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RESEARCH ARTICLE

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Smallholder farmers expand production area of the perennial crop enset as a climate coping strategy in a drought-prone indigenous agrisystem

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Societal Impact Statement
Climate resilient crops will become increasingly important, especially in regions where smallholder farmers are vulnerable to climate extremes. Enset, a multipurpose perennial staple crop consumed by over 20 million people in Ethiopia, purportedly provides food security during periods of drought. Here, we find evidence that frequent severe drought events led to an increase in enset production area. This is consistent with a broader pattern whereby farmers preferentially cultivate perennial and storable crops after long-term drought events, providing an example of adaptation to fluctuations in climate through crop choice in indigenous agrisystems.

Summary
- Smallholder farms in the semiarid and subhumid tropics are particularly vulnerable to increased climate variability. Indigenous agrisystems that have co-evolved with climate variability may have developed resilience strategies. In the Southwest Ethiopian Highlands, agrisystems are dominated by the multipurpose perennial staple enset (*Ensete ventricosum*), characterised by flexible harvest timing, high yield, long storage, and putative drought tolerance, earning it the name 'the tree against hunger'.
- We tested three hypotheses using crop production area and climate data. First, that enset production area is greatest in the most drought-prone locations. Second, that farmers respond to drought events by increasing enset production area. And third, that drought encourages shifts in agrisystem composition more widely towards perennial or storable crops.
- We found that regions with a higher severe drought frequency are associated with significantly higher proportion of enset production. Similarly, the Standardised Precipitation Evapotranspiration Index of the previous 3 years is significantly negatively correlated with enset production area time series, suggesting that prior drier conditions led farmers to increase the land under enset production. Regarding other crops, storage crops roots and tubers were also preferentially

selected after long-term drought over annual crops, indicating their capacity for longer-term resilience.

- Promoting the production of crops such as perennials, which have more extensive and established root systems, may be a strategy to ensure food security during drought or climate variability. These results indicate the potential of farmer's resilience strategies to improve food security in a changing climate.

KEYWORDS

climate change, drought tolerance, *Ensete ventricosum*, Ethiopia, food security

1 | INTRODUCTION

More than half of the world's food calories are grown on 380 million smallholder farms of less than two hectares (Samberg et al., 2016). Being largely rainfall dependent, with relative low levels of input and technology, smallholder farms are particularly vulnerable to climatic variability and extremes (Lin, 2011; Mbow et al., 2019; Morton, 2007). Rising temperatures and more variable rainfall often lead to reduced yields, especially for annual crops (Lobell et al., 2011; Ray et al., 2019; Vogel et al., 2019). Therefore, climate-related impacts to food security are projected to increase, particularly in the Global South (Aryal et al., 2021; Hoegh-Guldberg et al., 2018). This has resulted in greater focus on climate-resilient strategies based on indigenous agrisystems (Altieri et al., 2015) and in particular the identification of crops or cropping strategies that farmers use to tolerate climatic shocks such as drought.

Drought arises from a negative balance of water supply and demand and can be categorised in terms of intensity, duration, and extent (Funk & Shukla, 2020). Ethiopia has experienced multiple drought events over recent decades and is particularly exposed to climate-related impacts due to its dependence on rain-fed subsistence agriculture (Cochrane, 2017; Mekonnen et al., 2020). Extreme drought and famine in 1983–1984 resulted in over one million deaths from starvation and malnutrition (Fazzini et al., 2015) and more recent severe droughts occurred in 2000, 2002–2003, 2009, 2011, and 2015 (Bewket & Conway, 2007; Cochrane, 2017; Mera, 2018; Viste et al., 2013). Ethiopian farmers have reported a changing climate, characterised by increasing temperatures, greater rainfall variability and consequently more frequent drought (Bryan et al., 2009; Dalle & Daba, 2020; Demeke et al., 2011; Kreitzman et al., 2020; Shikuku et al., 2017). Rising temperatures and more variable seasonal precipitation are projected to increase the frequency and intensity of drought and potentially reduce Ethiopia's GDP up to 10% by 2045, further threatening the already vulnerable food security situation (World Bank Group, 2020). At the same time, the Ethiopian population is predicted to double to approximately 200 million people by 2050 (United Nations [UN], 2019), which will likely lead to increased fragmentation of smallholder farms (Cholo et al., 2018), further reducing food security and household incomes (Giller et al., 2021).

While multiple factors including climate change, land management, and population growth may have increased the impacts of drought in Ethiopia, the occurrence of periodic droughts in the Horn of Africa is not new (Kassaye et al., 2021). As an important center of crop diversity, characterised by the in situ domestication and development of numerous globally (e.g., coffee and sorghum) and regionally (e.g., enset and teff) important species, Ethiopia's indigenous agrisystems may have evolved attributes that provide resilience strategies to cope with environmental change and buffer food insecurity (Di Falco et al., 2011; Matewos, 2019; Waha et al., 2013). In the Southwest Ethiopian Highlands, where rainfall follows a bi-modal pattern comprising shorter spring rains (*Belg*) and longer summer rains (*Meher*), a prime example of an indigenous agrisystem putatively adapted to endure climate variability is enset-based agriculture. Enset (*Ensete ventricosum* (Welw.) Cheesman) is a starchy perennial crop that is only cultivated in Ethiopia, where it is consumed by more than 20 million people (Borrell et al., 2020). Enset, known as 'the tree against hunger' for its role in food security (Brandt et al., 1997), is exclusively grown on rain-fed smallholder farms in cropping systems containing a broad mix of other crops such as cash crops (e.g., coffee and khat), cereals, roots and tubers, pulses, vegetables, fruits and oilseeds, and in close conjunction with livestock (Borrell et al., 2020). Enset is valuable to smallholder subsistence farmers for its multiple uses (e.g., food, fiber, building material, animal fodder, medicine, and cultural value), rapid clonal propagation, high yield, flexible harvest time, storage potential, and perceived drought tolerance (Borrell et al., 2019; Morrow et al., 2022; Shumbulo et al., 2012); however, few studies have quantified the effects of climate on the area under enset production.

In this study, we collated 22 years of crop production area data and regional climate data and applied linear mixed-effects modelling to investigate the relationship between climate and crop production area, focusing on enset and associated food crops in Southwest Ethiopia. First, we tested the extent to which the spatial distribution and local importance of enset agriculture is explained by the historic regional prevalence of droughts. Second, using yearly crop production area data, we tested the hypothesis that farmers expand their enset cultivation over time, potentially as an insurance crop, in response to droughts. Third, we compared the effects of single or multiyear drought on the production area of co-occurring crops, including annuals and other perennials. We used these analyses to evaluate farmers' resilience strategies and their potential application under projected climate change.

2 | MATERIALS AND METHODS

2.1 | Crop production data

We collated yearly production area data in hectares (ha) for 52 crops grown in Ethiopia, from 1997 to 2019, from the agricultural surveys published by the Central Statistics Agency of Ethiopia (CSA, 2020). We focused on crop data from the 30 zones in Southwest Ethiopia where enset is cultivated (Figure 1). The CSA publishes yearly reports on total cropland area, volume of crop production, and yield of crops on private smallholdings across Ethiopia. Data are compiled at regional and zonal levels, and many crops are grouped into categories. In addition to enset, we gathered data on six important food crop categories as defined in the CSA survey reports (annual food crops—cereals [e.g., wheat, maize, teff, barley, and sorghum], oilseeds [e.g., niger, linseed, groundnut, and rapeseed], pulses [e.g., faba bean, haricot bean, and chickpea], vegetables [e.g., cabbage, peppers, and tomatoes], and root crops [e.g., taro, yam, potato, and sweet potato]—and perennial fruit crops [e.g., avocado, banana, orange, and mango]) (Table S1). We chose to use production area (ha) data in our analyses, as opposed to yield, because more comprehensive production area data were available (see Methods S1 and Figure S1). As the average age of most harvested enset is 4–6 years (Borrell et al., 2020), we estimated that the 22 years of crop data allows for around four to five enset crop cycles, which we considered sufficient to detect trends in farmers' decision making. We generated heat maps for all species across all available years from 1997 to 2019 to detect systematic outliers that might indicate survey or data entry errors, or reporting biases in certain crops (see Cochrane & Bekele, 2018). All data curation and analyses were conducted using R version 4.0.0 (R Core Team, 2020).

2.2 | Climate variables

To test the relationships between crop production area (ha) and climate, we sourced global 1 km gridded climate data from CHELSAcruts (Karger et al., 2017; Karger & Zimmermann, 2018). Using the R package 'raster' (Hijmans et al., 2021), we extracted monthly maximum temperature, minimum temperature and precipitation data for the study area to generate a suite of 29 climate variables, described below and listed in Supplementary Table S2.

The climate data covered the period of 1985–2016, starting 12 years before the first year of recorded crop data (1997), which we considered a sufficient period of time to detect climatic impacts on crops. Additionally, all climate data were cropped to the elevation range suitable for each crop that was analysed (e.g., enset variables were calculated with climate data between 1680 and 3045 m.a.s.l., based on the 95% range of enset distribution data from observations listed in Supplementary Dataset S1).

Concerning the variables, first, using the R package 'dismo' (Hijmans, 2004; Hijmans et al., 2020), we derived the standard WorldClim bioclimatic variables, representing annual trends (e.g., mean annual temperature and annual precipitation) seasonality (e.g., annual

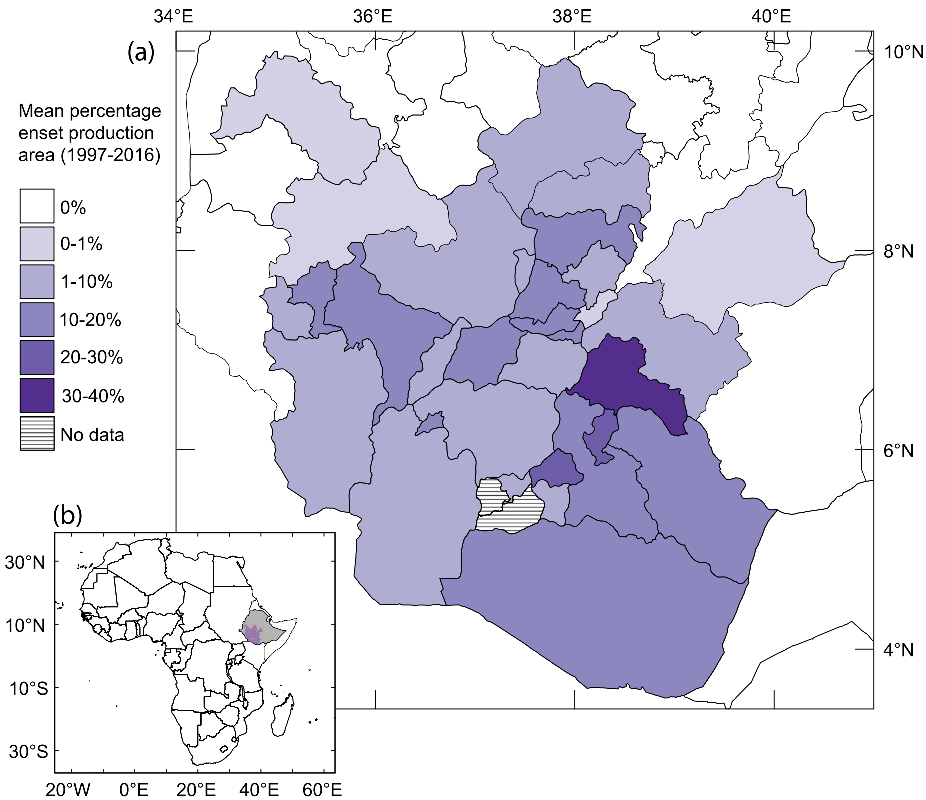

FIGURE 1 Spatial distribution of enset production area in Southwest Ethiopia. (a) Percentage of enset production area of total cropping area in the 30 enset-growing zones of Ethiopia (averaged over the period 1997–2019). (b) Location of the study area in Southwest Ethiopia.

range in temperature and precipitation) and extreme or limiting environmental factors (e.g., temperature of the coldest and warmest month, and precipitation of the wet and dry quarters). Second, we used monthly precipitation data to derive unique variables corresponding to the two major rainfall seasons in the study area: *Belg* (March to May) and *Meher* (June to September). Third, to capture information on water availability, we calculated mean monthly and annual Potential Evapotranspiration (PET) (Hargreaves method) using the R package 'SPEI' (Beguería & Vicente-Serrano, 2017) and summed monthly data for the *Belg* and *Meher* rainfall seasons to create seasonal PET values. Next, aridity index values (Precipitation/PET) for annual, *Belg* and *Meher* seasons were calculated following Trabucco and Zomer (2018). Finally, using the R package 'SPEI', we computed the annual Standardised Precipitation Evapotranspiration Index (SPEI), a drought indicator based on monthly PET and precipitation data (Vicente-Serrano et al., 2010), which is used to establish drought conditions related to climate change (e.g., Haile et al., 2020; Li et al., 2015; Potop et al., 2014) and is considered a comprehensive measure of water availability (Stagge et al., 2014).

Annual SPEI values were also calculated over the extended period of 1901–2016 to explore the impact of drought over the past century. To quantify the frequency of historical severe drought, we calculated the number of annual SPEI values less than −1.5 (the threshold of severe drought; Table 1) over the period 1901–2016, for each zone. As converting a continuous variable to a count variable using a threshold is very sensitive to small changes in calculations of the continuous variable, we tested two alternative SPEI estimations. The first version is the standard calculation provided by the SPEI package, and the second version used the period 1985–2016 as reference for calculation, to account for the greater accuracy of recent climate data. SPEI values needed to be less than −1.5 in both versions to be considered as a severe drought event. To account for factors not directly related to climate, we created three additional variables, population density for 2016 (WorldPop, 2018), mean enset habitat suitability index (Koch et al., 2022), and the mean poverty composite index of six regional health, well-being, and development indicators of 2016 (see Methods S2).

TABLE 1 Standardised Evapotranspiration Index (SPEI) drought categories, based on McKee et al. (1993).

SPEI value	Category
>2	Extremely wet
1.5 to 2	Severely wet
1 to 1.5	Moderately wet
−1 to 1	Normal
−1.00 to −1.5	Moderate drought
−1.5 to −2	Severe drought
<−2	Extreme drought

2.3 | Modelling the spatial variation of enset production area

To investigate whether the spatial variation in enset production area across the study area is a result of long-term adaptation to drought, we built a generalised least squares regression model with a Gaussian autocorrelation structure using the R package 'nlme' (Pinheiro et al., 2021). The response variable was the proportion of enset among the total cultivated crop area in each administrative zone (averaged from 1997 to 2016) and the four standardised explanatory variables were population density for 2016, mean enset habitat suitability index, the composite poverty index and the frequency of severe drought from 1901 to 2016. Following a stepwise selection to identify multicollinearity (using the R package 'usdm'; Naimi, 2017), we removed the composite poverty index variable from the regression model.

2.4 | Modelling the temporal response of enset production area to climate

To determine the climatic drivers of enset production across the period 1997–2016 for the 30 zones, we standardised all climate variables and excluded collinear variables through a stepwise procedure with the 'usdm' package. The six remaining (noncollinear) climate variables (isothermality, mean temperature of driest quarter, precipitation seasonality, precipitation of coldest quarter, precipitation of the *Belg* season, and the Standardised Precipitation Evapotranspiration Index) were computed at two different time scales to assess farmer decision making after short- and long-term climatic conditions. These comprised (i) the previous year and (ii) the sum of the previous 3 years, resulting in 12 explanatory variables. SPEI of the previous 3 years was calculated with R package 'SPEI' (described in Section 2.2). The regression model employed the linear mixed-effects function, a temporal autocorrelation structure and accounted for random effects by zone following Zuur et al. (2009) and using the R package 'nlme'. The response variable was the natural log of the ratio of enset production area (ha) for the 30 zones from the previous year, $y = ln(b/a)$, where a is enset production area (ha) of year n, and b is enset production area (ha) of year $n + 1$. Significant variables had p values <.05, but variables with p values <.1 were also considered 'marginally significant'. To check for spatial autocorrelation across the 30 zones, we calculated Moran's I using the R package 'ape' (Paradis & Schliep, 2019). We also plotted the model residuals against mean elevation for each zone to check for any heteroscedasticity associated with elevation (Figure S2).

2.5 | Comparing climatic impacts on enset and other crops in the enset agrisystem

The composition and diversity of the enset agrisystem varies across the study area. We studied here the most common food crops grown across the study area that broadly represent the enset agrisystem. We compiled annual crop production area (ha) data for six main crop categories (defined by the CSA) to detect changes from 1997 to 2019. The major cash crops coffee, khat, and sugarcane were excluded from the analysis to allow a truer comparison to enset (as a food crop) and to minimise other complex factors, such as local and export market demands and price fluctuations. We summed the production data (ha) of crops within categories (e.g., cereals) to construct the crop category area values. We then ran a generalised least squares regression with a temporal autocorrelation structure to detect crop trends in production area (ha) over the study period. To determine how all crop categories relate to drought in comparison to enset, we generated linear mixed-effects models for each of the crop categories. Like for enset, the explanatory variables were delimited by the 95% altitudinal range of each crop category based on georeferenced observation records (Supplementary Dataset S1). As in the temporal model of enset, the response variable was the natural log ratio of the sum of the production area (ha) of all crops in the category from the previous year and the two explanatory variables were short-term SPEI (SPEI of the previous year) and long-term SPEI (SPEI of the previous 3 years). These were then compared by plotting the t values of both short and long-term SPEI for each crop category. Significant variables had p values <.05, but variables with p values <.1 were also considered 'marginally significant'.

3 | RESULTS

3.1 | Historical climatic trends and events

Analysis of the SPEI drought index showed substantial temporal variability of drought incidence in the study region from 1985 to 2016 (Figure 2a). Drought severity was also highly variable across the 30 zones (Figure 2b), reflecting the diverse topography and climate of the Southwest Highlands. The driest years indicated by the SPEI values were consistent with notable drought events cited in literature concerning both the *Belg* and *Meher* rainfall seasons, such as in 2000 and 2002–2003 (Bewket & Conway, 2007; Cochrane, 2017; Mera, 2018; Viste et al., 2013).

3.2 | Spatial trends of enset production area

Cropping area under enset production (averaged from 1997 to 2016) varied across the 30 zones from 46 ha to 76,106 ha, comprising 0.03% to 34% of the total cultivated area (Figure 1). We found that relative enset production area had a significant positive relationship with severe drought frequency ($t = 2.81$, $p = .009$). Enset is particularly dominant in three zones (where it makes up more than 27% of all crops) that have experienced at least eight severe drought years in the period 1901–2016. The other explanatory variables, population density and enset habitat suitability index, were not significantly associated with the proportion of enset cultivation (Table 2).

3.3 | Temporal trends of enset production area

From 1997 to 2019, the average enset production area for all zones increased by 61%. Our regression model to determine the climatic predictors of the annual change in the enset production area identified two significant variables (Table 3). Annual change in enset production area had a significant positive relationship with short-term SPEI (SPEI of the previous year; $t = 2.09$, $p = .038$) and a significant negative relationship with long-term SPEI (SPEI of the previous 3 years; $t = -2.24$, $p = .026$). Three additional variables showed p values just above the .05 threshold and are thus considered marginal, that is, short-term precipitation of the *Belg* season had a negative correlation ($t = -1.93$, $p = .055$), whereas long-term precipitation of the *Belg* season ($t = 1.78$, $p = .076$) and long-term precipitation seasonality ($t = 1.88$, $p = .062$) had positive correlations with annual change in enset production area. The remaining explanatory variables were not significant ($p > .1$) (Table 3).

3.4 | Climatic impacts on enset agrisystems

From 1997 to 2019, the population of the study area nearly doubled from 23 to 42 million (World Bank Group, 2022) and the total cultivation area of all crops more than doubled. The regression of crop production showed that during the study period, the production area (ha) of all crops significantly increased ($p < .05$), with the exception of oilseeds (Figure 3).

The regression model of climate impacts on the different crop categories revealed that the annual change in production area of enset and root crops shared a similar pattern, having a negative correlation with long-term SPEI and a positive correlation with short-term SPEI (root crops long-term SPEI was highly significant at $p < .001$, enset long-term SPEI was marginally significant at $p > .05$ while both enset and root crops short-term SPEI were significant at $p < .05$). Pulse production area showed the opposite trend—a highly significant positive correlation ($p < .001$) with long-term SPEI and a highly significant negative correlation ($p < .001$) with short-term SPEI. Fruit production area had a significant positive correlation with short-term SPEI ($p < .05$), oilseeds a marginally significant negative correlation with short-term SPEI ($p < .1$), and vegetables a marginally significant positive correlation with long-term SPEI ($p < .1$). Cereal production area was not significantly correlated with short- or long-term SPEI in the study region (Table 4 and Figure 4).

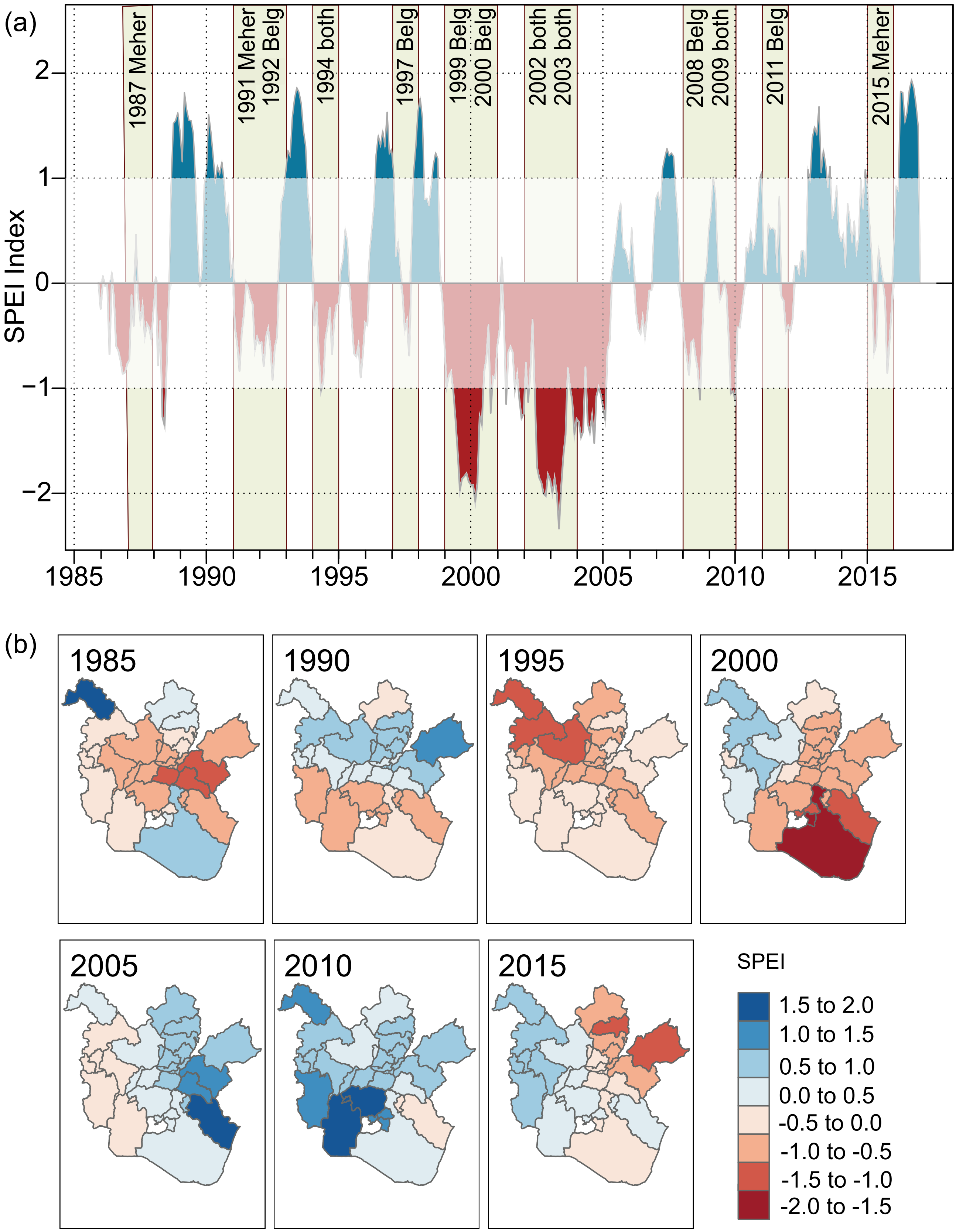

FIGURE 2 Temporal and spatial description of drought in Southwest Ethiopia from 1985 to 2016. (a) Timeline of the Standardised Precipitation Evapotranspiration Index (SPEI) averaged across the 30 study zones from 1985 to 2016. Red (negative) SPEI values indicate drier conditions while blue (positive) SPEI values indicate wetter conditions. Values greater than 1 or less than −1 indicate moderate to severe conditions. Vertical bars show notable drought events cited in literature affecting the Belg rainfall season (March–May), Meher rainfall season (June–Sept), or both seasons. (b) Annual SPEI plotted at 5-year intervals, showing the localised and varied occurrence of drought (negative SPEI) in the study area (red is drier and blue is wetter).

TABLE 2 Predictors of the spatial variation of the mean proportion of enset cultivation across the 30 zones. Asterisks indicate significant values ($p < .05$).

Variable	*t* value	*p* value
Population density (2016)	0.89	.381
Enset habitat suitability index	1.25	.221
Severe drought frequency (1901–2016)	2.81	.009*

TABLE 3 Climatic predictors of temporal variation in enset production area from 1997 to 2019. For period, short = previous year, long = previous 3 years. ** indicates significance at $p < .05$ and * indicates marginal significance at $p < .1$.

Variable	Period	Estimate	Adjusted standard error	*t* value	*p* value
Isothermality	Short	.01	.01	0.80	.423
Isothermality	Long	−.01	.01	−1.03	.303
Mean temp of driest quarter	Short	.02	.01	0.69	.489
Mean temp of driest quarter	Long	−.01	.03	−0.40	.689
Precipitation seasonality	Short	−.02	.01	−1.47	.142
Precipitation seasonality	Long	.03	.01	1.88	.062*
Precipitation of coldest quarter	Short	.01	.02	0.22	.823
Precipitation of coldest quarter	Long	−.01	.02	−0.26	.798
Precipitation of *Belg* season	Short	−.05	.02	−1.93	.055*
Precipitation of *Belg* season	Long	.04	.02	1.78	.076*
Standardised Evapotranspiration Index	Short	.03	.02	2.09	.038**
Standardised Evapotranspiration Index	Long	−.03	.01	−2.24	.026**

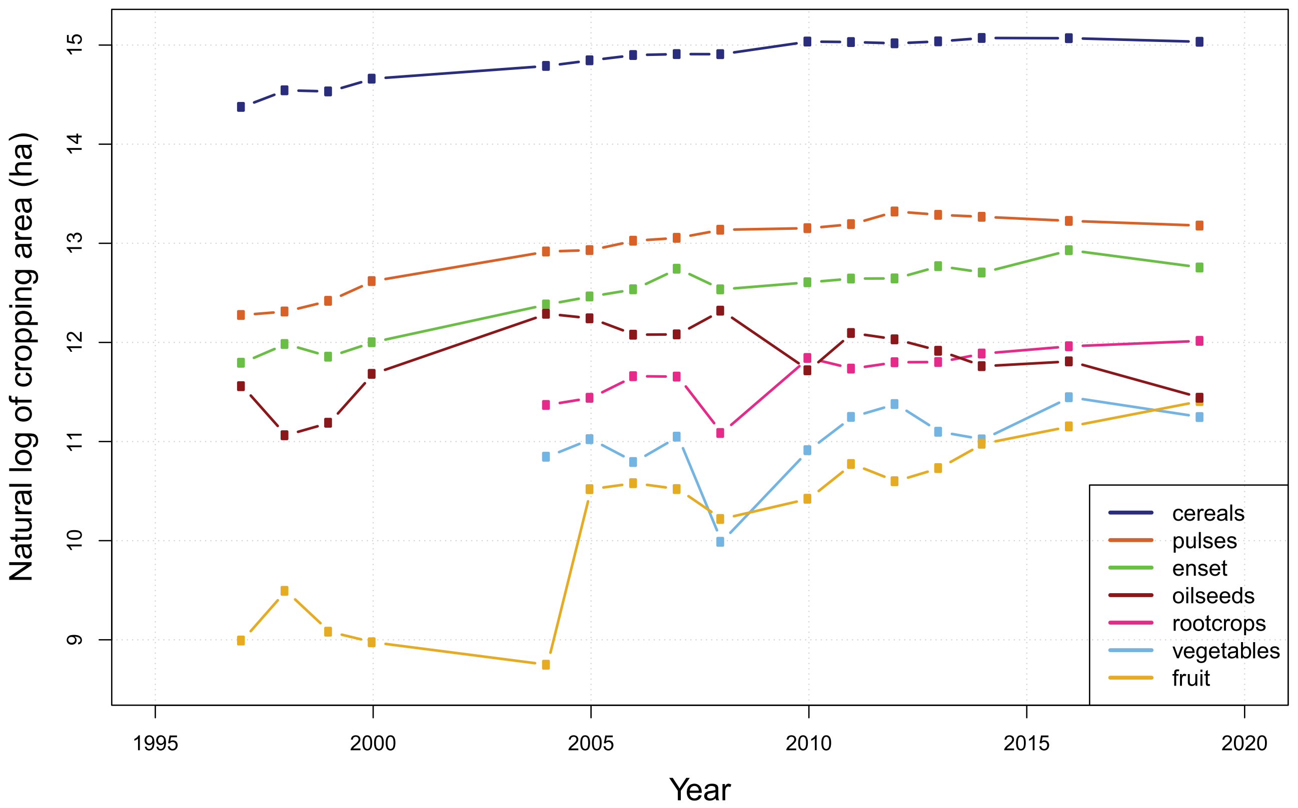

FIGURE 3 Food crop production in Southwest Ethiopia. Log change in production area (1000 ha) of the crop categories grown in the study area from 1997 to 2019.

TABLE 4 Impacts of short and long-term Standardised Precipitation Evapotranspiration Index (SPEI) on the production area (from 1997 to 2016) of enset and the other crop categories in the local agrisystem. Significant and marginally significant values denoted by **(p < .05) and *(p < .1), respectively.

Crop/category	SPEI period	*t* value	*p* value
Perennials			
Enset	Short	2.13	.034**
	Long	−1.68	.095*
Fruit	Short	2.02	.045**
	Long	−0.99	.322
Annuals			
Root crops	Short	2.30	.023**
	Long	−4.58	<.001**
Pulses	Short	−5.30	<.001**
	Long	5.16	<.001**
Oilseeds	Short	−1.73	.086*
	Long	0.96	.337
Vegetables	Short	−0.12	.902
	Long	1.71	.089*
Cereals	Short	0.57	.572
	Long	0.07	.941

4 | DISCUSSION

4.1 | Historical drought frequency influenced the spatial variation of enset production

Enset cultivation displays a highly heterogeneous and restricted distribution, being favoured by farmers in certain geographic zones but persisting as a minor crop on the periphery of this region and playing no role beyond this region. We show that the spatial variation in enset cultivation is associated with historical drought frequency, which supports the hypothesis that more enset is cultivated in drought-prone regions. This suggests that enset cultivation has become dominant in areas where the crop's attributes are most useful to buffer the impacts of drought, in line with related research showing that enset is managed as a green asset to buffer seasonal and interannual resource scarcity (Morrow et al., 2022). We note that while this holds as an explanation for the enset-growing region, the absence of enset elsewhere (e.g., Eastern and Northern Ethiopia) does not imply an absence of drought. Rather other climatic suitability variables, interacting with socioeconomic and cultural drivers, are likely responsible (Koch et al., 2022).

Our results are consistent with household surveys conducted in Ethiopia that report drought as an important factor in farmers' cropping decisions, such as diversifying home gardens and planting more enset compared to other crops (e.g., Belay et al., 2017; Negash & Niehof, 2004; Tsegaye & Struik, 2002). There is also evidence that planting more enset increases food security under drought. For example in Sidama, households that grew enset were found to be 111% less likely to experience the effects of drought than those without enset (Matewos, 2019) and enset-based agrisystems are reported to have received less emergency relief aid than other farming systems (Adimassu et al., 2014). More recently, in an analysis of World Bank household-level panel data, Morrow et al. (2022) suggested that households with a sufficient stock of mature enset were associated with significantly lower childhood stunting, higher dietary diversity and reduced food insecurity.

4.2 | Farmers planted more enset after drier conditions

We found that the annual change in enset production area is negatively correlated with long-term SPEI (SPEI of the previous 3 years), suggesting that farmers responded to longer-term drought events by increasing the proportion of enset in their home gardens, putatively as a resilience strategy (Borrell et al., 2019; Dessalegn, 1995; Morrow et al., 2022). Although the negative relationships between enset production area and long-term SPEI could also be interpreted as farmers responding to wetter conditions by decreasing enset production, there is no anecdotal evidence to support this scenario. Long-term precipitation seasonality (defined as the variation in monthly precipitation totals) has a marginally significant positive association with enset production area, further supporting the hypothesis that more climate variability has led to farmers planting more enset.

The positive relationship with short-term SPEI (SPEI of the previous year) suggests an increase in enset production area the year after wetter conditions or a decrease the year after drier conditions. The latter is regarded as the more plausible scenario, as a drier previous year often results in poor yields within the agrisystem, forcing farmers to harvest more enset than usual and thus reducing its cropping area (e.g., enset area decreased in 2009 after poor rains and significant crop losses; FAO, 2009). The marginally significant negative relationship between enset production area and short-term *Belg* precipitation suggests that these short-term drought conditions could be linked to a relatively drier *Belg* rainy season from March to May, when farmers typically plant newly propagated enset (Olango et al., 2014). Further examination of our climate data shows that rainfall variability over the study period was most pronounced during the *Belg* season (coefficient of variation [CV] = 21.98), compared to *Meher* (CV = 12.26) or annual (CV = 9.52) precipitation. A recent decline in *Belg* rain has also been reported by several authors (Bewket & Conway, 2007; Cochrane et al., 2020; Rosell, 2011) and delays in the start of the *Belg* season have resulted in shortened growing seasons, affecting cropping strategies (Rosell, 2011).

In our study, long-term SPEI represents water availability of the previous 3 years. The extended period between long-term drought (negative SPEI) and annual increase in enset production area in our model can be partially explained by the time constraints of enset growth and management, for it takes up to a year to propagate a mother plant to produce viable young plants, and then at least

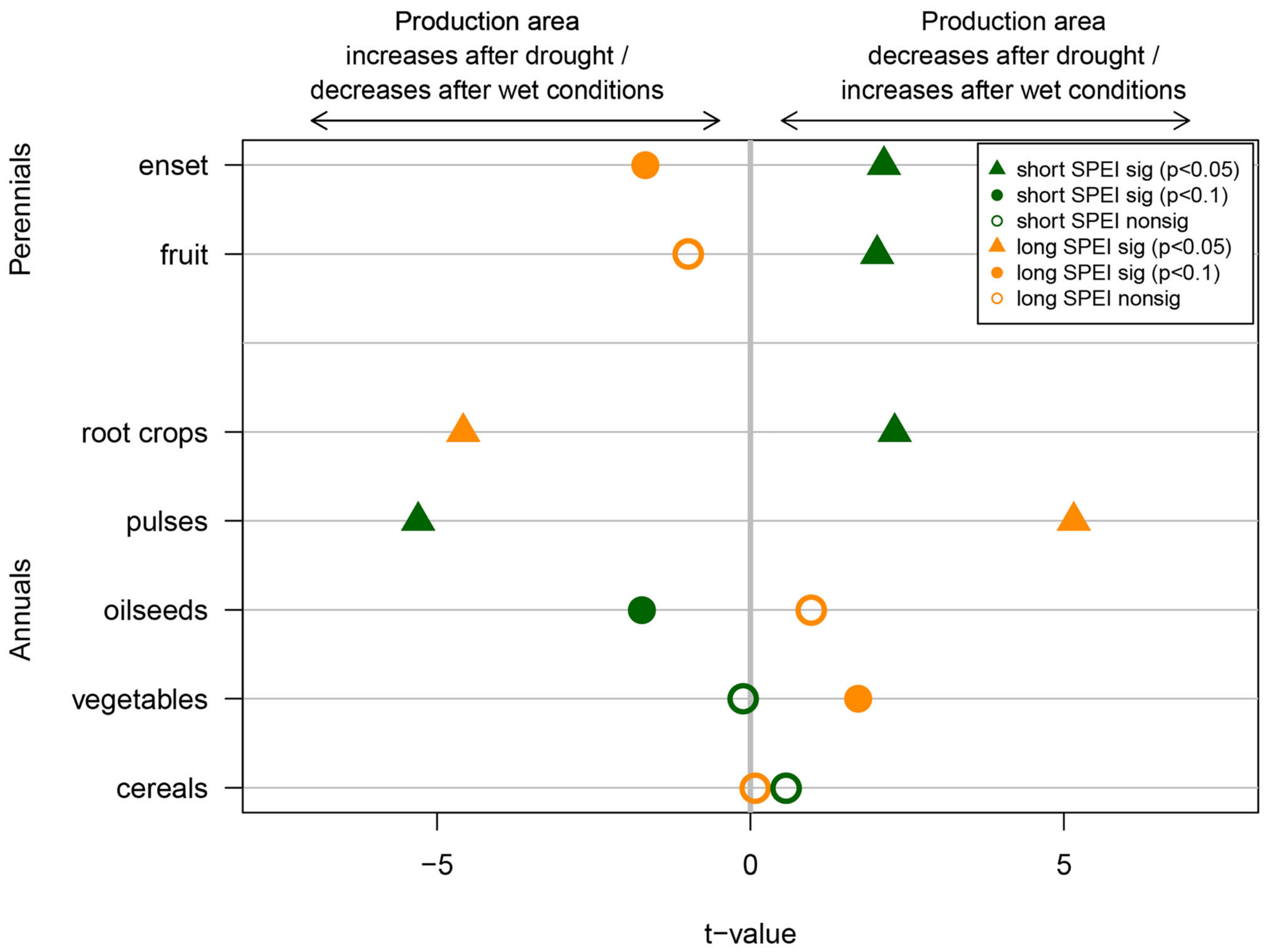

FIGURE 4 Response of different crop categories to short- and long-term SPEI. Multiple regression results (*t* values) of enset and other crop production area in the local agrisystem, comparing two explanatory variables—short-term Standardised Precipitation Evapotranspiration Index (SPEI) (of the previous year, in green) and long-term SPEI (of the previous 3 years, in orange) with significant values denoted by solid circles ($p < .05$) and marginally significant values denoted by triangles ($p < .1$). Empty circles indicate no significance ($p > .1$). In the legend, short = short-term, long = long-term, sig = significant and nonsig = not significant.

another year for young plants to mature to an extent that they take up space in the garden plot (Blomme et al., 2018; Tsegaye & Struik, 2002; Wondimu & Kebede, 2021). Furthermore, from a social perspective, this pattern corresponds well with resilience thinking and the adaptive cycle described by Fath et al. (2015), in which a crisis (in this case drought over a number of years) is followed by phases of innovation (choosing to plant more enset), new growth and conservation of buffers against future shocks (maintenance of enset as food security). This time-lagged behaviour was also observed by Lamichhane et al. (2020) in their study of climate change adaptation by smallholder farmers in Nepal.

In addition, it is likely that enset production area is affected by farmers' choices regarding co-existing crops (e.g., khat, cereals, vegetables, and coffee), coupled with other factors such as farm labour and input availability (e.g., fertiliser and manure), market access and other basic infrastructure (Manlosa et al., 2019; Matewos, 2019). For example, khat production has increased and may have replaced other crops including enset (Figure S3), although this trend is reported to be localised and largely associated with market access (Mellisse et al., 2018). Gender also plays a role in changes in enset production. Enset is typically propagated and planted by male farmers and managed, harvested, and processed by female farmers. Thus, a shortage of labour from either gender could influence the choices the farmers make regarding enset production, and ultimately their vulnerability to climate-related impacts (Matewos, 2019; Tsegaye & Struik, 2002).

4.3 | Food crop choices in response to short-term and long-term drought

Many crops co-exist in enset-based farming systems, and we found that crops are managed differently in response to short-term and long-term drought. Here, again we focused on farmers' responses to drier conditions (negative SPEI), but also considered the effects of wetter conditions (positive SPEI). Whereas the production area of perennial enset declines after short-term drought—potentially because more enset was harvested to compensate for the failure of other crops—it increases in the long-term as a resilience strategy. We also see a consistent pattern in the root and tuber crops, which although managed as annuals, have traits in common with perennials. For example, sweet potato can tolerate drought due to its deep rooting system and extensive vine network (Daryanto et al., 2016), while taro, although perhaps less drought tolerant, has a high yield, long shelf life and flexible availability (Dagne et al., 2014). The other perennial category, fruit crops, increased with short-term SPEI, suggesting that farmers expanded their cropping area of species such as avocados, bananas, and mangos after relatively wet years, but could have also decreased their production area after severe drought.

By contrast, the annual crops oilseeds and pulses have shorter cycles, which allow farmers to make adaptive decisions more quickly in response to climate (e.g., by sowing early, late, or different varieties) (Asfaw et al., 2013). Our results show that pulses, such as faba bean and chickpea, increased after short-term droughts or decreased after wetter conditions. Here, the latter scenario is considered more likely, as pulses often suffer from fungal diseases resulting from waterlogged conditions (Tadesse et al., 2008). Oilseeds show the same relationship to short-term SPEI as pulses, but with only marginal significance, perhaps because the most abundant oilseed species in the study area—niger and linseed—can tolerate a relatively wider range of environmental conditions (Alemaw & Alemayehu, 1997). After long-term drought, there were significant decreases in production area of pulses and vegetables. This is likely due to annuals favouring resource requisition over conservation and thus having less storage capacity compared to perennials (Kreitzman et al., 2020; Roumet et al., 2006), making them less attractive when a more resilient crop option is available.

Cereals do not show significant responses to long or short-term SPEI. Although this crop category had the biggest increase in production area over the study period, we cannot attribute cereal trends specifically to climate. The category 'cereals' is composed of species with different agroecological requirements and response mechanisms (e.g., drought tolerant sorghum and more drought susceptible maize) (Abera et al., 2018; Menamo et al., 2021), and it is likely that changes in cereal production area are due to a combination of nonclimatic factors and associations with other crops (Benin et al., 2003).

5 | CONCLUSION

Smallholder farmers may endure climate-related shocks and variability by using adaptive practices and crop choices. Here, we have shown that the relative importance of enset across the enset-growing area in Southwest Ethiopia is predicted by the historical frequency of drought events, suggesting that enset has become dominant in drought-prone areas. Second, we establish a temporal link between previous drought events and annual increase in enset production area, supporting the hypothesis that enset is cultivated by farmers in response to the adverse effects of drought. This provides empirical evidence of indigenous, locally adapted resilience strategies. Finally, we illustrated the complexity of farm crop choice in response to droughts, with contrasting responses from perennial enset and drought tolerant roots and tubers that increase with long-term drought and annual crops oilseeds and pulses that increase after short-term drought. Our findings indicate that Ethiopian smallholder farmers may already be adjusting crop choices in response to contemporary climate change. This study emphasises the value of surveying farmer resilience strategies and underutilised crops across the world's diverse indigenous agricultural systems, which may help guide policy decisions in regions vulnerable to climate change.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

RC, LB, and JB conceived and designed the study, with contributions from JR, NR, and AW. RC collected and curated the data. RC performed the analyses, with the help of JB and LB. RC wrote the original draft of the manuscript, and all authors reviewed and edited the original draft and approved the final manuscript.

DATA AVAILABILITY STATEMENT

The crop data used in this study are available from the Central Statistics Agency of Ethiopia (https://www.statsethiopia.gov.et/) and the climate data from CHELSA (https://chelsa-climate.org/chelsacruts/). Other data that support the findings of this study are available from the corresponding author upon reasonable request. Supplementary data are provided by link from the journal.

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REFERENCES

Abera, K., Crespo, O., Seid, J., & Mequanent, F. (2018). Simulating the impact of climate change on maize production in Ethiopia, East Africa. *Environmental Systems Research*, *7*(1), 1–12. https://doi.org/10.1186/s40068-018-0107-z

Adimassu, Z., Kessler, A., & Stroosnijder, L. (2014). Farmers' strategies to perceived trends of rainfall and crop productivity in the Central Rift Valley of Ethiopia. *Environment and Development*, *11*, 123–140. https://doi.org/10.1016/j.envdev.2014.04.004

Alemaw, G., & Alemayehu, N. (1997). *Highland oilcrops. A three decade research experience in Ethiopia*. Research Report No. 30. Institute of Agricultural Research.

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development*, *35*(3), 869–890. https://doi.org/10.1007/s13593-015-0285-2

Aryal, J. P., Rahut, D. B., & Marenya, P. (2021). Climate risks, adaptation and vulnerability in sub-Saharan Africa and South Asia. In G. M. Monirul Alam, M. O. Erdiaw-Kwasie, G. J. Nagy, & W. L. Filho (Eds.), *Climate vulnerability and resilience in the global south: Human adaptations for sustainable futures* (pp. 1–20). Springer International Publishing. https://doi.org/10.1007/978-3-030-77259-8_1

Asfaw, A., Almekinders, C. J. M., Struik, P. C., & Blair, M. W. (2013). Farmers' common bean variety and seed management in the face of drought and climate instability in southern Ethiopia. *Academics Journals*, *8*(22), 1022–1037. https://doi.org/10.5897/SRE12.732

Beguería, S., & Vicente-Serrano, S. M. (2017). *R package 'SPEI' version 1.8*. https://cran.r-project.org/package=SPEI. Accessed December 2021.

Belay, A., Recha, J. W., Woldeamanuel, T., & Morton, J. F. (2017). Smallholder farmers' adaptation to climate change and determinants of their adaptation decisions in the Central Rift Valley of Ethiopia. *Agriculture and Food Security*, *6*(1), 1–13. https://doi.org/10.1186/s40066-017-0100-1

Benin, S., Gebremedhin, B., Smale, M., Pender, J. L., & Ehui, S. (2003). Determinants of cereal diversity in communities and on household farms of the northern Ethiopian highlands. *EPTD Discussion Paper*, *105*(03), 65.

Bewket, W., & Conway, D. (2007). A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. *International Journal of Climatology*, *27*, 1467–1477. https://doi.org/10.1002/joc

Blomme, G., Jacobsen, K., Tawle, K., & Yemataw, Z. (2018). Agronomic practices with a special focus on transplanting methods for optimum growth and yield of Enset [*Ensete Ventricosum* (Welw.) Cheesman] in Ethiopia. *Fruits*, *73*(6), 349–355. https://doi.org/10.17660/th2018/73.6.5

Borrell, J. S., Biswas, M. K., Goodwin, M., Blomme, G., Schwarzacher, T., Heslop-Harrison, J. S., Wendawek, A. M., Berhanu, A., Kallow, S., Janssens, S., Molla, E. L., Davis, A. P., Woldeyes, F., Willis, K., Demissew, S., & Wilkin, P. (2019). Enset in Ethiopia: A poorly characterized but resilient starch staple. *Annals of Botany*, *123*(5), 747–766. https://doi.org/10.1093/aob/mcy214

Borrell, J. S., Goodwin, M., Blomme, G., Jacobsen, K., Wendawek, A. M., Gashu, D., Lulekal, E., Asfaw, Z., Demissew, S., & Wilkin, P. (2020). Enset-based agricultural systems in Ethiopia: A systematic review of production trends, agronomy, processing and the wider food security applications of a neglected banana relative. *Plants, People, Planet*, *2019*, ppp3.10084. https://doi.org/10.1002/ppp3.10084

Brandt, S. A., Spring, A., Hiebsch, C., McCabe, J. T., Tabogie, E., Wolde-Michael, G., & Tesfaye, S. (1997). *The "tree against hunger": Enset-based agricultural system in Ethiopia* (Vol. 56). American Association for the Advancement of Science.

Bryan, E., Deressa, T. T., Gbetibouo, G. A., & Ringler, C. (2009). Adaptation to climate change in Ethiopia and South Africa: Options and constraints. *Environmental Science and Policy*, *12*(4), 413–426. https://doi.org/10.1016/j.envsci.2008.11.002

Cholo, T. C., Fleskens, L., Sietz, D., & Peerlings, J. (2018). Is land fragmentation facilitating or obstructing adoption of climate adaptation measures in Ethiopia? *Sustainability (Switzerland)*, *10*(7), 2120. https://doi.org/10.3390/su10072120

Cochrane, L. (2017). *Strengthening food security in rural Ethiopia*" PhD dissertation. University of British Columbia.

Cochrane, L., & Bekele, Y. W. (2018). Average crop yield (2001–2017) in Ethiopia: Trends at national, regional and zonal levels. *Data in Brief*, *16*, 1025–1033. https://doi.org/10.1016/j.dib.2017.12.039

Cochrane, L., Lewis, S. C., Engdaw, M. M., Thornton, A., & Welbourne, D. J. (2020). Using farmer-based metrics to analyze the amount, seasonality, variability and spatial patterns of rainfall amidst climate change in southern Ethiopia. *Journal of Arid Environments*, *175*(November), 104084. https://doi.org/10.1016/j.jaridenv.2019.104084

CSA. (2020). "Central Statistical Agency (CSA), Federal Government of Ethiopia. 2020. Agricultural Sample Survey 2019/2020, Vol. 1: Area and Production of Major Crops." https://www.statsethiopia.gov.et. Accessed April 2020.

Dagne, Y., Mulualem, T., & Kifle, A. (2014). Development of high yielding Taro (*Colocacia esculenta* L.) variety for mid altitude growing areas of southern Ethiopia. *Journal of Plant Sciences*, *2*(1), 50–54. https://doi.org/10.11648/j.jps.20140201.19

Dalle, G., & Daba, D. (2020). Diversity and uses of Enset [*Ensete ventricosum* (Welw.) Cheesman] varieties in Angacha District, southern Ethiopia: Call for taxonomic identifications and conservation. *Genetic Resources and Crop Evolution*, *68*, 485–498. https://doi.org/10.1007/s10722-020-00998-1

Daryanto, S., Wang, L., & Jacinthe, P. (2016). Drought effects on root and tuber production: A meta-analysis. *Agricultural Water Management*, *176*, 122–131. https://doi.org/10.1016/j.agwat.2016.05.019

Demeke, A. B., Keil, A., & Zeller, M. (2011). Using panel data to estimate the effect of rainfall shocks on smallholders food security and vulnerability in rural Ethiopia. *Climatic Change*, *108*(1), 185–206. https://doi.org/10.1007/s10584-010-9994-3

Dessalegn, R. (1995). Resilience and vulnerability: Enset agriculture in southern Ethiopia. *Journal of Ethiopian Studies*, *28*(1), 23–51.

Falco, D., Salvatore, M. V., & Yesuf, M. (2011). Does adaptation to climate change provide food security? A micro-perspective from Ethiopia. *American Journal of Agricultural Economics*, *93*(3), 825–842. https://doi.org/10.1093/ajae/aar006

FAO. (2009). "FAO/WFP Crop and Food Security Assessment Mission to Ethiopia (Phase 2) 2009." www.reliefweb.int. Accessed April 2020.

Fath, B. D., Dean, C. A., & Katzmair, H. (2015). Navigating the adaptive cycle: An approach to managing the resilience of social systems. *Ecology and Society*, *20*(2), 24. https://doi.org/10.5751/ES-07467-200224

Fazzini, M., Bisci, C., & Billi, P. (2015). The climate of Ethiopia. In P. Billi (Ed.), *Landscapes and landforms of Ethiopia*. World Geomorphological Landscapes. https://doi.org/10.1007/978-94-017-8026-1_3

Funk, C., & Shukla, S. (2020). Chapter 2—Drought early warnings, definitions, challenges, and opportunities. In *Drought early warning and forecasting* (pp. 23–42). Elsevier Inc.. https://doi.org/10.1016/B978-0-12-814011-6.00002-6

Giller, K. E., Delaune, T., Silva, J. V., van Wijk, M., Hammond, J., Descheemaeker, K., van de Ven, G., Schut, A. G. T., Taulya, G., Chikowo, R., & Andersson, J. A. (2021). Small farms and development in sub-Saharan Africa: Farming for food, for income or for lack of better options? *Food Security*, *13*(6), 1431–1454. https://doi.org/10.1007/s12571-021-01209-0

Haile, G. G., Tang, Q., Leng, G., Jia, G., Wang, J., Cai, D., Sun, S., Baniya, B., & Zhang, Q. (2020). Long-term spatiotemporal variation of drought patterns over the greater horn of Africa. *Science of the Total Environment*, *704*, 135299. https://doi.org/10.1016/j.scitotenv.2019.135299

Hijmans, R. (2004). *Arc macro language (AML®) version 2.1 for calculating 19 bioclimatic predictors*. Calif, Museum of Vertebrate Zoology, University of California at Berkeley.

Hijmans, R. J., Phillips, S., Leathwick, J., Elith, J, & Maintainer Robert J Hijmans. (2020). R package "Dismo". https://cran.r-project.org/package=dismo. Accessed May 2020.

Hijmans, R., Van Etten, J., Sumner, M., Cheng, J., Baston, D., Bevan, A., Bivand, R., Busetto, L., Canty, M., Fasoli, B., Forrest, D., Ghosh, A., Golicher, D., Gray, J., Greenberg, J. A., Hiemstra, P., Hingee, K., Karney, C., Mattiuzzi, M., … Wueest, R.(2021). R package "Raster". Institute for Mathematics Applied Geosciences. http://cran.r-project.org/package=raster. Accessed April 2020.

Hoegh-Guldberg O., Jacob D., Taylor M., Bindi M., Brown S., Camilloni I., Diedhiou A., Djalante R., Ebi, K. L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S. I., Thomas, A., Warren, R., & Zhou, G. (Achlatis M. listed as contributing author). (2018). "Chapter 3: Impacts of 1.5°C Global Warming on Natural and Human Systems. In: Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Preindustrial Levels and Related Global Greenhouse Gas Emission Pathways […]." *Special Report, Intergovernmental Panel on Climate Change*, no. ISBN 978-92-9169-151-7: 175–311.

Karger, D. N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., Zimmermann, N. E., Peter Linder, H., & Kessler, M. (2017). Climatologies at high resolution for the Earth's land surface areas. *Scientific Data*, *4*, 1–20. https://doi.org/10.1038/sdata.2017.122

Karger, D. N., & Zimmermann, N. E. (2018). "CHELSAcruts—High resolution temperature and precipitation timeseries for the 20th century and beyond." EnviDat. https://doi.org/10.16904/envidat.159

Kassaye, A. Y., Shao, G., Wang, X., & Shiqing, W. (2021). Quantification of drought severity change in Ethiopia during 1952–2017. *Environment, Development and Sustainability*, *23*(4), 5096–5121. https://doi.org/10.1007/s10668-020-00805-y

Koch, O., Mengesha, W. A., Pironon, S., Pagella, T., Ondo, I., Rosa, I., Wilkin, P., & Borrell, J. S. (2022). Modelling potential range expansion of an underutilised food security crop in sub-Saharan Africa. *Environmental Research Letters*, *17*(1), 014022. https://doi.org/10.1088/1748-9326/ac40b2

Kreitzman, M., Toensmeier, E., Chan, K. M. A., Smukler, S., & Ramankutty, N. (2020). Perennial staple crops: Yields, distribution, and nutrition in the global food system. *Frontiers in Sustainable Food Systems*, 4(December), 1–21. https://doi.org/10.3389/fsufs.2020.588988

Lamichhane, P., Miller, K. K., Hadjikakou, M., & Bryan, B. A. (2020). Resilience of smallholder cropping to climatic variability. *Science of the Total Environment*, *719*, 137464. https://doi.org/10.1016/j.scitotenv.2020.137464

Li, B., Zhou, W., Zhao, Y., Qin, J., Zhongbo, Y., Liang, Z., & Acharya, K. (2015). Using the SPEI to assess recent climate change in the Yarlung Zangbo River Basin, South Tibet. *Water (Switzerland)*, *7*(10), 5474–5486. https://doi.org/10.3390/w7105474

Lin, B. B. (2011). Resilience in agriculture through crop diversification: Adaptive Management for Environmental Change. *BioScience*, *61*(3), 183–193. https://doi.org/10.1525/bio.2011.61.3.4

Lobell, D., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Soviet Opposition to Stalin*, *333*(July), 616–620. https://doi.org/10.4159/harvard.9780674333987.c22

Manlosa, A. O., Hanspach, J., Schultner, J., Dorresteijn, I., & Fischer, J. (2019). Livelihood strategies, capital assets, and food security in rural southwest Ethiopia. *Food Security*, *11*(1), 167–181. https://doi.org/10.1007/s12571-018-00883-x

Matewos, T. (2019). Climate change-induced impacts on smallholder farmers in selected districts of Sidama, southern Ethiopia. *Climate*, *7*(5). https://doi.org/10.3390/cli7050070

Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M. G., Sapkota, T., Tubiello, F. N., & Xu, Y. (2019). "Food Security. In: Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems," 437–550.

McKee, T. B., Doesken, N. J., & Kleist, J. (1993). "The relationship of drought frequency and duration to time scales." *Eighth Conference on Applied Climatology*. https://doi.org/10.1002/jso.23002

Mekonnen, A., Tessema, A., Ganewo, Z., & Haile, A. (2020). Climate change impacts on household food security and adaptation strategies in southern Ethiopia. *Food and Energy Security*, *10*, e266. https://doi.org/10.1002/fes3.266

Mellisse, B. T., van de Ven, G. W. J., Giller, K. E., & Descheemaeker, K. (2018). Home garden system dynamics in southern Ethiopia. *Agroforestry Systems*, *92*(6), 1579–1595. https://doi.org/10.1007/s10457-017-0106-5

Menamo, T., Kassahun, B., Borrell, A. K., Jordan, D. R., Tao, Y., Hunt, C., & Mace, E. (2021). Genetic diversity of Ethiopian Sorghum reveals signatures of climatic adaptation. *Theoretical and Applied Genetics*, *134*(2), 731–742. https://doi.org/10.1007/s00122-020-03727-5

Mera, G. A. (2018). Drought and its impacts in Ethiopia. *Weather and Climate Extremes*, *22*(June), 24–35. https://doi.org/10.1016/j.wace.2018.10.002

Morrow, N., Borrell, J. S., Mock, N. B., Büchi, L., Gatto Andrea, & Lulekal, E. (2022). "Green assets; Quantifying contributions of autochthonous tree-like perennials to food and nutrition security resilience in southern Ethiopian highlands abstract:" https://doi.org/10.31220/agriRxiv.2021.00081

Morton, J. F. (2007). The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(50), 19680–19685. https://doi.org/10.1073/pnas.0701855104

Naimi, Babak. (2017). "Package 'Usdm'. Uncertainty analysis for species distribution models." https://cran.r-project.org/package=usdm. Accessed May 2020.

Negash, A., & Niehof, A. (2004). The significance of enset culture and biodiversity for rural household food and livelihood security in southwestern Ethiopia. *Agriculture and Human Values*, *21*(1), 61–71. https://doi.org/10.1023/B:AHUM.0000014023.30611.ad

Olango, T. M., Tesfaye, B., Catellani, M., & Mario, E. P. (2014). Indigenous knowledge, use and on-farm management of enset (*Ensete Ventricosum* (Welw.) Cheesman) diversity in Wolaita, southern Ethiopia. *Journal of Ethnobiology and Ethnomedicine*, *10*(1), 1–18. https://doi.org/10.1186/1746-4269-10-41

Paradis, E., & Schliep, K. (2019). Ape 5.0: An environment for modern phylogenetics and evolutionary analyses in R. *Bioinformatics*, *35*, 526–528. https://cran.r-project.org/package=ape. PMID: Accessed October 2020.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., & Core Team, R. (2021). Nlme: Linear and nonlinear mixed effects models. *R Package Version*, *3*, 1–152.

Potop, V., Boroneanţ, C., Možný, M., Štěpánek, P., & Skalák, P. (2014). Observed spatiotemporal characteristics of drought on various time scales over the Czech Republic. *Theoretical and Applied Climatology*, *115*(3–4), 563–581. https://doi.org/10.1007/s00704-013-0908-y

R Core Team. 2020. "R: A language and environment for statistical computing. R foundation for statistical computing." Vienna, Austria. https://www.R-project.org/. Accessed March 2020.

Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS ONE*, *14*(5), 1–18. https://doi.org/10.1371/journal.pone.0217148

Rosell, S. (2011). Regional perspective on rainfall change and variability in the central highlands of Ethiopia, 1978–2007. *Applied Geography*, *31*(1), 329–338. https://doi.org/10.1016/j.apgeog.2010.07.005

Roumet, C., Urcelay, C., & Díaz, S. (2006). Suites of root traits differ between annual and perennial species growing in the field. *New Phytologist*, *170*(2), 357–368. https://doi.org/10.1111/j.1469-8137.2006.01667.x

Samberg, L. H., Gerber, J. S., Ramankutty, N., Herrero, M., & West, P. C. (2016). Subnational distribution of average farm size and smallholder contributions to global food production. *Environmental Research Letters*, *11*(12), 124010. https://doi.org/10.1088/1748-9326/11/12/124010

Shikuku, K. M., Winowiecki, L., Twyman, J., Eitzinger, A., Perez, J. G., Mwongera, C., & Läderach, P. (2017). Smallholder farmers' attitudes and determinants of adaptation to climate risks in East Africa. *Climate Risk Management*, *16*, 234–245. https://doi.org/10.1016/j.crm.2017.03.001

Shumbulo, A., Gecho, Y., & Tora, M. (2012). Diversity, challenges and potentials of enset (*Ensete ventricosum*) production: In case of Offa Woreda. *Food Science and Quality Management*, *7*(1974), 24–32.

Stagge, J. H., Tallaksen, L. M., Xu, C. Y., & Van Lanen, H. A. J. (2014). Standardized precipitation-evapotranspiration index (SPEI): Sensitivity to potential evapotranspiration model and parameters. *IAHS-AISH Proceedings and Reports*, *363*, 367–373.

Tadesse, N., Ahmed, S., Gorfu, D., Beshir, T., Fininsa, C., Abraham, A., Ayalew, M., Tilahun, A., Abebe, F., & Meles, K. (2008). Review of research on diseases food legumes. In *Increasing Crop Production through Improved Plant Protection – Volume I. Plant Protection Society of Ethiopia (PPSE)*.

Trabucco, A., & Zomer, R. J. (2018). "Global Aridity Index and Potential Evapotranspiration (ET0) Climate Database V2." *CGIAR Consortium for Spatial Information (CGIAR-CSI)*, no. November: 10.

Tsegaye, A., & Struik, P. C. (2002). Analysis of enset (*Ensete ventricosum*) indigenous production methods and farm-based biodiversity in major Enset-growing regions of southern Ethiopia. *Experimental Agriculture*, *38*(3), 291–315. https://doi.org/10.1017/S0014479702003046

United Nations (UN). (2019). World Population Prospects 2019 - Volume II: Demographic Profiles. World Population Prospects 2019 - Volume II: Demographic Profiles. Vol. II. https://doi.org/10.18356/7707d011-en

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multi-scalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Viste, E., Korecha, D., & Sorteberg, A. (2013). Recent drought and precipitation tendencies in Ethiopia. *Theoretical and Applied Climatology*, *112*(3–4), 535–551. https://doi.org/10.1007/s00704-012-0746-3

Vogel, E., Donat, M. G., Alexander, L. V., Meinshausen, M., Ray, D. K., Karoly, D., Meinshausen, N., & Frieler, K. (2019). The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, *14*(5), 054010. https://doi.org/10.1088/1748-9326/ab154b

Waha, K., Müller, C., Bondeau, A., Dietrich, J. P., Kurukulasuriya, P., Heinke, J., & Lotze-Campen, H. (2013). Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. *Global Environmental Change*, *23*(1), 130–143. https://doi.org/10.1016/j.gloenvcha.2012.11.001

Wondimu, H., & Kebede, A. (2021). The process of enset cultivation and its transplantation in Cheha Woreda south-western Ethiopia. *Academia Letters*, no. December. https://doi.org/10.20935/al4204

World Bank Group. (2020). "Climate Risk Country Profile - Ethiopia." https://climateknowledgeportal.worldbank.org/sites/default/files/2021-05/15463A-WB_Ethiopia%20Country%20Profile-WEB.pdf. Accessed November 2020.

World Bank Group. (2022). www.data.worldbank.org. Accessed May 2022.

Worldpop. (2018). www.worldpop.org. Accessed January 2021.

Zuur, A., Ieno, E., Walker, N., Saveliev, A., & Smith, G. (2009) *Mixed effects models and extensions in ecology with R. Smart society: A sociological perspective on smart living*. https://doi.org/10.4324/9780429201271-2

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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