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The structures underpinning vulnerability: examining landscape-society interactions in a smallholder coffee agroforestry system

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Abstract

Smallholder farmers dependent on rain-fed agriculture are particularly vulnerable to extreme climate events and, therefore, it is necessary to identify adaptive measures that would increase farmer resilience to these shocks. The management options in a low-input system, like forest coffee (*Coffea arabica*), are limited and there are several factors out of farmers' control driving their vulnerability to changing climatic conditions. These can relate to social structures and landscape factors, which can interact to reduce farmers' adaptive capacity, creating a state of contextual vulnerability. We explored the potential synergies of this interaction across elevation, patch area and shade management gradients for smallholder coffee farms around the UNESCO Yayu Coffee Forest Biosphere Reserve in Ethiopia before, during and immediately following the 2015/16 El Niño. We documented a dramatic collapse in coffee yields across all farms, resulting in coffee incomes 29.5% ± 18.0% and 19.5% ± 10.0% of 2014 incomes in 2015 and 2016, respectively. We identified farms at elevations between 1500 and 1600 m with canopy openness between 40% and 45% as being consistently low yielding over our study period. We found these farmers had the highest rates of income diversification and, therefore, were already exhibiting adaptive capacity. Farmers with the largest income losses were spatially concentrated between 1600 and 1700 m, located in larger patch areas with lower canopy openness. Farmers at this elevation have access to poor infrastructure, restrictions on shade management and reported higher dependence on income from coffee, indicating an interaction of biotic and social factors exacerbating their vulnerability. Unfortunately, due to a nationally declared state of emergency, we were unable to survey farmers on the adaptive measures they undertook; therefore, we are limited in assessing their resilience. However, we do show the importance of considering both biotically and socially-mediated influences for assessing smallholder vulnerability, particularly barriers to diversifying incomes.

Introduction

The concept of resilience, though utilized by several disciplines, was largely drawn from ecology [1], and applied to the development of the related fields of sustainability science and social-ecological systems (SES) analysis [2]. It provides a conceptual foundation for grappling with the hard to predict responses of complex systems undergoing stress acting over different spatial and temporal scales, and can be qualitatively or quantitatively assessed as the level of perturbation a system can experience while maintaining its overall functioning. It is also closely related to the concepts of adaptive capacity and vulnerability. In principle, resilience is a neutral term, whereby desirable and undesirable states can be maintained through a system's ability to adapt to changing conditions. Vulnerability, on the other hand, has been primarily defined as the susceptibility of a system to respond negatively to an external stress generally driven by a lack of adaptive capacity. Therefore, vulnerability and resilience could be considered inverse characteristics of a system, dynamically derived through changes to its adaptive capacity [3]. Through an extensive review of the literature, Adger [4] presents a commonly utilized framework of vulnerability with the primary components being exposure, sensitivity and adaptive capacity. Exposure relates to the magnitude of stress a system undergoes, sensitivity is the degree to which that perturbation affects that system and the ability to respond to that perturbation is its adaptive capacity. However, further scholarship highlights the importance of differentiating vulnerability of outcome versus contextual vulnerability [5]. As O'Brien *et al* [5] explain, framing vulnerability as contextual allows SESs to be analyzed as a whole, particularly how biophysically- and socially-mediated factors can interact to reduce adaptive capacity as opposed to focusing on how impacts of an external perturbation manifest and, therefore, inadvertently create a focus on technical interventions.

For managed systems, such as agriculture and agroforestry, the aim of minimizing the vulnerability of a system is often focused on maintaining crop yields. Certainly, in smallholder systems consistent levels of agricultural productivity are paramount for avoiding food insecurity [6] and, therefore, there is an assumption that reducing the interannual variability of yields will help a household to remain resilient to shocks. However, when considering an agricultural system through a resilience lens, it is important to recognize that crop productivity is only one of several variables that may be operating at a much faster timescale than other factors driving the resilience, desirable or undesirable, of a SES [7]. This can manifest as the unintended consequences of agricultural intensification [8, 9], the inconsistent influence weather variability may have on yield variability [10] and the proven benefit of diversifying incomes away from an individual crop to increase a household's adaptive capacity [11, 12]. Therefore, understanding the long-term dynamics, if possible, and structural attributes acting on a system becomes essential for assessing contextual vulnerability and, by extension, resilience.

There remains great uncertainty as to how agricultural systems in Africa will respond to changing climate [13]. The most likely adaptive measure farmers will take to increase their resilience to shocks will be, as mentioned, through the process of diversification [2, 14, 15]. The ability of farmers to prepare and respond to climate shocks are both constrained and enabled by social structures, which are widely held to be critical to understanding vulnerability [2]. Sewell [16]:19 defines social structures as 'sets of mutually sustaining schemas (patterns of thoughts and behaviors) and resources that empower and constrain social action and that tend to be reproduced by that social action'. These structures include class, gender, ethnicity, norms and customs, as well as forms of political and economic organization. Freidman *et al* [17], for example, highlight how, in Ghana's cocoa sector, the structure of gender relations shape patterns of vulnerability, playing a central role in determining women's access to land and non-farm opportunities. The establishment of protected areas can also have an impact on the ability of local communities to respond to climate shocks, particularly for relatively recent migrants who are often located along former forest frontiers [18]. As Mclaughlin and Dietz [19] note, much of the literature on vulnerability has tended to focus on socially-mediated structures (especially economic and political) and their role in environmental degradation, rather than considering social and ecological phenomena as integrated and mutually constitutive. This is often in response to concerns about producing analyses that slip into ecological determinism, where environmental conditions are understood to dictate social conditions [20]. This is widely held to be problematic because it de-politicizes analyses of environmental and social changes (e.g. by ignoring or marginalizing the role of colonialization, imperialism and slavery in explanations of social or ecological change) and neglecting the role of human agency[10] in shaping patterns of vulnerability. Therefore, a key aspect of gaining an interdisciplinary understanding of vulnerability, requires developing analyses that are sensitive to the risks of developing purely structural explanations of vulnerability while also interrogating the ways in which environmental and biophysical factors shape, and are shaped by, the variety of relevant social structures.

This paper aims to contribute to the development of such an interdisciplinary understanding of vulnerability, including how vulnerability can be spatially concentrated through the interaction of biophysical and social structures, by using an examination of the impact of a climate shock (the 2015/2016 El Niño) on coffee yields in southwestern Ethiopia around a UNESCO biosphere reserve. Specifically, we aim to assess how the characteristics of managing a consistently low yielding farm are influenced by factors outside of the control of the farmer (e.g. location in the

[10] Here agency refers to the process and capacity of individual and corporate actors to play a causal role in history, including to make their own free choices [2, 19].

landscape) and the extent to which that contributes to the vulnerability or drives the adaptation of those farmers to a climate shock. We appreciate, we are only considering the impact of the climate shock on coffee yields for this analysis, and therefore, will be presenting a limited view of the full range of adaptive measures available to our study farmers. These primarily consist of diversifying incomes beyond coffee, reducing dependence of total income on coffee and managing shade levels over coffee to optimize yields during shock years.

Methods

Study site

The Yayu Coffee Forest Biosphere Reserve is located in the Ilubabur administrative zone of Oromia Regional State, Ethiopia and was registered in UNESCO's World Network of Biosphere Reserves in 2010. The biosphere reserve is a genetic pool for the protection of wild varieties of *Coffea arabica* and is divided into a core area, where no coffee harvesting should occur, a buffer zone, where light management of coffee is allowed with minimal shade management, and a transition area where a variety of agricultural activities are permitted.

Sampling strategy

The data for this study were collected during 2014–2017 and have been analyzed to assess the effects of the 2015/16 El Niño shock. We assessed the variability of coffee productivity and income from coffee by farm across the landscape before, during and following the climate shock. As we know these farms to be lightly managed (e.g. no fertilizer or pesticide application and very low composting rates), we focused on the influences of elevation, forest patch area, soil condition (e.g. nitrogen limitation) and canopy gap as predictors of low shrub productivity, whether this dynamic remained consistent throughout the climate shock and if it predicts whether farmers are already undertaking adaptive measures.

The study landscape consists of low input forest coffee located within various sized forest patches in the buffer and transition areas of the biosphere reserve over an altitudinal range of 1300–1900 m. To capture this variation, monitoring of coffee shrubs was stratified across elevation, patch area and shade gradients (figure S1 is available online at stacks.iop.org/ERL/14/075006/mmedia). To assess the influence of landscape features, patch area classes were calculated based on a 0.7 threshold of a normalized difference vegetation index layer generated from a cloud-free Landsat image composite of the study region and divided into terciles of forest ln(area) [21]. Elevation classes were established as either above or below 1600 m based on a shuttle radar topography mission digital elevation model [22]. This cut-off was chosen so as to have comparable distributions of forest patch area for subsequent sampling. A mask was built for areas accessible throughout the seasons within the boundaries of the Yayu Coffee Forest Biosphere Reserve, and points were randomly placed at distances >250 m in each of the patch and elevation classes using The Sampling Design Tool in ArcGis 10 [23]. Each point was geolocated by GPS (Garmin 62s) during March 2013, and farmers were approached and asked if they would be interested to participate. The trade-offs between spatial representation and the ability to revisit plots inter-annually meant that farmers located in the most remote locales were not systematically sampled for this study. Canopy scope measurements [24] were taken at the center and corners of a 20 m by 20 m grid surrounding the point—with all plots then stratified by 3 classes of average shade intensity. This resulted in 18 contingencies, based on 3 patch area levels, 3 levels of shade and 2 elevation classes. We established a total of 54 plots, which included three replicates per contingency.

Data collection

In each of the 54 plots, seven productive coffee shrubs were monitored from flowering through to harvesting; these were randomly selected at each corner of the marked 20 m by 20 m plot and three shrubs located in the center of each plot. Three branches (at 20 cm, 40 cm and 60 cm from the apex) were tagged on a single productive main stem (orthotrophic shoot) and regularly monitored throughout berry development. During harvesting season of each monitored year, fresh cherry weights for each tagged branch were measured using portable scales as well as all fresh cherries for the whole productive main stem. Within a central 10 m by 10 m subplot of each plot, vegetation surveys were undertaken, including number and DBH of all productive stems per shrub. Farm characteristics within established plots were measured, including: percent canopy cover, species, DBH and height of shade trees. Soil samples were collected from all plots for the top 30 cm to assess bulk density, soil pH, soil texture, nutrient content (N, P, K, etc), cation exchange capacity and carbon content following ClimAfrica protocols (http://climafrica.net). To identify consistently low yielding farms, all monitored shrubs were grouped into quartiles by yield for each year separately and assigned a binary variable of '0' if in the top two quartiles and '1' if in the bottom half. If four or more monitored shrubs were identified as low yielding (>60% of all monitored shrubs), the farm was designated as low yielding for that year. If a farm was identified as low yielding for all three monitored years, it was designated as a consistently low yielding farm, although additional analyses were performed on farms that were low yielding for each year of monitoring separately. To estimate per hectare coffee yields for each year, the median yield of monitored stems was calculated per plot and multiplied by measured coffee stem density values from the vegetation survey.

To capture management and household-level livelihood data, a household survey was performed in early 2015, immediately following the 2014 harvest. Data collected from this survey included land area, cash outlays for labor and inputs as well as reported sources of income (more details can be found in [25]). Total coffee income for each year was calculated using per hectare coffee yields from monitored shrubs, reported coffee price recorded by the Yayu Coffee and Tea Office and farmer reported total land area. For identifying vulnerable farmers, we calculated the log ratio of the sum of incomes for 2015 and 2016 with coffee incomes in 2014. We chose to calculate the log ratio, as it provided a symmetric estimate of income variability for subsequent analysis. If the log ratio was negative that indicated farmers had not earned over two years what they received in one 'normal' year. Unfortunately, due to a nationally declared state of emergency, we were unable to perform subsequent household surveys; therefore, we relied on 2015 household-survey reported percent of total income from coffee, whether the farmer was in the bottom three coffee income quartiles and the number of reported income sources as proxies of adaptive capacity. Farmers were considered 'vulnerable' to the shock if they exhibited a negative income log ratio, reported greater than 50% of their income from coffee and were not in the top coffee income quartile in 2015.

To estimate the climatic impact of the El Niño in our site, we used TerraClim data [26], extracted from Google Earth Engine [27], to calculate monthly anomalies for maximum temperature, vapor pressure deficit (VPD) and precipitation for the time period 1986–2017. To assess the accuracy of TerraClim for our site, we regressed monthly measures with data from local Campbell Scientific climate stations we established at 1960 m elevation (precipitation) and under the forest coffee canopy at 1750 m elevation (maximum temperature and VPD). The resolution of TerraClim is ~5 km and, therefore, more fine-scale comparisons were not possible.

Data analysis

We were interested to assess whether managing a consistently low yielding farm, income diversification or vulnerability to climate extremes could be predicted by a farm's location in the landscape (e.g. elevation and patch area), soil condition (e.g. soil carbon nitrogen ratios) and their shade management. We also looked at reported cash outlays for labor, but did not find that predictive in any of our models. To assess this we fit quasibinomial generalized linear models with a logit link for both binary variables, an inverse gaussian link function for integer values and a gaussian link function for continuous variables using R v.3.5.1 [28]. We considered both landscape and management terms together, their interactions and quadratic terms for elevation and canopy gap. Models were compared using chi-square tests and the model with the lowest dispersion or AIC and highest R^2 was chosen to model probabilities of vulnerability, low yields and income diversification across the range of elevation, patch area, soil condition and shade values monitored in this study. Partial effects were plotted using the *effects* package [29]. R output from all final models are included in the supplemental materials.

Results

Climate anomalies

Comparisons between TerraClim data and ground station data showed strong correlations with maximum temperature ($R^2 = 0.94$, $p < 0.001$), maximum VPD ($R^2 = 0.94$, $p < 0.001$) and precipitation ($R^2 = 0.70$, $p < 0.001$) (figure S2). Climate anomalies for all three variables are depicted in figure S3. From these we see the climate shock manifested quite differently in 2015 and 2016, with 2015 exhibiting much higher anomalies in VPD and maximum temperature leading up to and during the strong El Niño conditions, then immediately dropping off following the end of the event. In contrast, during 2016 there was a relative collapse in precipitation following the end of the strong El Niño signal in March of that year, continuing until the harvest period in October. Also, maximum temperature anomalies have been predominantly positive for over a decade, indicating a strong warming trend has already been occurring over this region.

Yield/income impacts of shock

Over the 54 plots monitored, which overlapped with the farms of 78 households (many plots encompassed land belonging to multiple households), we saw a dramatic collapse in coffee yields and coffee incomes (figure 1) from 2014 to 2015 and, particularly, in 2016, coincident with the El Niño 2015/16 period described above. Median shrub yields were 0.3 ± 0.06 kg, 0.08 ± 0.04 kg and 0.05 ± 0.02 kg for 2014, 2015 and 2016 respectively. This related to median total farm harvests of 155 ± 390 kg, 43.9 ± 89 kg and 19.4 ± 100 kg for 2014, 2015 and 2016, respectively. Median coffee incomes were $29.5\% \pm 18.0\%$ and $19.5\% \pm 10.0\%$ of 2014 coffee incomes in 2015 and 2016, respectively. Seventy-eight percent (61/78) of monitored farmers exhibited a negative log ratio of incomes, where the sum of incomes from 2015 and 2016 were less than 2014 incomes. All values are reported with 95% confidence intervals.

Low yielding and vulnerable farmers

Twenty-three percent (18/78) of farmers were considered 'vulnerable' to the climate shock (figure 2(a)), which we defined as farmers exhibiting a negative income log ratio, reported greater than 50% of their income was from coffee and were not in the top coffee income

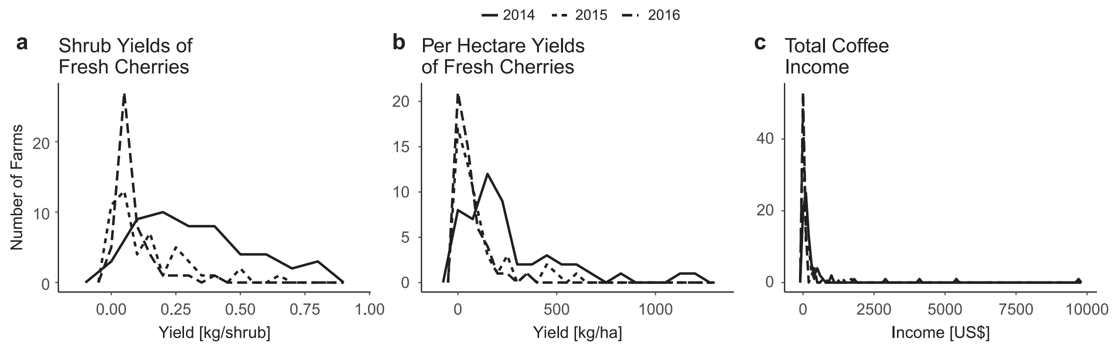

Figure 1. Monitored collapse in (a) coffee shrub productivity, (b) farm yields and (c) total income from coffee before, during and following 2015/16 El Niño.

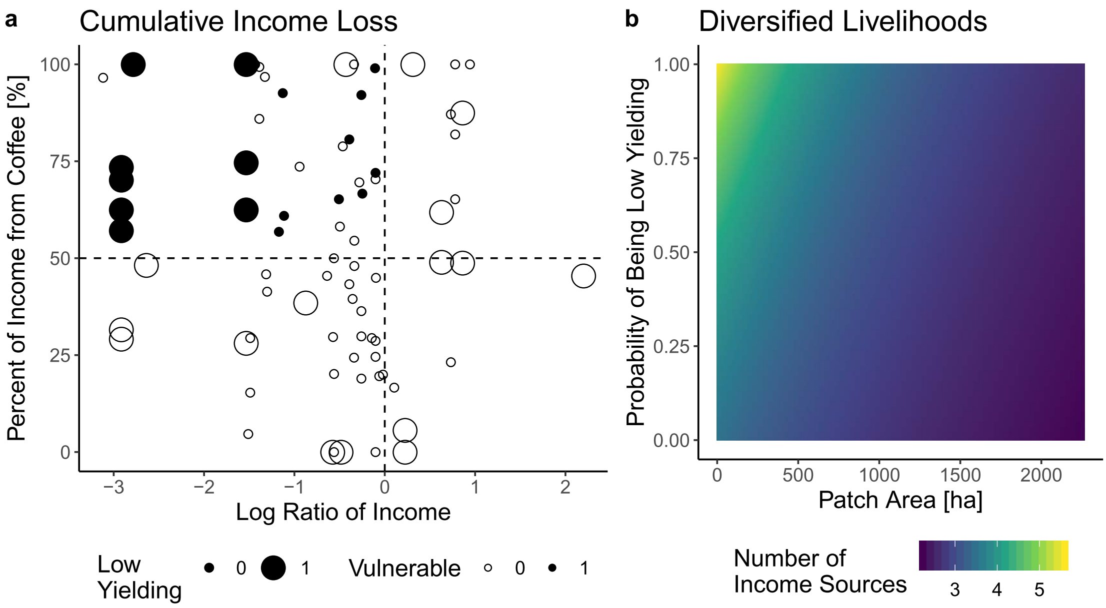

Figure 2. (a) Cumulative log ratio of coffee income in 2015 and 2016 to 2014 coffee income with reported dependence of the farmer's income on coffee. Consistently low yielding farms are designated in yellow and 'vulnerable' farmers are depicted as solid dots. Vulnerability farmers are defined as those who have a negative log ratio of cumulative income, report 50% or more income from coffee and were not in the wealthiest income quartile in 2014. (b) Presents the relationship between patch area of the location of a farm and the probability that farm is low yielding for predicting the number of income sources.

quartile in 2015. Thirteen percent of farmers (10/78) were considered low yielding for all three years and eight farms were identified as both consistently low yielding and vulnerable to the climate shock. Quadratic terms for elevation and canopy gap were identified as the strongest predictors for a farm being low yielding (figure 3(c)) ($R^2 = 0.525$, $p < 0.001$), whereby farms at elevations between 1500 and 1600 m with canopy openness between 40% and 45% were consistently low yielding over our study period. The characteristics of vulnerable farmers were related to a quadratic term for elevation and linear terms for canopy gap and patch area (figures 3(a), (b)) ($R^2 = 0.189$, $p < 0.01$), showing a spatial concentration of vulnerability, although not necessarily contiguous, between 1600 and 1700 m and decreasing with higher canopy openness and was particularly pronounced in larger patch areas. For some farmers, this elevation range overlapped with the buffer area of the biosphere reserve, which also exhibited lower canopy gaps ($F_{1,76} = 8.235, p < 0.01$). While statistically significant, being located within the buffer zone was a weak predictor of whether a farmer was identified as vulnerable to this climate shock ($R^2 = 0.056, p < 0.05$).

Through our household survey we are aware that the community located at this elevation and who farm predominantly within the buffer zone are primarily migrants, who arrived during the Ethiopian famine in the early 1980s [25]. However, when looking across all of our monitored farmers, identifying as a migrant was not significantly correlated to the likelihood of being vulnerable to this climate shock. The size of patch area a farm was located within was not a significant predictor of the probability a farm was consistently low yielding across all years; however, it did show a negative partial effect in 2014 and a positive partial effect in 2015 (figure S4). Soil nitrogen limitation, estimated by

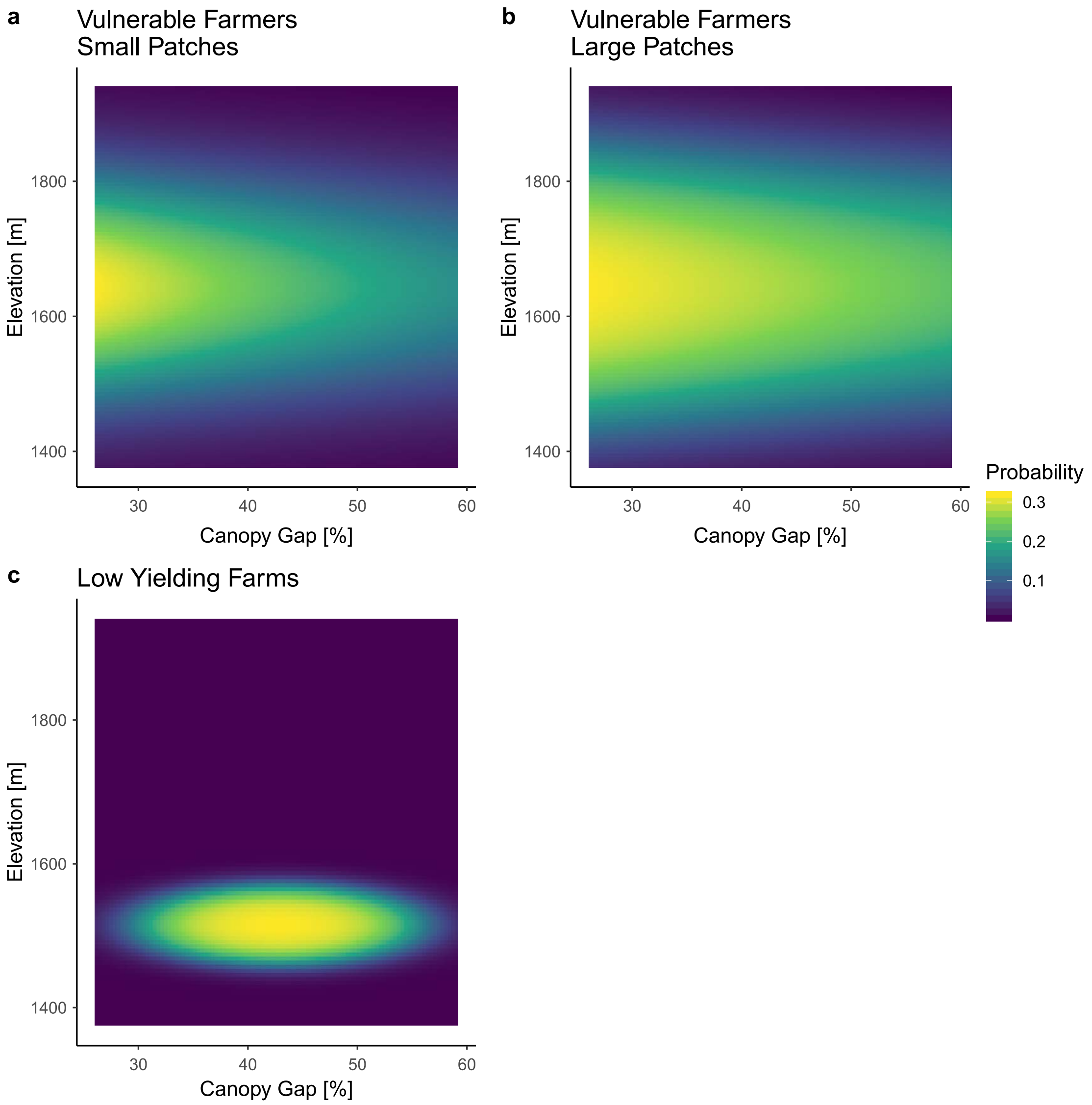

Figure 3. Influence of the interaction of elevation and canopy gap on the probability that a farmer was particularly vulnerable to the 2015/16 El Niño climate shock if located in a small patch (a) or a large patch (b) and whether a coffee farm will be consistently low yielding (c).

the ratio of carbon and nitrogen soil concentrations, was also not a significant predictor of a farm being consistently low yielding; however, it was a positive predictor of being low yielding in 2015 and 2016. In terms of the log ratio of income, one of the components of our vulnerability index, patch area was negatively related while canopy gap and elevation both showed nonlinear effects (figure S5) ($R^2 = 0.367$, $p < 0.001$). Finally, being located within small patch areas and having a consistently low yielding farm were significantly related to the number of income sources a farmer had reported in 2014 (figure 2(b)) ($R^2 = 0.116$, $p < 0.01$).

Discussion

Inter-annual variability in coffee yields is a common complaint across our study farms, which is a common feature of perennial crop systems. Coffee plants have their own reproductive cycles and their investment in flowers and berries any one year is often a consequence of the previous year's conditions [30]. Therefore, it is difficult to draw firm conclusions on the impact of this climate shock based on three years of coffee yield dynamics. However, analysis of our coarse climate data shows that temperature and VPD would have had greater influence on monitored yields in 2015, while several months of lower precipitation would have affected coffee berry development during 2016. It is likely that the 2015 conditions would be ameliorated at higher elevations, whereas low precipitation would likely affect coffee shrubs regardless of landscape context. This could explain why elevation and patch area were better able to predict low yielding farms during 2015, while 2016 yield dynamics exhibited a nonlinear relationship with elevation and positive relationship with canopy gap (figure S4). This may suggest an uneven distribution of rainfall, which our coarse resolution dataset would not have captured, and an ameliorating influence of shade cover during drier conditions. It was also interesting that soil nitrogen limitation was more influential and positively related during both climate shock years than during 2014. Considering farmers in this region are not applying fertilizers due to cost and availability, adaptive strategies for future climate shocks will require farmers finding additional mechanisms for enhancing their farms' soil nitrogen.

With the benefit of three years of yield data, we can confirm that consistently low yielding farms are located at the lowest elevations monitored, regardless of patch area, which is consistent with predictions of future suitable areas for *C. arabica* in the literature [31, 32]. It is interesting to posit why medium shade at low elevations would coincide with low yielding farms. Comparable studies of *C. arabica* along an elevation gradient, found important interactions between shade diversity, management intensity and elevation [33]. In their more intensive system, management intensity was a key determinant; however, farmers in our study system do not apply fertilizers and rarely compost, therefore, shade management is our primary metric of management intensity. It seems in our study system high shade level is coincident with low management intensity, which farmers at low elevations may be compensating for by investing in management under lower shade conditions. However, we were not able to confirm this using only data on pre-shock reported cash outlays for labor. We also found evidence that farmers managing low yielding farms were more likely to have diversified their incomes and, therefore, by our metrics would have been less vulnerable to the climate shock; although, we do not know how their other income sources may have been impacted. Diversified income sources were also related to smaller patch areas, which could be due to a number of factors. For instance, as the majority of low yielding farms are located at lower elevations already, small patch areas may be exhibiting particularly undesirable growing conditions for *C. arabica* and, therefore, providing a stronger signal for farmers to diversify.

The majority of farmers (~80%) exhibited a net loss of income over 2015 and 2016 relative to 2014; although, we observed that coffee incomes collapsed primarily within the mid-elevation, large-patch area and medium shade-level contingency (figure S5), similar with where we identified the most vulnerable farmers (figures 3(a), (b)). This component of our vulnerability metric was more spatially concentrated than whether a farmer reported being more dependent on coffee. Therefore, while it is unclear how localized exposure to the climate shock may have been, the sensitivity to the shock was spatially concentrated by biotic factors and then exacerbated for those with a higher dependence on coffee income, our proxy for low adaptive capacity. For some of our monitored farmers, this landscape contingency was coincident with the buffer zone of the Biosphere Reserve. The Yayu UNESCO Coffee Forest Biosphere Reserve was established in 2010, in particular the demarcation of its core, buffer and transition areas. As mentioned, there are differing intensities of management allowed depending on which area a farm is located within, and farmers within the buffer area are limited in their ability to remove shade trees. We did not monitor the extent to which these rules are being enforced for this study nor how they may be impacting the farmers' abilities to adopt additional income streams. However, we did find that shade-levels are higher for those farms in the buffer and are aware that farmers in this area are dependent on a poorly maintained road to access the closest market and are predominantly migrants. It is common among recently established protected areas to find the most recent migrants located in the former forest frontier [18]. Therefore, since we found that being a migrant alone was not a predictor of a farmer's vulnerability across the study communities, our findings suggest the location of a farm in the landscape was more influential. It would be interesting to further explore whether migrants are more likely to be located in less productive areas of this landscape; however, this is likely to be related to the historical distribution of access to coffee forest areas with those arriving later being relegated to regions deemed less desirable. From three years of yield data, we cannot conclude whether farms within this landscape contingency are particularly prone to interannual yield variability and, therefore, are generally more vulnerable to climate shocks; although, we do see that farms in larger patch areas at similar elevation and shade-levels exhibit much higher probabilities of being vulnerable (figure 3(b)). However, our results do suggest structural impediments to diversifying income as well as biotic drivers likely exacerbated income losses during this shock.

Smallholder systems can adopt 'adaptive strategies' to reduce their vulnerability to climate change and 'coping strategies' to manage the impacts of a disruption, the most effective strategies are those that diversify sources of livelihoods for households [34]. This has also been described as improving farmers' 'buffer capacity' to be less vulnerable to climate change or, at the least, reducing income variability under various disturbances [35]. The ability of farmers to adapt to climate change is dependent on the extent to which they are 'entitled to make use of resources' [36], a factor largely governed by social structures. Hirons *et al* [37] identify several structural issues which influence the resilience and vulnerability of coffee farmers in Ethiopia. These include the national policy priorities, rules and laws concerning the management of shade on farms, access to, and character of, agricultural extension and the structure of the coffee market. They also identified a lack of coordination among relevant governing agencies with jurisdiction around the Forest-Coffee Biosphere Reserve, which would hamper efforts to implement landscape-scale policies to support the adaptation of farmers to changing climate. These structures differentiate individual farmer's vulnerability and resilience by impacting their adaptive capacity. The findings of this study highlight how these can intersect with the structure of the landscape to amplify or dampen the vulnerability of farmers. This is critical to recognize within landscape planning processes for two reasons. First, because understanding these interactions could, in theory, lead to more effective policy design. And second because it highlights the complexity of landscape planning processes and the importance of engaging with existing social structures and biophysical constraints, something that is rarely facilitated by the length of funding cycles and policy programs [38].

Conclusion

SESs can be in resilient states whereby unfavorable conditions are maintained via 'lock-ins' or strong 'basins of attraction' [39, 40] as well as exhibiting contextual vulnerability to intermittent climate shocks [5]. Both of these are mediated through social and biotic factors that require interdisciplinary research to understand their underlying mechanisms [40]. Our results suggest farmers managing low yielding farms are spatially concentrated in a narrow altitudinal band due to biotic factors but are also exhibiting greater adaptive capacity through income diversification. In contrast, the farmers we identified as the most vulnerable to the 2015/16 El Niño, exhibited biotically-driven income losses and socially-imposed barriers to income diversification (e.g. poor infrastructure). The climatic dynamics experienced during this shock manifested very differently over our study period, being either temperature or precipitation driven, leading to dramatic drops in coffee shrub productivity that were not consistently mediated by a farm's location in the landscape. Therefore, efforts to reduce vulnerability in this system will not be realized through optimizing factors influencing coffee production, as that will be increasingly difficult to predict and/or manage with accelerating climate change. Instead, we argue a better understanding of the factors driving farmers' lack of income diversification and high reliance on income from coffee as necessary to effectively reduce vulnerability to climate variability in this system.

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Ethics statement

This study was carried out in accordance with the recommendations of the Statement of Ethical Practice for the British Sociological Association (www.britsoc.co.uk/about/equality/statement-of-ethical-practice.aspx) and the University of Oxford's Central University Research Ethics Committee (CUREC), with written or verbal informed consent from all subjects. Given the non-sensitive and non-physical/medical nature of the survey instrument, and the non-involvement of potentially vulnerable participants (e.g. there were no children involved), verbal informed consent was deemed acceptable. Especially in the case where respondents may be made to feel uncomfortable if, for example, they were illiterate and not able to sign a hard-copy paper form. This was considered to be consistent with the 'Statement of Ethical Practice for the British Sociological Association', whereby '[the researchers] will describe the nature and objectives of the study in appropriate detail and in terms meaningful to participants. They will offer them the option of providing verbal consent and/or signing a written consent form. The option of verbal consent may be preferred by some of the rural residence farmer participants (who may, for example, be illiterate)'. The protocol was approved by the University of Oxford's Central University Research Ethics Committee (CUREC).

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