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Ecological resilience to coffee rust: Varietal adaptations of coffee farmers in Copán, Honduras

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ABSTRACT

Coffee leaf rust (CLR) attacked Central American coffee farms during the post-2011 epidemic, driving production loss across the region. In response, smallholders are adapting agroecological and conventional practices. We compare varietal adaptations of small conventional and organic farmers in Copán, Honduras. We show farmers are growing a greater diversity of varieties after the outbreak. Both groups increased acreage of CLR-resistant varieties; however, our data suggests organic farmers maintained greater acreage of CLR-susceptible varieties than conventional farmers. These results have important consequences for the specialty market, fungicide use, and management. Understanding farmers' adaptive logic will be critical for aid and policy.

KEYWORDS

Agroecology; coffee; coffee leaf rust; farmer adaptation; genetic diversity; Honduras

Introduction

Agro-ecological resilience is increasingly important for small-scale farmers, particularly those in the tropics whose livelihoods are ecologically and socially most vulnerable to climate change (Altieri et al. 2015, Morton 2007). Climate change is expected to exacerbate the pest and pathogen pressures farmers face, necessitating better understanding of farmers' adaptations in order to best promote resilience-building efforts.

Biodiversity is a pillar of agroecological farming; the management of functional biodiversity can improve soil quality, nutrient cycling, and pest and disease management and, by extension, increase yields (Altieri 1999; Gliessman 1990; Kremen, Iles, and Bacon 2012). Intra-specific genetic crop diversity is one component of agroecological management that has been shown to reduce crop vulnerability to pests and diseases (Cruz et al. 2003; Finckh 2008; Hajjar, Jarvis, and Gemmill-Herren 2008; Johnson, Lajeunesse, and Agrawal 2006; Mundt 2002; Ngugi et al. 2001; Ratnadass et al. 2012; Smithson and Lenne 1996; Wolfe and Finckh 1997; Zhu et al. 2000). This

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improved disease control can be realized through increased distance between susceptible varieties, compatible host plants, and disease inoculum. Chemical and genetic differences between varieties may produce different types of resistance defense traits, like induced resistance, that may also contribute to disease suppression (Finckh 2008; Zhu et al. 2000).

However, it is often unknown how small farmers will adopt varietal diversity in crops; although best management practices may be within reach, farmer knowledge and perceptions of climatic, institutional, and socio-economic factors influence the feasibility of beneficial genetic management (Wood and Lenne 1997).

In this paper, we observe small farmers' varietal adaptations to the post-2011 coffee leaf rust (CLR) outbreak. Smallholders—who in Honduras produce 94% of the nation's coffee—will play a large role in shaping the changing diversity of coffee varieties (USDA—FAS 2016). The rate and extent of the adoption of new CLR-resistant varieties, and subsequent changes in the landscape composition of coffee diversity, will be determinant for the larger management challenges farmers face regarding pests and pathogens (Avelino et al. 2015; McCook and Vandermeer 2015; Van der Vossen 2009).

Farmers' varietal choices must balance ecological pressures with market pressures. The specialty and eco-certified market's preference for high-quality CLR-susceptible coffee varieties may incentivize organic farmers to maintain these varieties, increasing their vulnerability to CLR. We test for changes in coffee cultivar diversity between 2012 and 2015, for differences in variety adoption between organic and conventional farmers, and discuss the corresponding farmer perceptions of coffee variety change.

Background

The post-2011 coffee leaf rust epidemic infected 80,000 hectares (ha) of CLR-susceptible *C. arabica* coffee stands in Honduras. The Honduran National Institute of Coffee (IHCAFE) estimates that over 30,000 farmers lost more than half of their harvest and that 10,000 of these suffered complete losses. Smallholders are both a vulnerable and important population; they account for 84% of the registered coffee producers in the country, and their role in the coffee sector in turn supports the socio-economic stability of 1.2 million people employed by coffee-related activities (USDA—FAS 2012). Addressing CLR has become a high priority for growers, buyers, and researchers, many of whom promote CLR-resistant varieties as the most effective way to reduce CLR.

The coffee rust fungus, *Hemelia vasatrix*, primarily attacks *C. arabica* coffee varieties, which produce high-quality coffee beverages preferred by the specialty coffee market. The fungus appears first as yellow lesions on the undersides of leaves, which develop into distinctive orange uredospores, in effect "rusting" the leaves. The infection causes defoliation, which in later stages of the disease leads to severe crop loss when damaged or dead branches drop unripe coffee berries. Growers incur secondary losses when CLR-damaged coffee branches fail to produce the following year. Susceptibility to CLR is also determined by plant age and plant health; the ability of younger and well-nourished plants to regenerate foliage allows them to recover leaves lost to CLR, thereby decreasing both primary and secondary losses. Older and poorly nourished coffee stands, with lower growth rates, are more susceptible to CLR for this reason (Avelino et al. 2006).

Robusta coffee, *C. canephora*, offers genetic resistance to CLR but with significantly reduced beverage quality. The Timor Hybrid (a spontaneous cross between C. canephora and C. arabica) has been used to develop new introgressed coffee varieties that aim to capture both the CLR-resistance of the Timor Hybrid and the beverage quality of *C. arabica*. The Catimors are one such family of cultivars, a cross between the *C. arabica* dwarf variety Caturra and the Timor Hybrid. Local Catimors were developed in the 1970s and 80s and released by agricultural ministries across Central America (including Ihcafe-90 and Lempira in Honduras). However, they have not been widely promoted by agricultural ministries due to skepticism of the beverage quality offered by these "Arbusta" genotypes. Until the CLR outbreak, farmers still relied heavily on *C. arabica* cultivation, which comprised roughly 80% of Central American coffee stands in 2012 (Van der Vossen 2009).

In the wake of the CLR epidemic, farmers must replace diseased coffee stands. Their choices regarding cultivar adaptation should be understood in the context of 1) climatic factors, which determine the ecological vulnerability of coffee stands to both CLR and other disease pressures, 2) socio-economic factors, which influence farmers' investment choices and the market pressures they face, and 3) institutional factors, which serve to inform farmers' choices and provide access to newly developed varieties.

Climatic factors

Climate change plays an increasingly important role in the intensity of pest and pathogen pressures in coffee systems. Prior to the post-2011 CLR epidemic farmers considered small losses to CLR normal and expected. Present in the region since the 1970s, CLR has been largely controlled by improved fertilization and fungicide use and has been limited by the protectively cool temperatures above 1000–1100 meters above sea level (masl) (Avelino et al. 1991, 2006). CLR was not problematic above 1000 masl until the post-2011 epidemic, when CLR infestations of equal intensity were observed from 400 to 1400 masl (Avelino et al. 2015).

This change highlights the role climate has played in the CLR outbreak and will play in the future. Warmer temperatures are expanding the range of CLR to higher altitudes. Ghini et al. (2011) observe that warmer minimum temperatures contribute to a reduction in diurnal range, thus reducing the latency period for CLR and increasing epidemic intensity. Reduction in diurnal range is a key and consistent factor preceding CLR epidemics (Avelino et al. 2015). The increase in minimum winter temperatures and changes in precipitation patterns are consistent with the projected climate change scenarios for Central America. The recorded changes suggest that climate's role in the post-2011 CLR outbreak was not an anomaly but a warning of the impact of progressive climate change in coffee systems (Aguilar et al. 2005; Biasutti et al. 2012).

C. arabica coffee specifically has been called "unsustainable" in expected climate change scenarios, cited for its sensitivity to temperature (warmer temperatures increase the ideal altitude for *C. arabica* cultivation) and high susceptibility to pathogens including CLR and coffee berry borer (Jaramillo et al. 2011; Van der Vossen, Bertrand, and Charrier 2015). The characteristically low genetic diversity within *C. arabica* species cultivars is compounded by the local reliance on a few preferred varieties. Coffee production in the western region of Honduras (the location of this study) primarily produces Caturra and Catuai, dwarf *C. arabica* varieties with similar genetic susceptibility to pests and pathogens, which will be exacerbated by climate pressures (Bertrand et al. 1999; IHCAFE 2013). While improved management can fortify plant health to decrease susceptibility, the Earth's warming climate may make such a response untenable.

Socio-economic factors

Financial restrictions, particularly difficulty accessing credit, impede farmers' ability to invest in farm management (fertilizers, composts, fungicides, etc.) and in cultivar renewal. This can cause plants to weaken and thus increases their susceptibility to CLR. Interestingly, an international drop in coffee prices has preceded all CLR outbreaks in South and Central America, likely because lower profits for smallholders are tied to the reduced investment in farm management, and therefore increased plant susceptibility to CLR (Avelino et al. 2015). Increased pest, disease, and climatic pressures require greater investment in inputs to support the health of coffee stands (particularly of *C. arabica*) and, therefore, increased production costs for farmers.

Variety renewal is likewise restricted by available credit; renewal requires financing not only for replanting but also for the lag time of 2–3 years before coffee trees mature to produce fruit. Consequently, variety renewal has been slow; at the onset of the CLR crisis, Honduran agricultural ministries reported 42% of coffee stands were older than 20 years, while in neighboring Central American countries, a quarter of coffee stands had passed this age (Avelino et al. 2015; Insituto Hondureño del Café (IHCAFE) 2013). This, in part, explains the severity of the post-2011 CLR outbreak and present need for cultivar renewal.

Despite the susceptibility of *C. arabica* to CLR and its greater production costs, the growing specialty and eco-certified markets financially incentivize the production of high-quality *C. arabica* coffee with higher premiums for certified farmers (Bacon 2005). Although post-harvest processing, roasting, and preparation affect cup quality, *C. arabica* varieties are still widely preferred to Catimor hybrids, which carry a stigma for buyers (Barel 1994; Carvalho 1988; ICO 2014; Moschetto et al. 1996; Van der Vossen 2009). Certifications like Fair Trade (FLO), Fair Trade/Organic (FLO/ORG), Utz Certified, and Rainforest Alliance (RFA) require adherence to a set of ecologically or socially sustainable practices that may prove agro-ecologically and/or socially beneficial in some respects but that promote the specialty market's preferences for *C. arabica* coffee varieties, perpetuating the CLR-susceptibility of a narrow range of genetic diversity in coffee stands.

Institutional factors

National responses to the CLR crisis in Central America initially focused on providing aid to small farmers in fungicide (with the intent of preventing a second outbreak the following year), while long-term planning has focused on the promotion of CLR-resistant hybrid varieties. The mid- to long-term regional action plan coordinated under PROMECAFE (the Regional Cooperative Program for the Technological Development and Modernization of Coffee Cultivation) proposes combating CLR through the production and distribution of CLR-resistant materials and renewal of old and susceptible coffee stands. The plan also calls for a new regional breeding program, early warning system, and improvements in extension services but nevertheless reflects the general consensus among researchers and coffee experts that cultivar renewal with genetic CLR-resistance is the best long-term solution for the coffee sector.

In Honduras, education about hybrid coffee varieties and sales of hybrid seeds are primarily conducted through the Honduran National Institute of Coffee (IHCAFE). IHCAFE research centers developed local CLR-resistant Catimor varieties, including Lempira and Ihcafe-90, which are now widely promoted for cultivar renewal (Insituto Hondureño del Café (IHCAFE) 2013; USDA—FAS 2014). However, CLR resistance is by no means permanent. Hybrid cultivars lose resistance with time, suggesting that CLR can evolve to degrade genetic resistance (Rodrigues et al. 2000). In Columbia, large-scale renewal of coffee farms with the multi-line variety Colombia has mixed coffee genotypes with differing resistance to five strains of the fungus. This was effective in reducing CLR presence but over time has lost partial, and in some cases complete, resistance to CLR (Alvarado and Moreno 2005).

Continued degradation of CLR-resistance and climate-induced increases in pest and pathogen pressures will persist in these hybrid varieties. The neglect of genetic diversity—for example, in new hybrid monocultures—can perpetuate genetic vulnerability, creating a situation analogous to the vulnerability of *C. arabica* to CLR in in the post-2011 outbreak. If managed agroecologically, the inclusion of genetic diversity in cultivar renewal could reduce coffee susceptibility to CLR and other pest and disease pressures amplified by climate change.

Farmer motivations for coffee variety adaptation may be mediated by combinations of these factors: 1) climate change and ecological susceptibility to CLR, 2) access to credit for replanting and inputs and/or access to credit to mitigate increased production costs of *C. arabica*, 3) specialty and eco-certified market pressures, and 4) farmer knowledge, access to, and perception of varieties. Small farmers' decisions regarding future variety compositions will have consequences for the landscape composition of genetic diversity—and therefore vulnerability or resistance—to CLR as well as other pest and pathogens. In this paper, we observe the coffee varietal adaptations of small organic and conventional coffee farmers to the post-2011 CLR outbreak by documenting the changes in coffee cultivar diversity between 2012 and 2016 and recording the corresponding farmer perceptions of coffee variety change.

Methods

We observed small organic and conventional coffee farmers' variety adaptations to the post-2011 CLR outbreak in Copán, Honduras. Fieldwork was conducted over the course of 8 weeks during the summer of 2015. Six organic and four conventional farmers were interviewed in the municipality of Copán Ruinas (14°49′59.99″ N −89°08′60.00″ W) and four organic and six conventional farms in the municipality of Santa Rita (15°10′0.01″ N −87° 16′59.99″ W) for a total of 10 organic and 10 conventional participant farmers (Table 1). We analyze the changes in diversity, proportion of CLR-susceptible coffee varieties, and variety composition and discuss the perceived quality of the coffee varieties cultivated within this sample.

Farmers were contacted through two coffee cooperatives, CAFEL and COAPROCL, IHCAFE workshops, and farmer recommendations. Distance,

Table 1. Location, management, and average size (ha) of participating coffee farmers.

Municipality	Organic	Conventional	Average size (ha) 2012 2015	Altitude range (m)	Latitude (degrees)	Longitude (degrees)
Copán Ruinas	6	4	4.68 4.75	950–1400	14.93	−89.15
Santa Rita	4	6	5.38 3.9	1200–1500	14.86	−89.09

lack of infrastructure, safety concerns in rural areas, and time constraints prevented a completely random sample. Within the department of Copán, 20 small coffee farmers from the adjacent municipalities of Santa Rita and Copán Ruinas were interviewed. All of the farmers interviewed cultivated shade-grown coffee and categorized themselves as "small" growers, cultivating on average 0.7 hectares (ha) of coffee.

Roughly 90% of the growers in the region are defined as "small" growers, farming fewer than 14 hectares. This proportion is analogous to the national proportion of small growers—94% of the nation's 102,000 registered growers are smallholders (USDA—FAS 2016). The main varieties of Arabica coffee grown in the western region are Caturra, Catimor, Villa Sarchi, Catuai and Bourbon. The Robusta hybrid varieties grown are Lempira, Ihcafe-90, Icatu, Obata, Parainema, Revoltijo, Cuba, Sarchimor, and Paisano. Coffee growers in the department of Copán primarily produce shade grown coffee, with production altitudes ranging between 900 and 1300 meters (IHCAFE 2009). Farmers typically cultivate maize and beans in addition to coffee, but in recent years drought has threatened subsistence farming and increased dependence on revenue from coffee sales to sustain farmer livelihoods.

Surveys were used to collect data of the amounts of coffee varieties farmers were cultivating in pre-CLR in 2012 and post-CLR in 2015 (Tables 2 and 3). On some occasions, farmers did not know the specific variety name but classified a variety according to its family (e.g., Catimor). Semi-structured interviews opened discussion with farmers about their reaction to the CLR in 2012, perception of coffee varieties, and motivations for replanting or maintaining coffee varieties.

All participant organic farmers held affiliation with Fair Trade cooperatives. Both of the cooperatives participating in this study were formed in the wake of the coffee price crisis, in 1999 and 2000, and both completed the 3-year transi-

Table 2. Average quantities of *C. arabica* varieties in hectares (ha) among conventional and organic farmers.

		Caturra	Catuaí Amarillo	Catuaí	Villa Sarchí
2012	Org	1.89	0.56	1.64	0.07
	Conv	1.33	0.07	0.21	0.0
2015	Org	0.21	0.49	0.59	0.07
	Conv	0.17	0.03	0.0	0.0

Table 3. Average quantities of hybrid varieties in hectares (ha) among conventional and organic farmers.

		Catimor	Lempira	IHCAFE90	Icatu	Obata	Paisano	Cuba	Revoltijo	Sarchimor	Parainema
2012	Org	0.0	0.31	0.03	0.42	0.0	0.03	0.0	0.0	0.0	0.35
	Con.	0.35	1.89	0.63	0.0	0.35	0.0	0.0	0.0	0.0	0.0
2015	Org	0.0	1.38	0.03	0.56	0.19	0.03	0.0	0.03	0.03	0.35
	Con.	0.35	2.62	.94	0.0	0.42	0.0	0.07	0.0	0.0	0.07

tion to gain organic certification of their coffee. The cooperative COAPROCL reports 44 affiliated members growing certified organic coffee. CAFEL reported 260 affiliated growers, 60 of which cultivate certified organic coffee.

Fair Trade cooperatives typically hold additional partnerships with non-profit, religious, and government organizations, which provide resources, farmer-to-farmer partnerships, and technical aid to farmers. The cooperatives participating in this study employed agronomists and coordinators who assist the management and export of coffee. Some cooperatives, like COAPROCL, have formed long-term relationships with roasters through the Fair Trade network. Others, like CAFEL, sell to a wider range of coffee buyers.

Conventional farmers held affiliation with the National Honduran Institute of Coffee, IHCAFE, which offers workshops, varying degrees of technical assistance, and other forms of aid. Small conventional farmers generally sell to IHCAFE, and an unknown number of farmers sell contraband coffee to nearby Guatemala, where prices are higher.

To understand how the CLR outbreak (pre- and post-outbreak) and farm type (organic and conventional) impacted farmer's coffee varieties, we used generalized linear mixed effects models (GLMM) to model the response variables: proportion of susceptible varieties, variety richness, and variety diversity. Within each GLMM, farm type and CLR outbreak were included as fixed effects in addition to an interaction between terms. We also included farm site and farm region as random effects in the models to account for variation across regions and to pair pre- and post-outbreak responses within a farm.

The proportion of susceptible varieties was modeled with a binomial distribution, variety richness was modeled with a Poisson distribution, and variety diversity was modeled with a Gaussian distribution using the functions GLMER and LMER in the LMR4 package in the program R. We used Akaike Information Criterion (AIC) to compare models and identify important independent variables and interactions under a model selection framework (Burnham and Anderson 2002). We tested for normality using Kolmogorov-Smirnov tests of model residuals.

To examine the differences in variety composition across farm type and CLR outbreak, we used a nonmetric multidimensional scaling (NMDS) and analysis of similarity (ANOSIM) in the package Vegan in the program R to visually and statistically compare variety composition. For both analyses, we considered each farm as a replicate and used a Bray-Curtis similarity index to compare the composition of acreage of different coffee varieties within farms. The ANOSIM produces a global p-value that indicates differences in varietal composition. We used one ANOSIM test to compare how organic and conventional farms differed in variety composition. We used a second ANOSIM comparison to determine how variety composition differed across 2012 and 2015 (pre- and post-CLR outbreak). All statistical analyses were conducted in the program R 3.2.0.

Results

In total, coffee farmers grew 13 different varieties of coffee. The Catuaí variety was the most commonly grown prior to the outbreak, followed by Caturra and Lempira. In 2015, after the outbreak, Lempira and Ihcafe-90 were most common. Farmers considered four varieties, Catuaí, Caturra, Caturra Amarillo, and Villa Sarchí susceptible to CLR, while the remaining varieties were considered resistant (Tables 2 and 3).

We found that farmers are indeed altering the diversity and composition of Honduran coffee varieties. The richness of coffee varieties did not vary across organic and conventional farms or across the pre- (2012) and post- (2015) CLR outbreak (Table 4; Figure 1). However, our statistical models show that farmers increased the diversity of coffee varieties planted after the CLR outbreak by 53%

Table 4. Generalized linear mixed models comparing variety richness, variety diversity, and the proportion of susceptible varieties in organic and conventional coffee farms pre- and post-rust outbreak.

	Est±SE	z Value	*P*
Variety richness			
Intercept	0.6871 ± 0.2053	3.347	0.000817
Farm type	0.08685 ± 0.2111	0.411	0.680754
Rust outbreak	0.19416 ± 0.20818	0.933	0.351009
Variety diversity			
Intercept	0.4259 ± 0.1661	2.564	0.0431
Farm type	0.0525 ± 0.1709	0.307	0.7623
Rust outbreak	0.2497 ± 0.1035	2.412	0.0261
Prop. susceptible			
Intercept	−1.3901 ± 0.3603	−3.858	0.000115
Farm type	1.1331 ± 0.4568	2.48	0.013125
Rust outbreak	−1.1798 ± 0.2965	−3.98	6.90E-05

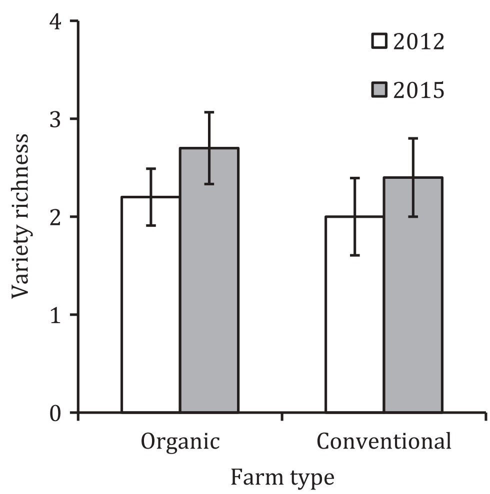

Figure 1. Coffee variety richness in organic and conventional farms in 2012 and 2015.

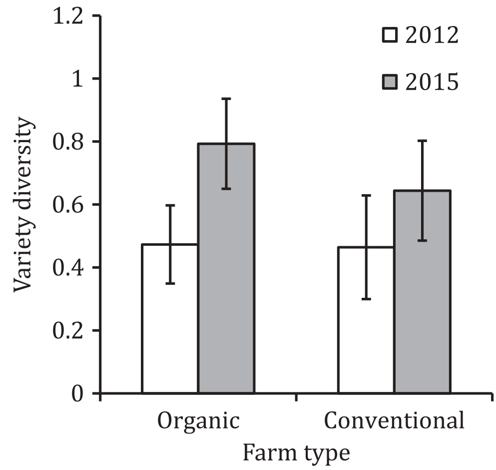

Figure 2. Coffee variety diversity in organic and conventional farms in 2012 and 2015.

compared to pre-CLR outbreak levels (Table 4; Figure 2). There was no statistical difference in the diversity of varieties planted in organic and conventional coffee farms. Further, there was no significant interaction between CLR outbreak and farm type; the interaction term did not improve model fit and was removed from the best-fit model.

Given the agroecological importance of diversity for reducing crop vulnerability, the genetic diversity within CLR-resistant and CLR-susceptible coffee varieties may benefit pest and disease management. Our data show that farmers cultivated 184% more acreage of susceptible varieties pre-CLR outbreak relative to post-CLR outbreak (Table 4; Figure 3). In 2012, 65% of fields were composed of susceptible varieties compared to

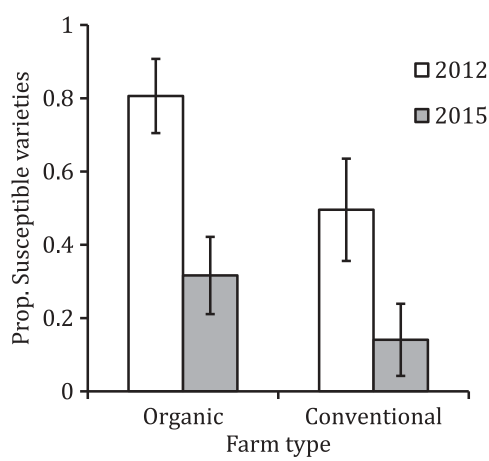

Figure 3. Proportion of rust-susceptible coffee varieties in organic and conventional farms in 2012 and 2015.

only 25% in 2015 (Figure 3). Interestingly, across both 2012 and 2015, organic farmers cultivated 76% more acreage in susceptible varieties than did conventional farmers (Table 4; Figure 3). Organic farmers cultivated an average of 56% of their acreage with susceptible varieties, while conventional farmers averaged 32% (Figure 3). Organic farmers decreased acreage of susceptible varieties from 81% in 2012 to only 32% in 2015, while conventional farmers decreased acreage from 50% in 2012 to 15% in 2015 (Figure 3). However, there was no statistical difference in the response of organic and conventional farmers to the CLR outbreak; the interaction term was not statistically significant, did not improve model fit, and was removed from the best-fit model.

The overall composition of coffee varieties on organic and conventional farms differed between 2012 and 2015. The ANOSIM models show that variety composition of organic farms was more similar to other organic farms than it was to conventional farms (ANOSIM R = 0.1249, $P = 0.007$). Similarly, the variety composition of farms in 2012 was more similar to other farms in 2012 than it was to farms in 2015 (ANOSIM R 0.1112, $P = 0.009$). Figure 4 shows the NMDS plot with ellipses representing the

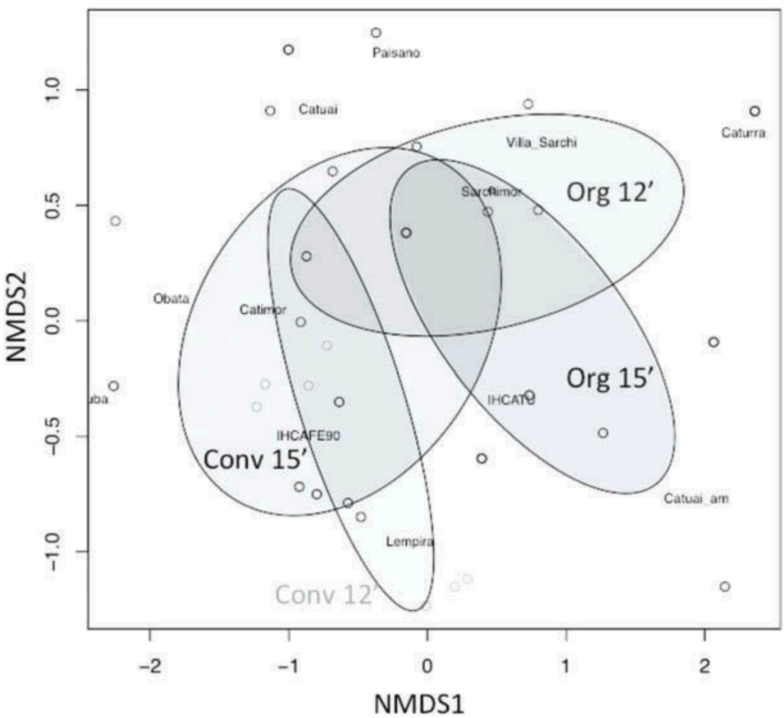

Figure 4. Composition of coffee varieties in organic and conventional farms in 2012 and 2015.

standard deviation in composition for organic versus conventional farms (Stress = 0.1165).

Discussion

In all cases, coffee growers adopted CLR-resistant hybrid coffee varieties in response to the post-2011 CLR epidemic. Our results show this did increase the genetic diversity of coffee cultivars but may not indicate intentional management of genetic diversity. Rather, it may reflect a temporary increase in diversity as farmers transition to hybrid cultivation over the course of several years.

Farmers were well aware of the vulnerability of commonly grown *C. arabica* varieties Caturra and Catuaí to CLR, which was expressed through both interview responses and the adoption of hybrid varieties—all cultivars planted between 2012 and 2015 were CLR-resistant hybrid varieties. However, farmer perceptions of cultivar diversity varied. Some denounced all non-hybrid *C. arabica* production, which to them represented the continued presence of CLR, and therefore continual degradation of CLR resistance in hybrid varieties. Other growers expressed concern that coffee cultivation had simply shifted from Caturra and Catuaí toward the two most common CLR-resistant varieties, Lempira and Ihcafe-90. As one organic grower noted, "*What they did was just leave Caturra, leave the coffee that gets this disease, and change to another*" (translation by author). In other words, farmers worried that the continued reliance on a small number of varieties would maintain the same narrow range of diversity that brought a CLR crisis of such severity.

Both of these attitudes—concern for degradation of CLR resistance and concern for the vulnerability to pest and disease outbreaks—point to the lack of resilience through cultivar diversity. Lempira and the rest of the Catimor progeny will likely lose CLR-resistance over time, just as the multi-line variety hybrid variety Colombia, released in 1981, which lost resistance to CLR in the early 2000s (Alvarado and Moreno 2005).

This threat may already be manifest; reports from end of the 2016 growing season warn that a new and more aggressive strain of CLR has overcome the CLR resistance of common hybrid varieties Lempira, Ihcafe-90, and Parainema in Honduras (La Prensa 2017). Although the consequences of this CLR strain remain to be seen, the report is evidence of the rapid evolution of CLR and the need for resistance through greater genetic diversity. If the strain proves to be as virulent as reports claims, it could incite a CLR epidemic precisely in the hybrid varieties farmers adopted to avoid it.

Multi-line varieties like Colombia and Castillo, which strengthen genetic resistance to CLR though mixed combinations of resistance genes, can slow, but not prevent, the evolution of CLR strains to overcome resistance (Alvarado, Posada, and Cortina 2013). The eventual loss of resistance jeopardizes harvests and livelihoods of coffee farmers, particularly if one preferred hybrid variety is adopted on a large scale. Additionally, hybrid varieties prioritize CLR resistance over other characteristics, such as drought tolerance, which may incite deeper vulnerability in the face of future climatic or ecological shocks. One suggested alternative is a cultivation of mixed varieties, with partial and complete resilience, but this has not yet been explored as a possibility on a large scale (McDonald and Linde 2002).

Organic and conventional growers both reduced their acreage of CLR-susceptible varieties; however, the composition and proportion of CLR-susceptible Arabica varieties differed between organic and conventional growers, suggesting a difference in adaptive logic and strategies. Organic growers cultivated a larger proportion of susceptible varieties, which could suggest more diverse resistance to CLR, or reflect a longer transition period to replace *C. arabica* cultivars. In fact, organic farmers did discuss the importance of nutrition for plant resilience to disease, crediting improved plant nutrition with comparative resistance to CLR. As Avelino et al. (2006) demonstrate, there is clear correlation between CLR intensity and soil nutrition, which plays a critical but understated role in the resistance or susceptibility to pests and diseases (Altieri and Nicholls 2003). However, this is not how farmers explained their decisions concerning varietal change. Rather, discussion with farmers suggested that the primary motivation to continue growing *C. arabica* varieties is high beverage quality of Arabica coffee.

Quality has become a point of pride for Honduran coffee producers, particularly organic producers, who have recently earned international acclaim for high scoring coffee. As Bacon (2005) notes, nearly all eco-labeled coffee is also considered specialty coffee. The Honduran National Institute of Coffee, IHCAFE, has played a key role in the development of Honduran high-quality coffee standards. In 2004, the institute held the first "Cup of Excellence" competition, in which Honduran coffee gained international recognition for its high quality. IHCAFE has also delineated six distinct coffee regions in Honduras and marketed distinct qualities to niche markets. Although the number of specialty coffee growers is increasing, it is relatively small, making up 26% of exports for the 2013–14 season (IHCAFE 2013).

Quality is not only a matter of pride but of livelihood sustainability. Organic farmers seek to offset the increased costs of organic production with higher premiums, which rely on forging and maintaining relationships with specialty buyers. The importance of coffee quality to the specialty market is important for this discussion in two ways; first, coffee growers catering to specialty coffee buyers have added incentive to continue cultivating high-quality *C. arabica* varieties. Second, should the trends toward replacement of *C. arabica* with lower-quality hybrid varieties continue, Honduran coffee quality in general may decline, thus affecting the specialty markets promotion of Honduran coffee.

C. arabica coffee consistently receives the highest quality scores, although as Van der Vossen (2009) notes, high quality is not out of reach for hybrid varieties. Good management and processing can produce high quality in hybrid varieties on par with traditional *C. arabica* varieites. For example, a small study comparing the cupping scores of Castillo and Caturra shows no statistically significant difference between the blind tasting cup quality scores (Sheridan 2015). This study, like others, aims to shift the perception of hybrid coffee cultivars and represents one of the main challenges of coffee variety development—the perception within the specialty market must change to accept hybrid coffee quality as competitive with *C. arabica*.

The specialty market has become an important proponent of "sustainable" coffee through its affiliation with the social-justice and environmental goals of organic and fair trade certifications (Bacon 2010). Here, though, ecological sustainability has not been pursued in congruence with quality. The CLR outbreak continues to motivate farmers to renew coffee stands with new varieties and therefore offers an opportunity for resilience building in a crop that, by nature of its long production life, will be critical for farmers stability and resilience during the coming decades.

Developing strategies for the agroecological management of varietal diversity will be an important part of constructing agroecological varietal resistance to CLR as well as to the increasing disease and pest pressures expected with climate change. Coffee varieties show diversity in their strengths and vulnerabilities, demonstrated in the recently released catalog by World Coffee Research. Coffee varieties differ in tolerance and susceptibility to CLR, coffee berry disease, and nematodes (*Meloidogyne spp*. and/or *Pratylenchus spp*.), as well as cup quality potential and optimal production altitude (Coffee Varieties of Mesoamerica and the Caribbean 2016). Just as varieties have been interspersed to combat pest and pathogen spread in wheat, rice, and sorghum systems, similar strategies could be implemented in coffee systems for broad pest and pathogen resilience (Ngugi et al. 2001; Smithson and Lenne 1996; Zhu et al. 2000).

Conclusions

Changing climate arguably played the largest role in the post-2011 Central American CLR outbreak and will play an integral role in future pest and pathogen adaptations. Researchers have called the CLR outbreak a "warning" of the kind of pest and pathogens pressures that will become increasingly common as climate change progresses.

We show that farmers are growing a significantly greater diversity of coffee varieties after the CLR outbreak. Both groups increased acreage of CLR-resistant varieties; however, our data suggests organic farmers maintained greater acreage of CLR-susceptible varieties than conventional farmers.

The specialty and eco-certified market preference for high-quality CLR-susceptible coffee varieties may be a source of increased vulnerability for organic farmers. At the same time, new CLR strains attacking hybrid varieties may necessitate greater genetic diversity across both organic and conventional farmers to build CLR resistance. This is both a challenge and an opportunity for farmers to build agroecological resistance to CLR through genetic diversity, but they will be more successful if cooperative structures and specialty market buyers champion and incentivize agroecological practices and principles and, in doing so, align the demands of the specialty market with the best interest of farmers and future coffee production.

Increased genetic diversity may benefit pest and pathogen management beyond the current CLR crisis. However, intentional implementation of this strategy, and research exploring its potential, is needed. Cooperative structures and coffee institutions offer a powerful platform to improve coffee farmers' genetic resilience to attacks from pests and diseases through agroecological production of diverse coffee varieties. Especially in light of rapidly evolving CLR strains, future research is needed to study the benefits of genetic diversity in coffee cultivars, the co-benefits and synergies possible through specialty market incentives, and the ecological and market pressures driving farmers' adaptation decision.

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References

Aguilar, E., T. C. Peterson, P. Ramírez Obando, R. Frutos, J. A. Retana, M. Solera, J. Soley, et al. 2005. Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. *Journal of Geophysical Research: Atmospheres* 110 (D23). doi:10.1029/2005JD006119.

Altieri, M. A. 1999. The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment* 74:19–31. doi:10.1016/S0167-8809(99)00028-6.

Altieri, M. A., and C. I. Nicholls. 2003. Soil fertility management and insect pests: Harmonizing soil and plant health in agroecosystems. *Soil and Tillage Research* 72:203–11. doi:10.1016/S0167-1987(03)00089-8.

Altieri, M. A., C. I. Nicholls, A. Henao, and M. A. Lana. 2015. Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development* 35:869–90. doi:10.1007/s13593-015-0285-2.

Alvarado, G., and L. G. Moreno. 2005. Cambio de la virulencia de Hemileia vastatrix en progenies de Caturra × Hibrido de Timor. *Cenicafe* 56:110–126

Alvarado, G., H. E. Posada, and H. A. Cortina. 2013. *Castillo: Nueva variedad de café con resistencia a la roya.*

Avelino, J., R. A. Muller, C. Cilas, and H. Velasco Pascual. 1991. Development and behavior of coffee orange rust (Hemileia-Vastatrix Berk and BR) in plantations undergoing modernization, planted with Dwarf varieties in South-East Mexico. *Café Cacao Thé* 35:21–37.

Avelino, J., H. Zelaya, A. Merlo, A. Pineda, M. Ordoñez, and S. Savary. 2006. The intensity of a coffee rust epidemic is dependent on production situations. *Ecological Modelling* 197:431–47. doi:10.1016/j.ecolmodel.2006.03.013.

Avelino, J., M. Cristancho, S. Georgiou, P. Imbach, L. Aguilar, G. Bornemann, P. Läderach, F. Anzueto, A. J. Hruska, and C. Morales. 2015. The coffee rust crises in Colombia and Central America (2008–2013): Impacts, plausible causes and proposed solutions. *Food Security* 7:303–21. doi:10.1007/s12571-015-0446-9.

Bacon, C. 2005. Confronting the coffee crisis: Can fair trade, organic, and specialty coffees reduce small-scale farmer vulnerability in northern Nicaragua? *World Development* 33:497–511. doi:10.1016/j.worlddev.2004.10.002.

Bacon, C. M. 2010. Who decides what is fair in fair trade? The agri-environmental governance of standards, access, and price. *The Journal of Peasant Studies* 37:111–47. doi:10.1080/03066150903498796.

Barel, M. J. 1994. La qualité du café: Ses causes, son appréciation, son améliorationCoffee quality: Its causes, appreciation and improvement. *Plantations, Recherche, Développement (Francia)* 1:5–13.

Bertrand, B., G. Aguilar, R. Santacreo, F. Bertrand Anzueto, B. Rapidel, J. Avelino, A. Eskes, et al. 1999. *El mejoramiento genético en América Central. Desafíos de la caficultura en Centroamérica*. No. IICA-E11 12. IICA, San José (Costa Rica). PROMECAFE. CIRAD, París, Francia.

Biasutti, M., A. H. Sobel, S. J. Camargo, and T. T. Creyts. 2012. Projected changes in the physical climate of the Gulf Coast and Caribbean. *Climatic Change* 112:819–45. doi:10.1007/s10584-011-0254-y.

Burnham, K. P., and D. R. Anderson. 2002. Information and likelihood theory: A basis for model selection and inference. In *Model selection and multimodel inference: A practical information-theoretic approach*, 49–97. Springer-Verlag, New York.

Carvalho, A. 1988. Principles and practice of coffee plant breeding for productivity and quality factors: Coffea arabica. *Coffee Agronomy* 4:129–65.

Coffee Varieties of Mesoamerica and the Caribbean. 2016. World coffee research. www.varieties.worldcoffeeresearch.org (accessed November 26).

Cruz, C. M. V., N. P. Castilla, T. W. Mew, and Y. Zhu. 2003. Using rice cultivar mixtures: A sustainable approach for managing diseases and increasing yield. *International Rice Research Notes* 28:1–1.

Finckh, M. R. 2008. Integration of breeding and technology into diversification strategies for disease control in modern agriculture. *European Journal of Plant Pathology* 12:399–409. doi:10.1007/s10658-008-9273-6.

Ghini, R., E. Hamada, P. Júnior, M. José, and R. R. D. V. Gonçalves. 2011. Incubation period of Hemileia vastatrix in coffee plants in Brazil simulated under climate change. *Summa Phytopathologica* 37:85–93. doi:10.1590/S0100-54052011000200001.

Gliessman, S. R. 1990. Understanding the basis of sustainability for agriculture in the tropics: Experiences in Latin America. In *Sustainable agricultural systems*, Soil and Water Conservation Society, Ankeny, Iowa 378–90.

Hajjar, R., D. I. Jarvis, and B. Gemmill-Herren. 2008. The utility of crop genetic diversity in maintaining ecosystem services. *Agriculture, Ecosystems & Environment* 123:261–70. doi:10.1016/j.agee.2007.08.003.

ICO. 2014. World coffee trade 1963–2013: A review of the markets, challenges and opportunities for the sector. http://www.ico.org

Insituto Hondureño del Café (IHCAFE). 2009. Informe Annual Cosecha 2008-2009. IHCAFE. http://www.ihcafe.hn/index.php?option=com_phocadownload&view=category&id=6&Itemid=148 (accessed October 15, 2016).

Insituto Hondureño del Café (IHCAFE). 2013. Informe Annual Cosecha 2012-2013. IHCAFE. http://www.ihcafe.hn/index.php?option=com_phocadownload&view=category&download=106:informe-de-cierre-2013-2014&id=6:informes-de-cierre&Itemid=148 (accessed October 15, 2016).

Jaramillo, J., E. Muchugu, F. E. Vega, A. Davis, C. Borgemeister, and A. Chabi-Olaye. 2011. Some like it hot: The influence and implications of climate change on coffee berry borer (*Hypothenemus hampei*) and coffee production in East Africa. *PLoS One* 6:e24528. doi:10.1371/journal.pone.0024528.

Johnson, M. T. J., M. J. Lajeunesse, and A. A. Agrawal. 2006. Additive and interactive effects of plant genotypic diversity on arthropod communities and plant fitness. *Ecology Letters* 9:24–34.

Kremen, C., A. Iles, and C. M. Bacon. 2012. *Diversified farming systems: An agroecological, systems-based alternative to modern industrial agriculture*. Ecology and Society 17(4).

La Prensa, D. 2017. Nueva raza de roya causará hambruna en zonas cafetaleras. Diario La Prensa. http://www.laprensa.hn/honduras/1060126-410/nueva-raza-de-roya-causar%C3%A1-hambruna-en-zonas-cafetaleras (accessed May 10, 2017).

McCook, S., and J. Vandermeer. 2015. The big rust and the red queen: Long-term perspectives on coffee rust research. *Phytopathology* 105:1164–73. doi:10.1094/PHYTO-04-15-0085-RVW.

McDonald, B. A., and C. Linde. 2002. Pathogen population genetics, evolutionary potential, and durable resistance. *Annual Review of Phytopathology* 40:349–79. doi:10.1146/annurev.phyto.40.120501.101443.

Morton, J. F. 2007. The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences* 19680–85. doi:10.1073/pnas.0701855104.

Moschetto, D., C. Montagnon, B. Guyot, J. J. Perriot, T. Leroy, and A. B. Eskes. 1996. Studies on the effect of genotype on cup quality of *Coffea canephora*. *Tropical Science* 36:18–31.

Mundt, C. C. 2002. Use of multiline cultivars and cultivar mixtures for disease management. *Annual Review of Phytopathology* 40:381–410. doi:10.1146/annurev.phyto.40.011402.113723.

Ngugi, H. K., S. B. King, J. Holt, and A. M. Julian. 2001. Simultaneous temporal progress of sorghum anthracnose and leaf blight in crop mixtures with disparate patterns. *Phytopathology* 720–29. doi:10.1094/PHYTO.2001.91.8.720.

Ratnadass, A., P. Fernandes, J. Avelino, and R. Habib. 2012. Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: A review. *Agronomy for Sustainable Development* 32:273–303. doi:10.1007/s13593-011-0022-4.

Rodrigues, Jr, C.J., V. Várzea, M. C. Silva, L. Guerra-Guimarães, M. Rocheta, and D. V. Marques. 2000. Recent advances on coffee leaf rust. In *Proceedings of the international scientific symposium on coffee*, Bangalore, India pp. 179–193.

Sheridan, M. 2016. Castillo or Caturra? A Simple Question. The Specialty Coffee Chronicle. August 4, 2015. http://www.scaa.org/chronicle/2015/08/04/castillo-or-caturra-a-simple-question/ (accessed October 23, 2016).

Smithson, J. B., and J. M. Lenne. 1996. Varietal mixtures: A viable strategy for sustainable productivity in subsistence agriculture. *Annals of Applied Biology* 128:127–58. doi:10.1111/j.1744-7348.1996.tb07096.x.

USDA Foreign Agricultural Service (FAS). 2012. Honduran 2012/2013 coffee exports continue to roast. *Honduras coffee annual*, USDA-FAS. HO-Café.

USDA Foreign Agricultural Service (FAS). 2014. Rust-related 2013 /14 production decline erased in 2014 /15. *Honduras coffee annual*, USDA-FAS HO1402.

USDA Foreign Agricultural Service (FAS). 2016. Honduras coffee annual 2016. *Honduras coffee annual*, HO1603.

Van der Vossen, H. A. M. 2009. The cup quality of disease-resistant cultivars of Arabica coffee (*Coffea arabica*). *Experimental Agriculture* 45:323–32. doi:10.1017/S0014479709007595.

Van der Vossen, H., B. Bertrand, and A. Charrier. 2015. Next generation variety development for sustainable production of arabica coffee (*Coffea arabica* L.): A review. *Euphytica* 204:243–56. doi:10.1007/s10681-015-1398-z.

Wolfe, M. S., and M. R. Finckh. 1997. Diversity of host resistance within the crop: Effects on host, pathogen and disease. *Resistance of Crop Plants against Fungi*. 378–400.

Wood, D., and J. M. Lenne. 1997. The conservation of agrobiodiversity on-farm: Questioning the emerging paradigm. *Biodiversity and Conservation* 6:109–29. doi:10.1023/A:1018331800939.

Zhu, Y., H. Chen, J. Fan, Y. Wang, Y. Li, J. Chen, J. Fan, et al. 2000. Genetic diversity and disease control in rice. *Nature* 406:718–22. doi:10.1038/35021046.