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RESEARCH ARTICLE

Using local knowledge to reconstruct climate-mediated changes in disease dynamics and yield—A case study on Arabica coffee in its native range

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Societal Impact Statement

Adapting agriculture to climate change requires an understanding of the long-term relationship between climate, disease dynamics, and yield. While some countries have monitored major crop diseases for decades or centuries, comparable data is scarce or non-existent for many countries that are most vulnerable to climate change. For this, a novel approach was developed to reconstruct climate-mediated changes in disease dynamics and yield. Here, a case study on Arabica coffee in its area of origin demonstrates how to combine local knowledge, climate data, and spatial field surveys to reconstruct disease and yield time series and to postulate and test hypotheses for climate–disease–yield relationships.

Summary

- While some countries have monitored crop diseases for several decades or centuries, other countries have very limited historical time series. In such areas, we lack data on long-term patterns and drivers of disease dynamics, which is important for developing climate-resilient disease management strategies.
- We adopted a novel approach, combining local knowledge, climate data, and spatial field surveys to understand long-term climate-mediated changes in disease dynamics in coffee agroforestry systems. For this, we worked with 58 smallholder farmers in southwestern Ethiopia, the area of origin of Arabica coffee.
- The majority of farmers perceived an increase in coffee leaf rust and a decrease in coffee berry disease, whereas perceptions of changes in coffee wilt disease and *Armillaria* root rot were highly variable among farmers. Climate data supported farmers' understanding of the climatic drivers (increased temperature, less rainy days) of these changes. Temporal disease-climate relationships were matched by spatial disease-climate relationships, as expected with space-for-time substitution.
- Understanding long-term disease dynamics and yield is crucial to adapt disease management to climate change. Our study demonstrates how to combine local

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knowledge, climate data and spatial field surveys to reconstruct disease time series and postulate hypotheses for disease-climate relationships in areas where few long-term time series exist.

KEYWORDS
climate change, coffee berry disease, coffee leaf rust, coffee wilt disease, disease dynamics, local knowledge, perception, yield

1 | INTRODUCTION

Climate change is threatening agricultural systems and the livelihood of agricultural communities worldwide through climate-mediated increases in disease levels and decreases in yield (Altizer et al., 2013; Dupre et al., 2022; Ray et al., 2019). This is particularly true for low- and middle-income countries, as these farming systems are more frequently rain-fed (Asante et al., 2017; Harvey et al., 2018; Ray et al., 2019). To adapt agricultural systems to increasing temperatures, shifts in rainfall, and changes in the frequency of extreme events, we need insights into the long-term relationship between climatic variables, disease dynamics, and yield (Peltonen-Sainio et al., 2010; Zhan et al., 2018). While several of the rich countries can capitalize on a wealth of historical data on climate, diseases, and yield, as collected at research stations for decades or even centuries, comparable data is scarce or non-existent for many of the countries that are most vulnerable to changes in the climate (Adenle et al., 2017; Muis et al., 2015). One unexplored approach to re-create long-term time series is the use of local knowledge. Local knowledge can provide insights into long-term changes in climate, diseases, and yield, as well as on climate–disease–yield relationships. This knowledge can subsequently be validated by comparison with high-resolution re-analyses models of the historical climate, as well as by comparison with spatial field surveys within the framework of space-for-time substitution. Reconstructing climate-mediated changes in diseases and yield is important for developing sustainable, climate-resilient management strategies.

Global changes in temperature, rainfall, and extreme events are expected to induce shifts in disease levels, outbreaks dynamics, and the emergence of new diseases (Morton, 2007). Climate-induced changes in disease levels can cause significant damage by reducing crop yields and increasing production costs, thereby reducing the economic and social sustainability of the farmers (Avelino et al., 2015). As one example of climate-induced disease outbreaks, coffee leaf rust, *Hemileia vastatrix*, severely damaged coffee production across Central America over the past decades due to an increase in temperature (Avelino et al., 2015). As a result, food insecurity and migration increased throughout Central America, particularly among smallholder coffee farmers (Bacon et al., 2017; Dupre et al., 2022). Another example is the coffee wilt disease *Fusarium xylarioides*, which strongly affects coffee production in Africa and has become more severe with increasing temperatures (Flood, 2022; Zhang et al., 2023). To mitigate the negative effects of climate change, we need to be able to predict changes in disease dynamics and yield, for which we can use relationships obtained from long-term time series of climate, disease levels, and yield. While some countries have monitored the major diseases on their crops for several decades or centuries, other countries have lacked such opportunities, and there are no or few historical time series.

To recreate an understanding of the past without written records, one can tap into local knowledge (Jessen et al., 2022). While this approach has been taken in several scientific fields, such as landscape ecology (Lauer & Aswani, 2010; Lucet & Gonzalez, 2022), botany (Popoola & Obembe, 2013), and entomology (Segura et al., 2004), it has not been applied to the field of pathology and the study of yield. One method is the semi-structured questionnaire, which allows the collection of both quantitative and qualitative data through the use of multiple-choice questions, ranking exercises, and open-ended questions. Local knowledge, which includes indigenous, traditional, and other knowledge systems, is increasingly seen as valuable by providing new facts, new perspectives, and unique insights (Salmon et al., 2022; Tengö et al., 2014). Yet, interview data on climate-induced changes in diseases and yield might be noisy, for example, due to variation among local farmers in their experience and memory, as well as biased, for example, due to temporal changes in memories (e.g., "everything used to be better"). Hence, if possible, it is important to follow multiple leads of evidence, and thereby independently validate the findings from the interviews. One way to validate farmers' knowledge of climate-disease-yield relationships is to take advantage of re-analysis data of the historical climate (Varlas et al., 2022). By testing whether climatic variables proposed to drive changes in disease and yield have actually been changing through time according to meteorological records, we can assess the strength of evidence for whether the climatic driver identified by local knowledge might indeed underlie the perceived changes in diseases and yield. An alternative approach to validate farmers' knowledge is to compare patterns through time to patterns across space within the space-for-time substitution framework (De Frenne et al., 2013). If the temporal and spatial relationships between climate, disease, and yield give us the same insights, we can have a stronger belief in the generality of the hypothesized climate–disease–yield relationship. As one example, disease levels of stem rust and leaf rust on wheat are known not only to have increased with increasing temperatures due to climate change but also higher at low, warm elevations than at high, cold elevations (Meyer et al., 2021).

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Ethiopia is one of the main centers of indigenous diversity of Arabica coffee (*Coffea arabica* L.). Arabica coffee is the country's most important agricultural commodity, accounting for one-quarter of the total export revenues and providing a livelihood income for approximately 15 million persons (Davis et al., 2012; Moat et al., 2017). Of the total coffee production in Ethiopia, about 90% is produced by smallholder farmers under different management intensities (Davis et al., 2018). Coffee production in Ethiopia is threatened by climate change (Davis et al., 2012; Moat et al., 2017) and various pests and diseases (Ayalew et al., 2022), of which coffee leaf rust (*H. vastatrix*), coffee berry disease (*Colletotrichum kahawae*), coffee wilt disease (*Gibberella xylarioides*), and Armillaria root rot (*Armillaria mellea*) are the major diseases in the study region (Adugna et al., 2009; Zewdie et al., 2020, 2021). In the study area, coffee leaf rust is sometimes heavily attacked by the fungal hyperparasite *Lecanicillium lecanii* (Zewdie et al., 2021).

Our overarching aim was to understand the relationships between climate change, disease dynamics and coffee yield in one of the centers of indigenous diversity of Arabica coffee in southwestern Ethiopia by exploring past changes. For this, we took an interdisciplinary approach where we first interviewed 50 smallholder farmers as well as 8 managers at commercial coffee plantations on their perception of long-term changes in the climate, major fungal diseases (coffee leaf rust, coffee berry disease, coffee wilt disease, and Armillaria root rot), a hyperparasite, and yield. Second, we asked about their perceptions of the relationship between climate and long-term changes in fungal disease levels and subsequently tested whether these relationships were supported based on meteorological data. To further strengthen the evidence for the relationships uncovered, we examined whether there was a concordance between patterns through time and across space (i.e., space-for-time substitution). More specifically, we addressed the following questions:

- What changes in the climate did the farmers perceive during the period from 1990 to 2020?
- What changes did farmers perceive in the level of the four major fungal diseases, total pests and diseases, hyperparasite, and coffee yield? Did the four fungal diseases change rank in terms of their perceived impact on yield?
- Are hypotheses on the potential link between climate change, disease dynamics, and yield, as based on answers from interviews with smallholder farmers and plantation managers, supported by climate data?
- Is variation in the perception of long-term changes in the four fungal diseases, total pests and diseases as well as yield related to spatial variation in local climatic and management variables? Is variation in the perception of the relative ranking of the four fungal diseases related to spatial variation in local climatic and management variables?
- Do farmers who perceived long-term changes in disease levels and yield use different management actions compared with farmers who did not perceive long-term changes in disease levels and yield?

2 | MATERIALS AND METHODS

2.1 | Study area and system

The study was conducted in Goma and Gera districts (7°37′–7°56′N and 36°13′–36°39′E) in Jimma zone, southwestern Ethiopia (Figure 1a). The region has a long history of coffee-based agricultural practices and is known for being one of the centers of indigenous diversity of Arabica coffee. It is also one of the major coffee-producing regions in Ethiopia (Ango et al., 2014; Zewdie et al., 2020). The landscape consists of a mosaic of primary and secondary moist Afromontane forests and forest fragments, within which coffee is frequently produced, as well as a variety of other land uses such as agricultural land, grazing land, and human settlements (Koelemeijer et al., 2021). The region has a mean daily minimum and maximum temperature of 12.0 and 26.4°C, respectively (Zignol et al., 2023). Rainfall follows a unimodal pattern with low rainfall from November to February and a rainy season between June and September, with annual rainfall ranging between 1500 and 2000 mm. The coffee farms of the interviewed farmers are located between 1506 and 2159 m above sea level (Zewdie et al., 2020).

Arabica coffee is native to the moist Afromontane forests of southwestern Ethiopia, where it still can be found growing naturally as an understory tree. Within the same landscape, coffee is also growing along a broad gradient of management intensity, ranging from minimal management in the natural forest to moderate management in smallholder farms and intensive management in commercial plantations (Zewdie et al., 2022). Several studies have warned that coffee production is threatened by climate change (Davis et al., 2012; Moat et al., 2017), which might be partly due to climate-mediated changes in pests and diseases (Jaramillo et al., 2011). There are four major fungal diseases in the study area (Figure 1b–e). Coffee leaf rust, caused by *H. vastatrix*, causes defoliation and branch dieback (Avelino et al., 2004; Zewdie et al., 2021). Coffee berry disease, caused by *C. kahawae*, causes mummification and premature drop of coffee berries (Hindorf & Omondi, 2011; Motisi et al., 2022). Coffee wilt disease, caused by *G. xylarioides*, infects the vascular system of the coffee tree, after which the tree wilts and eventually dies (Girma et al., 2009). Armillaria root rot, caused by *A. mellea*, infects the roots and kills the coffee tree (Zewdie et al., 2020). Coffee plantations and some smallholder farmers in the study area use locally-selected cultivars resistant to coffee berry disease (Burger et al., 2022; Zewdie et al., 2022). Previous studies have found no evidence for cross-resistance (or the reverse, susceptibility) between coffee berry disease and other diseases, such as coffee leaf rust (Daba et al., 2019; McDonald & Linde, 2002).

2.2 | Interviews

To understand perceptions of climate change and the long-term dynamics of the four major fungal diseases, hyperparasite, and yield, as well as the relationships between climate, disease, hyperparasite, and

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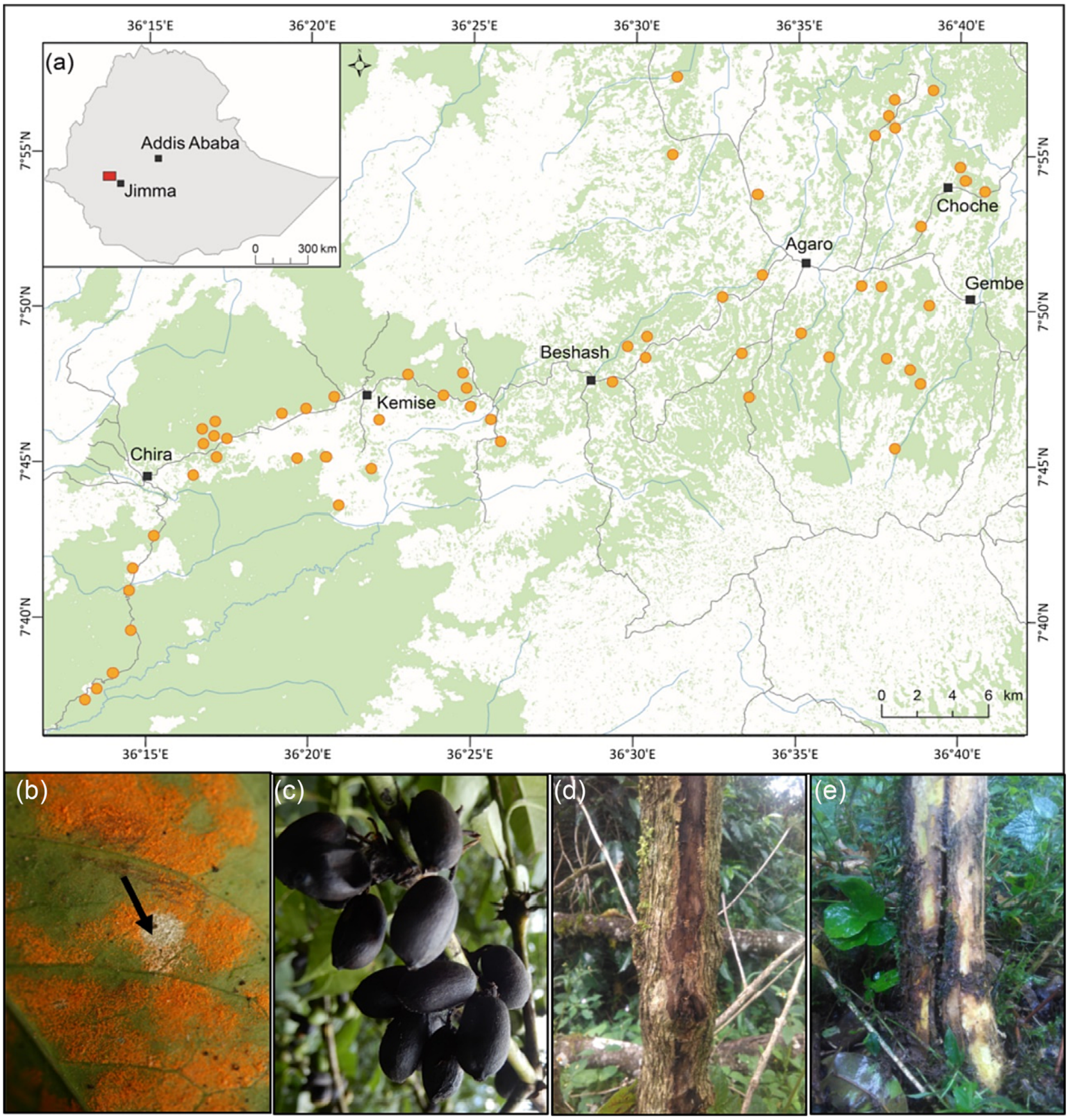

FIGURE 1 Overview of the study location in Jimma zone, southwestern Ethiopia. Panel (a) shows a map of the 50 × 50 km study area, with the inset showing the location of the study area (red rectangle) within southwestern Ethiopia. The 58 study sites are visualized as orange circles, and the green and white background colors represent wooded and open areas, respectively. Panels (b–e) show the four major fungal diseases and the hyperparasite: (b) the orange-colored uredospores of coffee leaf rust (*Hemileia vastatrix*) and the white spores of its hyperparasite (*Lecanicillium lecanii*) (arrow), (c) berries mummified by coffee berry disease (*Colletotrichum kahawae*), (d) a wilted stem caused by coffee wilt disease (*Gibberella xylarioides*), and (e) a cracked stem caused by *Armillaria* root rot (*Armillaria mellea*) (photos credit: Biruk Ayalew).

yield, we interviewed 50 smallholder farmers and 8 commercial coffee plantation managers (from eight plantation sites, as distributed across four large plantations) between February and March 2020 (henceforth all referred to as “farmers”). The surveyed coffee farms were previously selected with the aim to represent a broad gradient of coffee management, ranging from minimal management in the natural forest to moderate management in the smallholder farms and intensive management in the commercial coffee plantations (for more details on site selection, see Zewdie et al., 2020). Of the 58 farmers interviewed, nearly all (95%) were males, and the farmers were between 27 and 82 years old, with an average of 49.1 ± 15.2 (±SD). Surveyed farmers did not receive compensation for the survey, and all ethical procedures were followed including the consent of study participants.

The interviews were conducted using a semi-structured questionnaire in Afaan Oromo and Amharic, which are the common languages used by the local community. Interviews were conducted either on the farm or at the farmer's house and lasted 70–90 min. To document farmers' perceptions of climate change and long-term changes in the incidence of the four major fungal diseases, the hyperparasite, and yield, farmers were asked about their (i) perceptions of long-term changes in climatic variables, (ii) perceptions of long-term changes in the levels of the four major fungal diseases, both in absolute terms and as ranked in comparison with each other, (iii) perceptions of long-term changes in the hyperparasite, (iv) perceptions of long-term changes in yield, (v) perceptions of the relationships between climate and long-term changes in disease levels, hyperparasite, and yield, and

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(vi) management strategies used against diseases. We also asked farmers about their perceptions of the total level of pests and diseases; while this metric is not solely focusing on diseases, as are the other metrics, we think it is still informative. During the interview, we allowed farmers to report non-linear patterns through time using reference points such as the reign of Haile Selassie (c. 1970), the fall of the Derg (1990), the leadership of Meles Zenawi (c. 1991–2012), and the election of Abiy Ahmed (2018). Yet, with few exceptions, farmers reported linear increases, decreases, or no change, and we hence took the fall of the Derg as the reference point as it is a well-defined period in history. In those cases where farmers had no memory of this period due to young age ($n = 3$), we sought assistance from their older neighbors. For the full set of interview questions, see Methods S1. To avoid leading questions, we asked both open-ended and closed questions during the interview and ordered the questions so that we expected only true relationships to appear. If the farmer did not recognize the names of the diseases and hyperparasite, we used photographs of symptoms of the four fungal diseases and hyperparasite, or, if the interview was conducted on the farm, we pointed them out directly.

2.3 | Climate and management variables

To examine whether farmers' perceptions of the causal relationships between climate and long-term changes in fungal disease levels, hyperparasite and yield were supported by changes in climatic data, we extracted climate variables for each of the 58 sites, focusing on those climatic variables that farmers reported as the drivers of change. Because local historical data are few in the region, we used the global re-analysis data set ERA5-Land, which has a horizontal resolution of approximately 11.1 km (released on a regular 0.1° × 0.1° grid), and is freely available at the website https://cds.climate.copernicus.eu (Muñoz Sabater, 2019). We had a total of 12 grid cells across the 58 sites, and for each grid cell, we extracted the annual means of the climatic variables and calculated the average temperature and rainfall for the past climate (1980–1994, which encompasses the historical reference point of the fall of the Derg as used in the interviews) and current climate (2006–2020).

To understand spatial variation among farmers in their perception of long-term changes in climate, disease levels, hyperparasite, and yield, we recorded local air temperature using iButtons (model DS1921G-F5, Maxim Integrated, San Jose, CA, USA) at each of the 58 study sites for a full year from March 2019 to February 2020. The iButtons were attached to branches of coffee at a height of approximately 1.5 m above the ground using an iButton wall mount (Maxim Integrated). The iButtons were placed to avoid direct sunlight and were set to record every 3 h. For each study site, we calculated the annual mean temperature. For rainfall, we had no local data, and we therefore extracted annual mean rainfall for the period 1991–2020 from the ERA5-Land global re-analysis data set. We further obtained management variables from plots previously established on the farms (Ayalew et al., 2022; Zewdie et al., 2020). In short, in 2017, we established a 30 × 30 m plot in each of the 58 farms, where we collected data on canopy cover (based on five canopy photos; Ayalew et al., 2022), coffee management intensity (which ranges from 1 for coffee with little or no management to 3 for intensively managed coffee; Zewdie et al., 2021), and the proportion of coffee cultivars resistant to coffee berry disease (as based on interviews with the farmers and field observations; Ayalew et al., 2024). The elevation of each study site was measured with a Garmin GPS MAP 64 s (Figure 1).

2.4 | Statistical analysis

All statistical analyses were conducted in R v. 4.1.3 (R Core Team, 2020).

To examine general trends in farmers' perceptions of long-term changes in climatic variables, disease levels, hyperparasite, and yield, we used Chi-square goodness-of-fit tests. As very few farmers responded with "no change" (see Section 4), we used two classes in the test (increase, decrease), omitting those responding "no change," with the null expectation defined as 50:50 (R Core Team, 2020). To examine changes in the relative ranking of disease levels, we used 4 × 2 (rows × columns) contingency tests. For both goodness-of-fit and contingency tests, we used the function *chisq.test* in base R.

To examine whether farmers' perceptions of the causal relationships between climate and long-term changes in fungal disease levels, hyperparasite and yield were supported by changes in climatic data, we first formulated hypotheses based on farmers' answers on the relationship between climate, long-term changes in fungal diseases, hyperparasite, and yield (Table 1). We then compared the past (1980–1994) and current climate (2006–2020) to test whether these hypotheses were supported by climatic data or not. When there was a match between the hypotheses and test statistics, we inferred that there was meteorological support for the hypothesis. Means from both periods were compared using a *t*-test using the function *t.test* in base R.

To examine spatial variation among farmers in their perception of long-term changes in disease levels, hyperparasite, and yield, we modelled the perception of long-term changes in each of the four fungal diseases, total pest and disease levels, the hyperparasite, and yield as functions of mean annual temperature (March 2019 to February 2020) and rainfall (1991–2020). As also factors other than climate can influence the perception of long-term changes in disease levels, hyperparasite, and yield, we further included the variables canopy cover, management intensity, and proportion of coffee berry disease-resistant cultivars. As few farmers responded with "no change," we modelled the direction of change (0 = decrease; 1 = increase) with a binary distribution and logit link. Models were implemented using the function *glm* in the R package *lme4* (Bates et al., 2015). To examine spatial variation among farmers in their perception of the relative rank of the four fungal diseases, we modelled perception of the relative rank of each of the four fungal diseases as functions of mean annual temperature (March 2019 to February 2020), rainfall (1991–2020), canopy cover, management intensity, and proportion of coffee

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TABLE 1 Overview of hypotheses generated on climatic drivers of changes in disease levels (total pests and diseases, coffee leaf rust, coffee berry disease, coffee wilt disease, and Armillaria root rot) and yield, and an evaluation of whether the hypotheses received meteorological support. Hypotheses were generated based on answers from the farmer interviews, where we asked explicitly about climate–disease–yield relationships. Past climate data is based on the period 1980–1994, and current climate data is based on the period 2006–2020. These dates were chosen to match the baseline year 1990, as well as the year of the interviews (2020). We used a *t*-test to test whether the perception of farmers about the link between climatic variables, diseases, and yield was supported by meteorological data. When there was a match between the hypotheses and test statistics, we inferred that there was meteorological support for the hypothesis. Test statistics and associated degrees of freedom are reported in Table S1.

Response variable	Perception of link between climatic variables, diseases, and yield	Climatic variable	Mean ± SE		*p*-value	Support for hypothesis
			Past	Current		
Total pest and disease levels	The incidence of pests and diseases has increased over time due to an increase in mean annual temperature.	Temperature (°C)	16.5 ± 0.1	17.0 ± 0.1	<0.001	Yes
Coffee leaf rust	The incidence of coffee leaf rust has increased over time due to an increase in mean temperature during the dry season.	Temperature (°C)	17.2 ± 0.1	18.1 ± 0.1	<0.001	Yes
Coffee berry disease	The incidence of coffee berry disease has decreased over time due to an increase in mean temperature during the rainy season (i.e., June–September).	Temperature (°C)	15.5 ± 0.1	15.9 ± 0.1	0.007	Yes
	The incidence of coffee berry disease has decreased over time due to a decrease in the quantity of rainfall during the rainy season (i.e., June–August).	Rainfall (mm)	654.0 ± 13.7	643.0 ± 19.7	0.60	No
	The incidence of coffee berry disease has decreased over time due to a decrease in the number of rainy days during the rainy season (i.e., June–August).	Number of rainy days	89.0 ± 0.4	86.3 ± 0.8	0.01	Yes
Coffee wilt disease	The incidence of coffee wilt disease has increased over time due to an increase in mean annual temperature.	Temperature (°C)	16.5 ± 0.1	17.0 ± 0.1	<0.001	Yes
Armillaria root rot	The incidence of Armillaria root rot has decreased over time due to an increase in mean annual temperature.	Temperature (°C)	16.5 ± 0.1	17.0 ± 0.1	<0.001	Yes
Yield	Coffee yield has decreased due to an increase in mean annual temperature.	Temperature (°C)	16.5 ± 0.1	17.0 ± 0.1	<0.001	Yes
	Coffee yield has decreased due to an increase in mean temperatures during flowering (i.e., February–March)	Temperature (°C)	17.7 ± 0.1	18.6 ± 0.1	<0.001	Yes

cultivars. For this, we used ordinal models (with 1 = least problematic and 4 = most problematic) using the function *clm* in the *ordinal* package (Christensen, 2020). We scaled continuous variables to mean zero and unit variance (Schielzeth, 2010), and tested for significance using the function *Anova* in the car package (Fox & Weisberg, 2018).

To examine if management strategies were affected by perceptions of long-term changes in disease levels and yield, we used permutational multivariate analysis of variance (PERMANOVA) as implemented in the function *adonis2* (with the argument by = “margin”) in the *vegan* package (Oksanen et al., 2020). As a response variable, we used the management actions-by-site matrix, where we included the 10 most common management actions (use of improved cultivars, fertilizer application, herbicide application, shade management, organic matter application, mulching, slashing [weeding], intercropping, hoeing, as well as soil and water management). As management actions were binary variables, we used the Jaccard metric to create the dissimilarity matrix. The predictor variables were the perceptions of changes in each of the four fungal diseases, total pest and disease levels, and yield. To visualize the patterns and drivers, we used non-metric multidimensional scaling (NMDS) using the *metaMDS* function in the R package *vegan*, based on dissimilarities calculated using binomial dissimilarity (Oksanen et al., 2020).

3 | RESULT

3.1 | Perceived changes in climate

All 58 interviewed farmers perceived changes in one or more climatic variables during the 30-year period from 1990 to 2020 (Figure 2). Of

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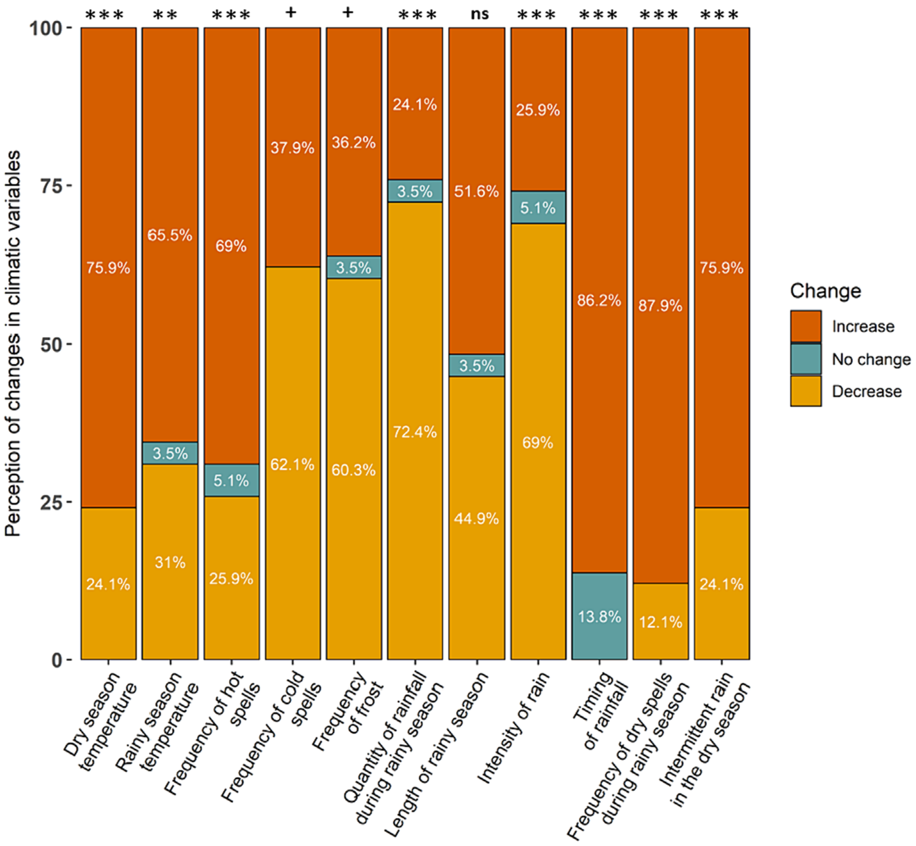

FIGURE 2 Perceived changes in climatic variables during the period 1990–2020 by 58 farmers in Jimma zone, southwestern Ethiopia. Shown are the percentages of farmers that perceived an increase (red), decrease (orange), or no change (blue) in a given climatic variable. Above each vertical bar is shown the significance (*** = <.001, ** = <.01, * = <.05, + = <.1; ns = non-significant) of a chi-square goodness-of-fit test testing for a 50:50 proportion of farmers reporting an increase or decrease.

the temperature-related variables, the majority of farmers perceived an increase in temperature during the dry (75.9%; $\chi^2 = 15.51$; $p < .001$) and the rainy season (65.5%; $\chi^2 = 7.14$; $p = .007$) and an increase in the frequency of hot spells (69%; $\chi^2 = 33.37$; $p < .001$). Of the rainfall-related variables, the majority of farmers perceived a decrease in the quantity and intensity of rainfall during the rainy season (72.4%; $\chi^2 = 13.99$; $p < .001$ and 69%; $\chi^2 = 15.51$; $p < .001$, respectively), as well as shifts in the timing of rainfall in the form of a later start of the rainy season (86.2%; $\chi^2 = 50.11$; $p < .001$), an increase in the frequency of dry spells during the rainy season (87.9%; $\chi^2 = 33.38$; $p < .001$) and an increase in the frequency of intermittent rain during the dry season (75.9%; $\chi^2 = 15.52$; $p < .001$).

3.2 | Perceived changes in fungal disease levels and coffee yield

While the majority of farmers perceived an overall increase in pest and disease levels (70.2%; $\chi^2 = 16.49$; $p < .001$), patterns differed among individual diseases (Figure 3). The majority of farmers perceived an increase in coffee leaf rust (82.5%; $\chi^2 = 27.66$; $p < .001$) and a decrease in coffee berry disease (58%; $\chi^2 = 6.56$; $p = .01$), whereas perceptions of changes in coffee wilt disease (52.7%; $\chi^2 = 1.58$; $p = .21$) and Armillaria root rot (49%; $\chi^2 = 1.0$; $p = .32$) were highly variable among farmers. Of the five farmers who remembered coffee diseases during Haile Selassie's reign, four farmers reported the absence of coffee leaf rust, and one farmer reported the absence of coffee berry disease. The pattern of perceived changes in disease levels matched the pattern of perceived changes in the relative rank of the diseases with regards to their impact on yield, which showed an increase in the relative impact of coffee leaf rust and a decrease in the relative impact of coffee berry disease (Figure S1). None of the farmers recognized the hyperparasite. Half of the farmers reported a decrease in yield (48%), whereas the other half perceived an increase in yield (51.7%; $\chi^2 = 1.9$; $p = .17$; Figure 3).

3.3 | Meteorological support for climate-mediated changes in disease levels and yield

Based on answers from the farmers on the relationship between climate, disease, and yield, we set up hypotheses on the relationships between climatic variables, the four fungal diseases, as well as yield, as presented in Tables 1 and S1. We then compared historical and current meteorological data to test whether there was statistical support that the postulated climate–disease–yield relationships could have driven the perceived temporal changes in disease levels. Regarding total pests and diseases, climate data supported an increase in pest and disease levels due to higher annual mean temperatures (Tables 1 and S1). Regarding coffee leaf rust, climate data supported the hypothesis of an increase in coffee leaf rust due to

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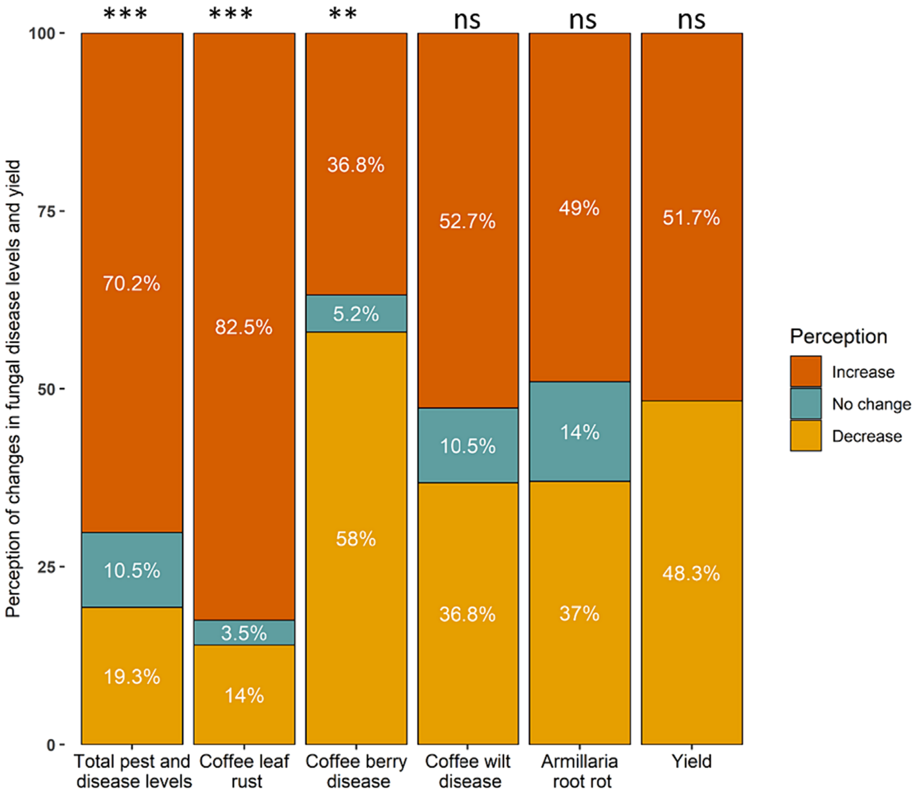

FIGURE 3 Perceived changes in total pest and disease levels, fungal disease levels, and coffee yield during the period 1990–2020 by 58 farmers in Jimma zone, southwestern Ethiopia. Shown are the percentages of farmers that perceived an increase (red), decrease (orange), or no change (blue) in total pest and disease levels, fungal disease levels, and yield. Above each vertical bar is shown the significance (*** = <.001, ** = <.01, * = <.05, ns = non-significant) of a chi-square goodness-of-fit test testing for a 50:50 proportion of farmers reporting an increase or decrease.

higher mean temperatures during the dry season (Tables 1 and S1). For coffee berry disease, the support was mixed: We found support for the hypothesis that the decrease in coffee berry disease was due to increased mean temperatures and a decrease in the number of rainy days during the rainy season, but not for the hypothesis of a decrease in coffee berry disease due to a decrease in the quantity of rainfall during the rainy season (Tables 1 and S1). Beyond the climatic drivers, farmers mentioned that the decrease in coffee berry disease was due to an increase in the use of resistant cultivars and increasing management intensity. While there was much variation among farmers in their perception of temporal changes in coffee wilt disease and Armillaria root rot (i.e., there was no general consensus), climate data did support the hypotheses generated based on farmer interviews that coffee wilt disease increased and Armillaria root rot decreased due to higher annual mean temperatures (Tables 1 and S1). Regarding yield, climate data supported the hypotheses of a decrease in yield due to an increase in mean annual temperature and an increase in mean temperature during the coffee flowering period (Tables 1 and S1).

3.4 | Drivers of spatial variation in the perception of long-term changes in disease levels and yield

Variation among farmers in their perception of changes in disease levels and yield were strongly related to variation in current local mean annual temperature and rainfall, albeit differently for the different diseases (Table S2). The probability that farmers perceived an increase rather than a decrease in total pest and disease levels, coffee leaf rust and coffee wilt disease were higher in sites with higher mean temperatures, whereas the probability that farmers perceived an increase in coffee yield was higher in locations with a lower mean temperature (Figure 4a–d, Table S2). The probability that farmers perceived an increase in coffee berry disease was higher in locations with higher mean annual rainfall and in locations with a low proportion of coffee cultivars (Figure 4e–i, Table S2). The probability that farmers perceived an increase in total pest and disease levels was higher in locations with higher canopy cover and with a low proportion of coffee cultivars (Figure 4f–h, Table S2). The probability that farmers perceived an increase in coffee leaf rust was higher in locations with higher management intensity (Figure 4g). Perceptions of other diseases and yield were not related to canopy cover, management intensity, and the proportion of cultivars (Table S2).

The relative ranking of the four fungal diseases was related to spatial variation in climatic and management variables (Figure S2, Table S3). The probability that farmers perceived coffee leaf rust and coffee wilt disease as the major problem was higher at locations with higher mean temperatures, whereas coffee berry disease was perceived to be less problematic in relation to the others at locations with high temperatures (Figure S2a–c, Table S3). The probability that farmers perceived coffee leaf rust as the major problem was lower at locations with high rainfall, whereas coffee berry disease and Armillaria root rot were perceived to be relatively more problematic at locations with high rainfall (Figure S2d–f, Table S3). The relative ranking of the diseases was also affected by canopy cover, management intensity and the proportion of cultivars used (Table S3).

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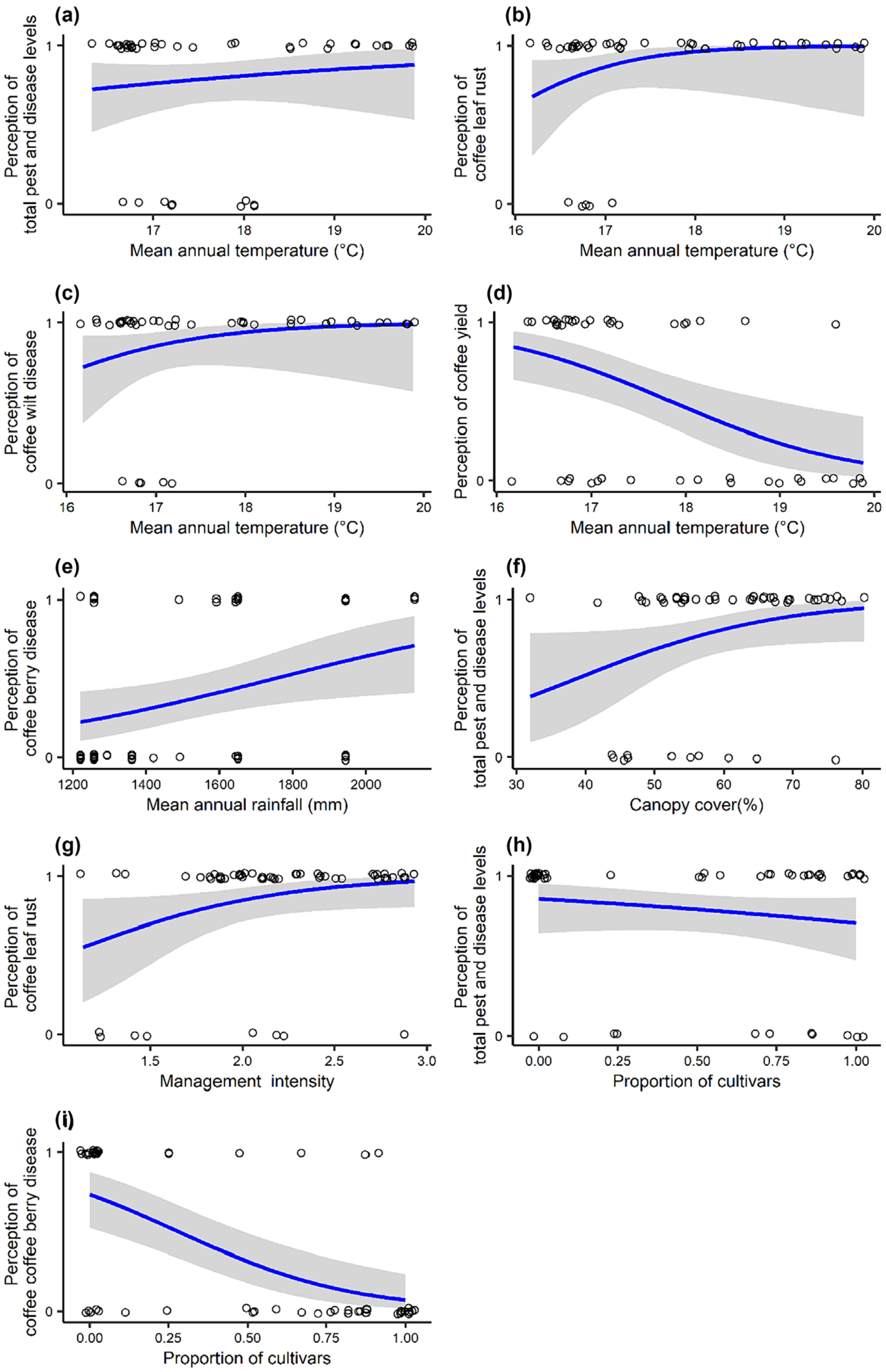

FIGURE 4 The relationship of mean annual temperature (March 2019 to February 2020), mean annual rainfall (1991–2020), and management variables with spatial variation among 58 farmers in the perception of long-term changes in disease levels and yield. Shown are the relationships of mean annual temperature with perception of changes in (a) total pest and disease levels, (b) coffee leaf rust, (c) coffee wilt disease and (d) coffee yield, (e) the relationship of mean annual rainfall with perception of changes in coffee berry disease, (f) the relationship of canopy cover with perception of changes in total pest and disease levels, (g) the relationship of management intensity with perception of coffee leaf rust, as well as the relationships of the proportion of cultivars with perception of changes in (h) total pest and disease levels and (i) coffee berry disease. The vertically-jittered binary data points represent the perception by a farmer of a decrease (0) or increase (1) in the response variable. The blue solid trend line represents a significant relationship obtained from a simple generalized linear model with binomial distribution. Shaded areas represent the 95% confidence interval. Statistical summaries from the models are presented in Table S2.

3.5 | The relationship between management strategies and the perception of changes in long-term disease dynamics and yield

The perception of climate-mediated long-term changes in coffee berry disease was strongly related to the composition of management practices ($R^2 = .13$), while the perception of climate-mediated long-term changes in yield was weakly related to the composition of management practices ($R^2 = .06$), and perceptions of changes in other diseases were not related to differences in management practices (Table S4; Figures 5 and S3). Farmers who perceived a decrease in coffee berry disease more frequently used soil and water conservation, shade management, weeding, and coffee berry disease-resistant cultivars (Figure 5).

4 | DISCUSSION

We used local knowledge to reconstruct climate-mediated changes in disease levels, a hyperparasite, and coffee yield in the area of origin of

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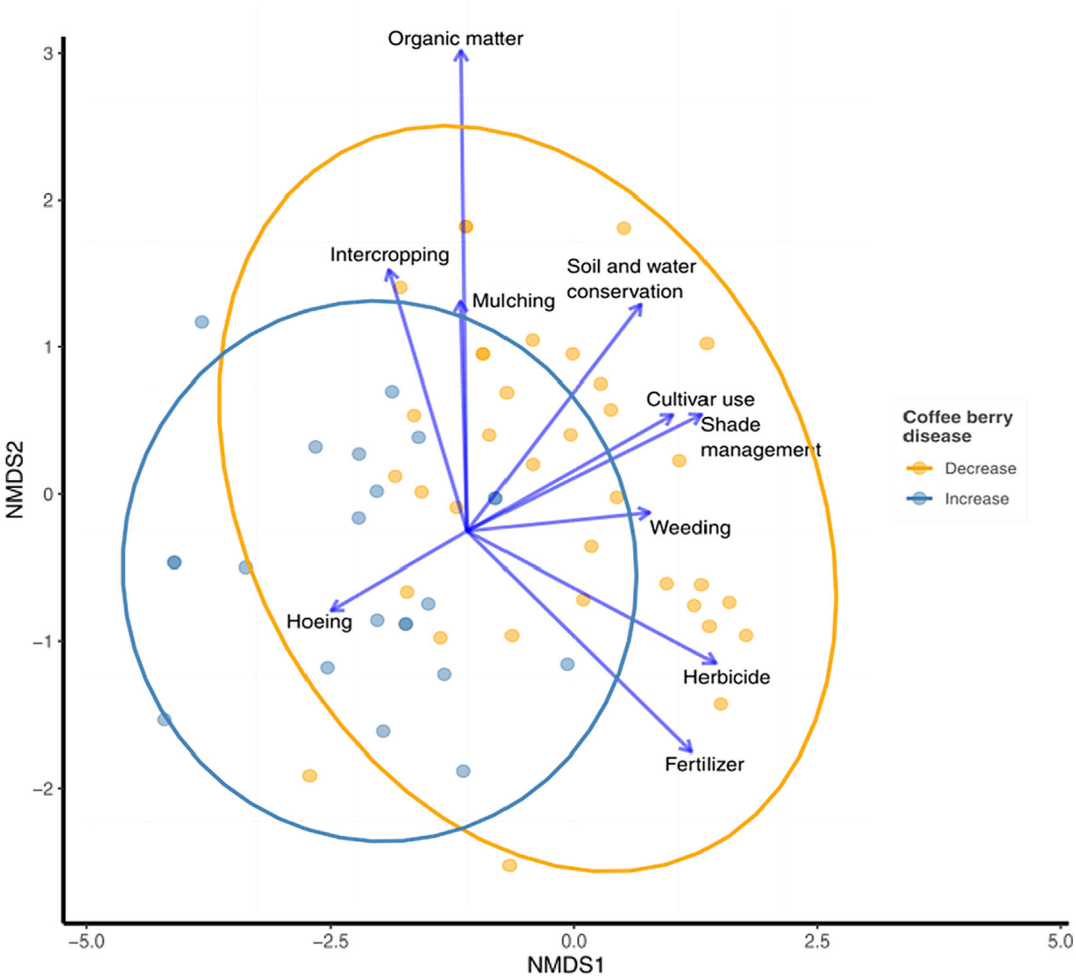

FIGURE 5 The relationship between farmers' perceptions of long-term changes in coffee berry disease and management actions in Jimma zone, southwestern Ethiopia. Visualization is based on non-metric multidimensional scaling (NMDS) using the binomial metric (stress value = 0.11). Plot ellipses represent the 95% confidence regions surrounding each group. Blue and orange circles indicate an increase and decrease in the perception of long-term changes in coffee berry disease. Vector names represent management actions.

Arabica coffee in southwestern Ethiopia. All farmers perceived long-term changes in one or more climatic variables, and the majority of farmers perceived an increase in coffee leaf rust (83%) and a decrease in coffee berry disease (58%). None of the farmers recognized the hyperparasite. Meteorological data and space-for-time substitution largely supported hypotheses on climate–disease–yield relationships generated based on farmers' answers in the interviews. Our findings highlight that the approach we adopted—combining local knowledge, climate data, and field surveys—enabled us to reconstruct disease time series and postulate and validate hypotheses for climate–disease–yield relationships in areas where long-term historical time series data are lacking. As a next step, these hypotheses can be tested further using experimental studies. These insights are important to develop sustainable climate-resilient management strategies.

Almost all farmers perceived changes in the climate during the past three decades. The most commonly observed changes related to an increase in temperature during the dry and wet seasons and the frequency of hot spells, as well as a decrease in the quantity, and shift in the timing, of rainfall. These patterns generally matched well with meteorological studies within the study region, which reported increases in temperature and shifts in the timing of rainfall (Abazinab et al., 2022; Fekadu et al., 2020; Gemeda et al., 2021), illustrating that farmers are well aware of long-term climatic changes. Yet, one discrepancy was apparent: farmers' perceptions of a decrease in rainfall during the rainy season were not supported by meteorological data (Gemeda et al., 2021; Habte et al., 2021). Discrepancies between farmers' perceptions and meteorological data are often thought to indicate that climatic events or trends are misinterpreted or wrongly remembered for a variety of reasons related to educational, cultural, psychological and social factors, and influenced by exposure to the media (Asare-Nuamah & Botchway, 2019; Habte et al., 2021; Niles & Mueller, 2016). Yet, we think it is equally likely that sparse, often far away, and intermittent long-term meteorological records, and regional climate models calibrated on them, might not capture the local climate experienced by the farmers, especially for climatic variables that are notoriously difficult to record and model, such as rainfall (Simelton

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et al., 2013). Hence, while concordance between farmers' perceptions and climate models strengthens the evidence for climatic changes, discordance highlights aspects of the climate that require further meteorological enquiry and ground-truthing.

Regarding long-term changes in disease levels and yield, the majority of farmers perceived an increase in total pest and disease levels and coffee leaf rust, and a decrease in coffee berry disease, whereas farmers' perceptions of changes in coffee wilt disease, Armillaria root rot, and yield were highly variable among farmers. This pattern was also reflected in the perceived changes in the relative rank of the four fungal diseases in terms of their impact on yield. In agreement with our findings, a climate-mediated increase in coffee leaf rust has been reported in Tanzania (Mbwambo et al., 2021) and Central America (Bacon et al., 2017; Dupre et al., 2022), as well as in coffee wilt disease in Africa (Zhan et al., 2018). Similarly, coffee plantation experimental research in Cameroon showed that the severity of coffee berry diseases decreases with increasing temperature (Mouen Bedimo et al., 2012), but we lack comparable data on the relationship between climate change and Armillaria root rot. Interestingly, of the five farmers who remembered Haile Selassie's reign (c. 1970), one farmer reported that coffee berry disease was absent during that period, and four farmers reported that coffee leaf rust was absent during that period. While there is strong scientific consensus that coffee berry disease was indeed absent from Ethiopia before 1971 (van der Graaff, 1981), coffee leaf rust was already reported by European explorers when they passed through the Ethiopian coffee zones in the 1850s (McCook, 2006; Sylvain, 1958). This might suggest that coffee leaf rust has until recently been patchily distributed or present in very low densities, as is common for wild plant pathogens (Burdon & Laine, 2019). Regarding the hyperparasite, none of the farmers were aware of the presence of the hyperparasite and its potential role in regulating coffee leaf rust (Zewdie et al., 2021). The lack of knowledge of fungal hyperparasites among smallholder farmers matches reports of the lack of knowledge on insect parasitoids in Central America (Morales, 2002; Segura et al., 2004), but contrasts with the presence of local knowledge on other species groups that provide ecosystem services, such as pollinators and predators of insect pests (Hevia et al., 2021; Martínez-Sastre et al., 2020). We suggest there are several mutually non-exclusive explanations for the lack of awareness about the existence and role of the hyperparasite: (i) the pathogen–hyperparasite interaction is difficult to observe, as it plays out over several days or weeks, (ii) the hyperparasite plays only a weak, or no, role in suppressing disease levels, (iii) as coffee leaf rust attacks the leaves, which are not harvested, the disease is perceived to have a lower impact on crop yield, and natural enemies on leaf diseases thus receive less attention, and (iv) the low educational level of the farmers. Creating awareness about the hyperparasite and its role in controlling rust might be important for sustainable coffee production.

We also directly asked farmers about their perceptions of causal relationships between climate, diseases, and yield and used their responses to generate and test hypotheses on the drivers of long-term climate-mediated changes in disease and yield levels. The meteorological data largely supported farmers' perceptions of climate–disease–yield relationships. Matching the paradigm that climate change is increasing the overall pest and disease burden on crops (Chaloner et al., 2021), farmers perceived that increasing temperatures were the main driver of increases in total pest and disease levels. Yet, there was much species-specific variation hiding behind this general pattern. Farmers perceived that increasing temperatures during the dry season were the main driver of increases in coffee leaf rust, whereas increasing temperatures during the rainy season were the main driver of a decrease in coffee berry disease. The meteorological data also confirmed farmers' perceptions of a decrease in coffee berry disease due to a decrease in the number of rainy days in the rainy season, and we thus have multiple, non-mutually exclusive hypotheses for the temporal dynamics of coffee berry disease. In line with our findings, several authors reported that a lower number of rainy days may limit spore dispersal and infection (Griffiths & Waller, 1971; Mouen Bedimo et al., 2012). While farmers did not agree on whether or not coffee wilt disease increased (i.e., there were equal numbers of farmers who perceived a decrease or increase), meteorological data supported farmers who linked an increase in coffee wilt disease with rising annual temperatures. A positive relationship between temperature and coffee leaf rust and coffee wilt disease matches previous studies (Adugna et al., 2008; Avelino et al., 2012; Gagliardi et al., 2020; Zhang et al., 2023), and the mechanisms are likely that temperature increases pathogen development rate, is harmful to host physiology, and decreases host resistance (Elad & Pertot, 2014; Pautasso et al., 2012). While farmers did not agree on whether or not coffee yield increased, meteorological data supported those farmers who perceived a decrease in coffee yield due to an increase in mean annual temperature and temperature during flowering. This matches previous reports that increasing temperature is associated with reduced coffee yield (Bunn et al., 2015; Kath et al., 2020; Pham et al., 2019) and that high temperatures during flowering can cause flower abortion and increase the formation of malformed star flowers (Cannell, 1985; Craparo et al., 2015; Pham et al., 2019). In general, our findings highlight that farmers' perceptions of the relationships between climate, disease, and yield were largely supported by meteorological data, confirming the value of local knowledge for understanding climate-mediated disease dynamics. Yet, there are also other factors than climate that may influence the temporal dynamics of pest and disease levels, such as coffee price fluctuations. For example, low coffee prices during the first decade of the second millennium negatively affected management practices in Latin America, resulting in higher pest and disease levels (Rhiney et al., 2021). While low coffee prices might also have left an imprint in the temporal dynamics of pests and diseases in SW Ethiopia, we argue that this is less likely for several reasons: (i) coffee management is generally extensive in SW Ethiopia, with small plots (ii) smallholder farmers do not use costly chemical inputs, and (iii) much of the coffee consumption is local. From talking to the farmers, we did however get the strong impression that low coffee prices in the market discourage further intensification. Beyond coffee prices, also changes in management and the increases and decreases in other pests and pathogens might explain (part of) the temporal dynamics in our focal diseases (Muneret

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et al., 2018; Simler-Williamson et al., 2019). As such, we think that it is important that future studies will focus on factors other than climate that may have caused temporal changes in pest and disease dynamics. Finally, as our data is correlative by nature, it is important for future research to validate the causal mechanisms underlying the temporal dynamics of disease levels using experimental research, for example, by climate-controlled growth chamber or reciprocal field inoculation studies with a variety of local strains and coffee genotypes, to assess the impact of temperature and other climatic variables on disease dynamics (Belachew et al., 2015; Cruz et al., 2019; Zhang et al., 2023).

The perception of climate change and its impacts on crop disease and yield may not be uniform across the landscape because environmental factors such as local climate and other site-specific characteristics are highly heterogeneous. For example, if a disease is favored by temperature, a small increase in temperature might be perceived as more problematic, and thus more apparent, at locations where the temperature is already high. In agreement with this hypothesis, we found that farmers' perceptions of changes in disease levels and yield were spatially variable and strongly related to local mean annual temperature and rainfall, but differently for the different diseases. For example, farmers perceived not only long-term increases in total pest and disease levels and coffee leaf rust with rising temperatures but also more frequently reported such changes at locations with a higher temperature. This may suggest that a small increase in temperature might be more problematic in already warm places. Overall, our findings indicate that a warmer climate will shift the composition of the disease community by favoring coffee leaf rust, and possibly coffee wilt disease, but disfavoring coffee berry disease. Additionally, a decrease in the number of rainy days and an increase in CBD-resistant cultivars will have a negative impact on coffee berry disease. Regarding yield, we found that the probability that farmers perceived an increase in coffee yield was higher in colder locations, which are generally also characterized by higher soil moisture and lower evapotranspiration (Kath et al., 2022). This implies that coffee farms located at relatively cool locations are now better suited for coffee production than they were in the past. Interestingly, this matches observations by the authors and others (e.g., Moat et al., 2017) that farmers are currently initiating coffee production above the traditional elevational range for coffee cultivation. In contrast, coffee cultivation at low-elevation sites characterized by high temperatures might become less favorable, and hence adaptation strategies to mitigate the effects of warming are particularly critical at low elevations.

Farmers' perceptions of climate-mediated changes in disease levels and yield may shape management strategies (Harvey et al., 2018; Segura et al., 2004; Valencia et al., 2018). Matching this expectation, our results show that management strategies differed among farmers who perceived long-term climate-mediated changes in coffee berry disease and—to a lesser extent—yield. Farmers who perceived a decrease in coffee berry disease more frequently used soil and water conservation, shade management, weeding, and improved cultivars than farmers who did not perceive changes in coffee berry disease. This supports previous reports that the use of irrigation, shade management, and improved cultivars can help to reduce coffee berry disease incidence (Benti et al., 2021; Garedew et al., 2017; Mouen Bedimo et al., 2007). In contrast, other diseases had no effect on management strategies. These data suggest that farmers take adaptation measures in response to the most problematic disease (i.e., coffee berry disease). However, the extent to which the management actions were driven by climate adaptation remains unclear.

From a methodological perspective, our study used local knowledge, climate data, and spatial field surveys to co-create knowledge on disease time series and test climate–disease–yield relationships. While there are few examples of the use of local knowledge within the field of plant pathology, our study highlights that local knowledge can provide us with an understanding of the long-term patterns and drivers of disease dynamics, which is crucial for developing climate-resilient disease management strategies. Yet, we also learned that there are several caveats to be aware of and potential for improvement. One limitation of this approach was that our interviews revealed few non-linear long-term changes in climate variables and disease levels, even though we explicitly referred back to well-known historical reference points in our questions, such as the reign of Haile Selassie (c. 1970), the fall of the Derg (1990), the leadership of Meles Zenawi (c. 1991–2012), and the election of Abiy Ahmed (2018). Moreover, the majority of farmers reported either increases or decreases, with very few farmers reporting no change, despite the fact that we took care not to ask leading questions. We suggest that this is partly related to cultural background, as the same pattern was found by Tesfaye (2022) and Habte et al. (2021) in their studies of farmers' perceptions of the long-term impacts of climate change and variability in Ethiopia. In order to improve the information obtained from farmers, and as complementary to semi-structured interviews, participatory research and group discussion might be helpful to identify other factors that drive the temporal dynamics of plant diseases, such as coffee prices, management practices, and increases or decreases in other pests. Moreover, future experiments can directly target the hypotheses co-created during the interviews. In general, our findings highlight that using local knowledge, climate data, and spatial field surveys enables us to reveal climate-mediated changes in diseases and yield in areas with few long-term time series data. Our finding is particularly important for the many countries that cannot capitalize on a wealth of historical data but are at the same time often most vulnerable to changes in the climate, many of which are in the Global South.

AUTHOR CONTRIBUTIONS

Biruk Ayalew, Kristoffer Hylander, and Ayco J. M. Tack conceived the ideas. Biruk Ayalew, Kristoffer Hylander, Lowe Börjeson, and Ayco J. M. Tack designed the questionnaire. Biruk Ayalew and Dinkissa Beche conducted the interviews. Biruk Ayalew translated and transcribed the data. Francesco Zignol worked on quality-checking of the data loggers. Biruk Ayalew analyzed the data. Biruk Ayalew led the writing of the manuscript, and all authors contributed to the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available on request from the corresponding author.

ETHICS STATEMENT

Fieldwork was led by Biruk Ayalew. Interviewees were told about the aims, potential outputs and methodology of the study, and prior informed consent (PIC) was gained verbally before interviews. The process for PIC followed guidelines provided by Stockholm University's Research ethical policy (dnr: SU FV-1.2.1-4285-20) that is grounded in "The European Code of Conduct for Research Integrity" (All European Academies, ALLEA, 2017).

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