owning coffee processing facilities, but it is an investment which proffers certain benefits to the farmer over the long term including the ability to access the direct trade and specialty markets, having more control over processing protocol and techniques, and increasing ‘traceability’ by being able to separate lots by plot and/or harvest period. Aside from initial cost, another disadvantage of having milling facilities is that (at least in Tarrazù) farmers who do so are not allowed to be members of farmers’ cooperatives, which can be a valuable source of information sharing and expert knowledge.

This RI was measured with questions regarding various aspects of on-farm coffee processing, and was assigned a 3 point value, categorized as follows:

- 1 point given for owning wet milling facilities OR employing processing techniques which do not require a wet mill
- ½ point given for owning dry milling facilities
- 1 point given for adaptations to drying which protect from rainfall (greenhouses, sharing mechanical drying facilities with another farm)

7.7. RI 7: Access to credit/crop insurance

While most of the RIs designated in this research have to do with building adaptive capacities as a risk management technique, the accessibility of financial instruments for risk transfer are also a key component of climate resilience for small coffee farmers (See section 3.10 Coffee farming communities).

This RI was measured with questions about whether or not the farmer had used a line of credit in the last 10 years or a crop insurance policy, and was assigned a 2 point value, with 1 point given for using each of these financial tools.

7.8. RI 8: Amount/level of involvement from younger generation

High levels of involvement from younger generations may motivate farming families to find long term solutions and to take immediate action towards improving climate resilience. Younger generations are likely to be more educated, speak more English, and to be more comfortable using computers, internet-based information and forecasting, social media for brand marketing, etc. Younger people also tend to be more open to new ideas, and may be willing to take risks - such as trying new cultivars, management techniques, or coffee processing styles - which the older generations would not take.

This RI was difficult to measure (‘involvement’ being hard to quantify and subject to change), but was attempted by a question regarding the people employed on the farm, their ages, family relationship (if any), educational background, and role on the farm. Observational data was also used to fill out the picture of the farming family structure. This RI was assigned a 2 point value, equated with the presence of at least one family member under 35 working full-time on the farm.

7.9. RI 9: Efficiency of farm management systems (water, waste, energy)

The type and degree of efficiency in farm management systems for water, waste and energy has a considerable impact on farmers’ ability both to adapt to and to mitigate the impacts of climate change (see section 3.5 Water management). The ‘three Rs’ (reduce, reuse, recycle) are relevant to these three systems, in order to reduce the farm’s exposure to climate risks including drought (low water levels) and extreme weather events (disruptions in the electrical grid), and reduce dependence on external inputs (e.g. using solar panels; using nutrient rich organic compost to offset some portion of fertilizer application).

Water management should focus on reducing water demands, and also on reuse possibilities for coffee processing wastewater. Irrigation systems, especially in nurseries and young coffee plots, are an important adaptive mechanism to increasingly extreme temperatures and unpredictable rainfall patterns. Regarding waste, most types of on-farm waste (coffee pulp and husk, shade tree clippings, organic household waste etc.) can be used as nutritionally-rich compost and mulch in the coffee plots.

Costa Rica has committed to carbon neutrality and a 100% renewable power grid by 2030 (IHA 2017) yet about 75% of total electricity consumed is hydropower-fueled (IHA 2017), which may be sensitive to future climate-change related drought conditions. There are several types of alternative renewable energy sources which can be utilized on a small coffee farm. Solar energy is used for coffee drying on patios and raised beds, and adding solar panels could provide hot water and/or electricity for the farm household. Various types of biomass, such as dry coffee husks and pruned or coppiced wood fuels, can be used to heat dry milling facilities, as well as for household cooking and heating. Biogas capture from coffee wastewater processing or animal waste could also be utilized to produce energy.

This RI was measured with questions regarding water management (specifically irrigation), on-farm energy sources, and the use of organic compost or mulch. This RI was assigned a 5 point value, categorized as follows:

- 1 point was given for the utilization of low-water coffee processing styles
- 1 point was given for having a functional irrigation system in place
- ½ point was given for the application of coffee cherry pulp to the coffee plots
- ½ point was given for efforts to improve nutrient cycling from coffee waste (speed decomposition/neutralize)
- 1 point was given for using electricity from a renewable energy source OR not using electricity on the farm at all
- 1 point was given for on-farm energy production (solar panels, biogas capture, etc.)

7.10. RI 10: Access to natural resources (notably water)

Ready access to freshwater resources is a key component of climate resilience, given the fact that increasing temperatures and potentially longer drought periods are frequent impacts of climate change. Rainfall in the region of Tarrazú averages 2400 mm/year, and there are abundant streams in this mountainous region which is heavily cultivated with coffee (de Jesús Crespo et al 2020).

This RI was measured with a question regarding on-farm sources of freshwater (springs, streams, etc.) and was assigned a 2 point value, given for the presence of natural springs on the farm property.

7.11. RI 11: Access to information and forecasting

Weather, climate, and agronomic information and forecasting can have a significant impact on farmers' decision-making process. This may include weather information and predictions about local climate trends; information sharing in farmer community groups (formal or informal); and agronomic information from government extension services, private institutions, NGOs, etc.

This RI was measured with questions regarding which sources of weather and agricultural information were utilized and was assigned a 2 point value categorized as follows:

- 1 point given for using weather and climate forecasting information (web/phone apps)
- 1 point given for using information from extension visits from agricultural engineers, community information sharing, etc.

7.12. RI 12: Demonstrated long-term planning to build farm resilience according to climate predictions

The four farmers who responded to the questionnaire affirmed that the climate in Tarrazú has changed over the past decades, most notably in increased temperature extremes and highly irregular rainfall patterns. Long-term resilience-focused planning may look slightly different in each farm setting, but this RI sought to identify the various ways in which farmers are responding to climate risks, whether or not the farmer himself explicitly acknowledged his actions as such.

This RI was measured by more open-ended questions regarding perception of climate risk and their farm's resilience, responses to observed climate changes, desired future adaptations, challenges faced, and how the farmers think coffee farming in the region may change in the next 10/30 years. This RI was assigned a 1.5 point value for demonstrating long-term planning for climate adaptations (whether underway or desired).

8. Results

Table 2. Resilience Indicator Index

			Possible points	Points earned			
				Farm A	Farm B	Farm C	Farm D
Resilience Indicators	1	Agricultural products for consumption or sale	2	1	1	0	1
	2	Non-agricultural on-farm income	2	0	0	0	2
	3	Coffee varieties	3	1.5	3	2	3
	4	Use of shade	3	0	3	3	3
	5	Diversity of marketing channels	3	2.45	1.8	2.8	2.5
	6	Control of coffee processing technology	2.5	2	2	2.5	2
	7	Access to credit/crop insurance	2	1	1	1	1
	8	Involvement from younger generation	2	2	2	2	2
	9	Efficiency of farm management systems	5	3	4	3.5	2.5
	10	Access to freshwater resources	2	2	0	2	2
	11	Access to information	2	2	2	2	0
	12	Demonstrated long-term resilience planning	1.5	0.5	1.5	0.5	1.5
		Total points	30	17.45	21.3	21.3	22.5

9. Discussion

Before examining the RI index and various cross-comparisons between the four farms in the case study, it is relevant to provide some context in terms of how these four farms compare to average coffee farms in Costa Rica in terms of size, yield, varieties produced, and processing technology. First of all, the farms surveyed in this case study were significantly larger (12 ha, 14 ha, 25 ha, 100 ha) than the average coffee farm size of 2.5 ha in Tarrazu (ICAFE 2015), or 3.2 ha in Costa Rica (Arroyo 2018). In terms of yields, there was extreme disparity among the farms surveyed, ranging from 4.25 fanegas[12] per hectare (farm B) to 57.14 fanegas per hectare (farm C). The average yield in Tarrazu is around 31.8 fanegas per hectare (ICAFE 2015). The most common varieties of *C. arabica* grown in Costa Rica are Caturra (42%), Catuaí (34%), CR-95 (9%), and 15% others (Arroyo 2018). These varieties were all represented among the farms studied, though not in this ratio, and several other varieties are also grown such as Geisha, SL-28, Typica, Bourbon, Mundo Novo, and Moka. The most outstanding common feature of the case study farms is that three out of four of them have micromills (wet milling facilities). As of February 2018 there were 191 micromills (246 total mills) in Costa Rica, representing 6.3% of total coffee production (Arroyo 2018). Considering

[12] A fanega is a volumetric measurement of coffee cherries in Costa Rica and is roughly equivalent to 100 lbs or 46 kg.

that 43,035 families produce coffee (Arroyo 2018), this feature places the surveyed farms in the 99th percentile of Costa Rican coffee farmers. These characteristics, considered in light of the following RI Index analysis, suggest that the farms surveyed may have greater climate resilience than the average coffee farm in Costa Rica.

The four farmers interviewed had relatively close RI index values, with their total scores all falling within 5,05 points of one another. The RIs for which they all had values within 1.5 points of each other (and no 0 scores) were RI 3 (within 1.5 points), RI 5 (within 1 point), RI 6 (within 0.5 point), RI 7 (same value), and RI 8 (same value). As mentioned in section 6.1 Sample selection, some of these similarities can be explained by the very fact of relationship between these farmers and the author (notably RIs 5 and 6). All of these farmers have a high degree of control over coffee processing technology and are thus able to sell over 80% of their coffee to the specialty market. It is important to note that while RI 6 can be a valuable tool of climate resilience, particularly in this local context, most smallholder coffee farmers around the world lack the possibility (whether for financial or legal reasons) to own their own processing technologies, and in these cases weight would be shifted to alternative adaptive techniques.

Considerable attention was paid to the weight of the index values. For example, three of the farmers scored 1 out of 2 possible points for RI 1. For farms A and D, this represented a 5% contribution to household food consumption yielded by a vegetable garden and other food crops (banana, lemon, avocado, beans) grown on the farm. Yet for farm B, this same score represented the fact that they have a plantation of young avocado trees under cultivation, which they intend to sell when the trees become productive. It seems likely that the significance of farm B’s avocados in terms of income contribution will eventually greatly outstrip the home gardens grown by farms A and D. Since the avocados are not yet generating any income, however, it was impossible to calculate this differential and adjust the RI index accordingly.

Similarly, farm D was the only one to earn a score for RI 2, which is due to their agrotourism activities. While they have hosted friends, visitors, and educational tours on their farm for years, they only recently established a business plan for this segment of their on-farm activities. However, the COVID-19 global pandemic meant that in 2020 they have not had any income from tourism. If 2020 had been a more ‘normal’ year, then agrotourism could have accounted for some percentage of their income, to the extent that perhaps the weighted value of RI 2 should have been increased.

The most difficult RI to define was RI 3, due to the fact that cultivating several coffee varieties has value only insofar as the varieties themselves are actually ‘climate resilient’. In order to assign appropriate values to the components of this RI it would have been necessary to construct a separate RI index for all varieties of *C. arabica* which are cultivated on these farms, accounting for a constellation of interrelated factors. This would certainly be a valuable addition to this research - and the WCR’s

Global Catalog of Coffee Varieties contains many of the necessary data points - but was outside the scope of the current project.

Despite the fact that all four farmers answered the same questionnaire, there was considerable variability in the amount of detail which they included in their answers. Also, some responses were missing, incomplete, or unclear. The process of communication back and forth was rather slow due to the many other obligations which these farmers have, and also including the time for translation into Spanish and back into English. The author was able to conduct a follow-up interview with farm D, but this was made possible by the fact that this farmer is comfortable speaking English, whereas some of the other farmers are not. Notably, farm C's responses regarding whether or not they have an irrigation system, and whether or not they have any non-agricultural on-farm income were difficult to discern, and if there was misunderstanding on the author's part, this would have had considerable impact on their RI score.

While most RIs depended on easily quantifiable data (e.g. RI 6 'do you have a wet mill?'), some depended on more interpretive data (e.g. RI 4 'what percentage of your coffee plots are shaded?'). RIs 4, 8, and 12 required more qualitative and observational data. Regarding RI 4, it would have been particularly helpful to have had observational data from farm A. The author has either visited or seen extensive video/photo documentation of farms B, C, and D, which puts them at an advantage in this regard. Perhaps the fruit trees which act as natural barriers around the coffee plots on farm A farm do confer some of the benefits of a coffee agroforestry system and perhaps not, but it was hard to tell based on the information provided. The use of shade in coffee farming is a complex phenomenon, and each farmer who uses shade had a different primary explanation for shade species selection (fast growing/wind protection; nitrogen fixation; shade provided). This RI was weighted slightly more due to the fact that all three farmers who use shade responded that as an adaptive response to climate change, shade had the greatest impact on their farms. This observation is affirmed by scientific research as an accessible, effective adaptation which boosts the climate resilience of coffee farmers (see section 3.6 Shade management).

In order to evaluate RI 8, the author used both personal observational data and information from a specialty coffee trading partner (Selva Coffee) in order to ascertain the family structure and the roles of the actual respondents since, for farms A and C the questionnaire was filled out by the son and daughter, respectively, of the primary farmer, and these respondents did not include themselves in the list of farm employees. The farm D response was filled out by the primary farmer himself, and the farm B response was filled out by the younger son of the primary farmer.

RI 9 was the most complex RI, and had the highest possible point value because it included three on-farm management systems (water, energy, waste). Regarding energy use, external data was used to enrich the farmers' responses by clarifying that the electrical grid in this region (the Pirris watershed) is primarily hydropowered (de Jesús Crespo et al 2020), so all four farms received 1 point for using energy from a renewable source (farm A specified that his electricity is from a wind-powered source (CoopeSantos), while farm B does not have electricity on his farm at all). Regarding water, farms B and C both use irrigation, while farms D and C are the only two farms who use water in coffee processing. Perhaps in part due to the fact that he does not have easy access to a natural source of freshwater in his coffee plots (RI 10), farm B seems to have the most efficient water management system, and he also received the highest score overall for RI 9 (4/5, including ½ point for the planned addition of solar panels).

RI 11 was intended to be a relatively straight-forward quantitative data point, and it was expected that all respondents would simply name their weather source of choice. However, in the interview farm D stated that he bases most of his weather-dependent decisions on observation rather than following a weather report, due to the fact that the mountainous terrain in Tarrazu creates a patchwork of microclimate zones. Accordingly, his daily observations from the highest point of his farm (2100 masl) where he has been farming coffee for nearly 40 years have proven more helpful to him when he needs to decide whether to pick coffee, apply fertilizer or pesticides, etc. based on the weather. farm C later mentioned a similar practice ('daily weather visualization'), and presumably the other respondents also make these types of observations which have an impact on their decision-making process - perhaps even more than official weather forecasting data. Unfortunately the question was not composed with enough nuance to include these details.

RI 12 was the most subjective measure, and was accordingly given a lower value to minimize possible skewing of the results. It was important, however, to account for the fact that all four farmers made remarks about future changes which they would like to implement in response to perceived climate risks. These comments illuminated the priorities and perceived strengths and weaknesses (or lack thereof) which each farmer sees in his own farm:

- Farm A is not concerned about his farm's climate resilience due to the performance of the coffee varieties which he grows (predominantly Red Catuaí), and he is interested in continuing the reforestation efforts which were begun 3 years ago on his farm (RI 12: 0.5/1.5).

Farm A was assigned a lower score because his lack of concern was based on the performance of a cultivar which has, according to WCR's Variety Catalog, 'very high susceptibility' to CLR, Coffee Berry Disease, and nematodes (WCR 2020b). Also, presumably the reforestation efforts are not integrated with coffee production as he doesn't mention shade management practices.

- Farm B is concerned about resilience and wants to improve the efficiency of his irrigation system in response, as well as diversifying the farm's income with avocado sales and continuing to improve their use of shade to reduce the impact of extreme temperatures and winds at their high-altitude farm (RI 12: 1.5/1.5)

Farm B received a full score for this RI because the adaptations which he is making seem to be clearly aligned with climate change projections and his efforts towards increasing income diversity will buffer the impact of coffee-related losses/challenges if and when they occur.

- Farm C is concerned with his farm's resilience to climate change, and his response so far has included shade management, timely applications of fertilizers and pesticides, and investment into their farm's roasted coffee brand, while in the future he would like to hire a full-time agronomist for constant advice (RI 12: 0.5/1.5).

Farm C received a lower score because, despite having responded to climate changes so far with improved precision in production practices, his plan to hire a full-time agricultural engineer is not a resilience-focused response.

- Farm D is concerned about resilience and he is very interested in reducing chemical use on his farm and eventually having organic or 'half-organic' production, as well as diversifying income through agrotourism (RI 12: 1.5/1.5)

Farm D received a full score because the adaptations which he is making/wants to make are, like farm B, aligned with climate change projections (management of shade, soil, and pests and diseases), and his plans for agrotourism demonstrate a flexible, forward-thinking approach which will contribute to income diversification, and is completely compatible with existing farm activities. Incidentally, farm D also received the highest RI index score overall (22.5/30).

One important consideration is the fact that, even among these 4 farmers who have - relatively speaking - so much in common, there is a high level of variability in terms of land ownership (inherited affluence), land position and elevation, access to freshwater resources (RI 10), and family structure/interest from the younger generations (RI 8). Many of these variables are static or are outside of the farmers' control, and it was difficult to define the RI Index in light of this tension between choices of production practice and fixed farm characteristics. For instance, farm B is making impressive adaptive efforts to observed climate changes, including establishing an avocado plantation to diversify on-farm income, installing solar panels, collaborating with other farmers to use their wet mill and/or drying facilities, experimenting with coffee varieties, using mostly no-water coffee processing styles, using biocontrol methods like *Tricoderma*, using irrigation in young coffee plots, and prioritizing a highly biodiverse coffee agroforestry system. Farm B farm is also by far the largest (100 ha), but cultivates just 20 ha of coffee. They produce about 13% of what is produced by farm C in a similar cultivated area due to farm B’s low-yielding high-quality primary cultivar, Geisha.

Farm C, by contrast, uses most of their land for coffee cultivation (84% of their 25 ha are coffee), and produced 1200 fanegas of coffee in 2019/2020. Most of their production practices are fairly traditional and conservative, with a focus on maximizing yields. They are hesitant to use shade from fruit trees as this reduces coffee yield and can increase the incidence of pests and diseases, and grow mostly Caturra and Catuaí. They have freshwater springs in most of their coffee plots (unlike farm B). They also have complete ownership of their coffee processing technology, including wet and dry mills and in this regard they were unique among the farms surveyed. Yet despite the many differences between farms B and C, especially their very different priorities, production practices and general willingness to innovate, their final RI scores were identical. This suggests that while developing “human capital” through adaptive decision-making and innovations (OECD 2020) has apparent value, financial capital (particularly asset ownership) obviously enables resilience-building at least in the short- to medium-term.

It would be interesting to expand this research in order to more fully account for the potential synergies between adaptation and mitigation techniques employed (Rahn et al 2013), and how these impact and are impacted by various forms of capital (financial, social, intellectual, human, natural etc.). For instance, a relevant RI would be to account for the natural capital of carbon stocks held on each farm (notably farm B which is 65% forest), and where applicable to weight each RI more precisely based on its carbon offset or output.

10. Conclusion

Overall, the goal of diversification is to stabilize farm income and increase the resilience of coffee farmers by reducing their exposure to any single type of risk. This is not a new strategy for Central American coffee farmers, as diversification has been a response to coffee price crises in the past[13] but the particularities of *how and where to diversify* are complex and hyperlocal. The future of coffee is highly uncertain and it is an enormous challenge for farmers to plan for such a future. Mitigation is, of course, the bedrock of any long term response to climate change, but for the millions of small farmers who are growing coffee right now adaptive techniques that will bolster resilience for the farm and household economies are also essential.

- The use of climate-resilient cultivars is one of the most important adaptations which farmers can use, especially because it is a medium- to long-term solution.

[13] In the 1980s during a coffee price decline Costa Rica considered alternative crops such as macadamia nuts, flowers, and forestry (Varangis et al 2003)

- The use of shade is an accessible, effective adaptation - all three farmers who use shade noted that it has so far been the most effective adaptation measure they have so far employed.
- Income diversity is another way for coffee farmers to reduce their vulnerability to climate risk, and can be compatible with current farming activities whether or not the income source is agriculturally-based.
- Maximizing the efficiency of management systems (water, waste, energy) is both an adaptation and mitigation measure. It is a way to reduce inputs - notably of water and fertilizer - and simultaneously reduce GHG emissions.

The RI Index developed in this research provides a method of evaluating the level of climate resilience on a coffee farm. Within this index various types of diversification measures served as a partial proxy for climate resilience because in such a short-term study of just four farms it is difficult to identify trends and to know how these farms will manage in the face of climate change risks over the long term. If the farmer questionnaire was filled out each year over several consecutive years then it would begin to demonstrate trends and become a more valuable climate response tool. Even so, the scientific literature confirms that diversification boosts climate resilience.Yet while it is true that coffee farmers should not just be farming coffee, diversification alone does not assure climate resilience.

Through communication with these four farmers it became clear that a key attribute of climate resilience also has to do with ingenuity and entrepreneurship. Farmers who are able to innovate, take risks, and work collaboratively in the midst of a rapidly changing business and natural environment also seem more likely to make decisions which will lead to increased climate resilience for the long term. Farms B and D had relatively high scores in the RI Index, and incidentally they also seemed most responsive to changes in their ecosystems, to farm managerial requirements and to global trading conditions. In order to develop sustainable resilience that will allow these farms to survive for the following generations, they must not confine themselves to the traditional methods and structures which dominate coffee production in their area. Whether or not this can be done and the extent to which this can be done is therefore an underlying factor of climate resilience.

11. Appendices

11.1. Appendix A: **Table 1 Characteristics of Case Study Farms**

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