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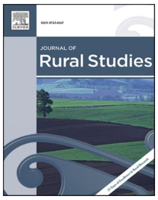

The potential effects of climate change on subsistence farmers’ wellbeing in tropical (sub)montane homegardens. A case study on Mount Kilimanjaro

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ABSTRACT

Tropical agroforestry systems support the wellbeing of millions of subsistence farmers. Owing to their ecosystem services, these agricultural systems are often advocated in government, policy, and literature as a potential adaptation to climate change measure despite emerging evidence that agroforestry systems could succumb to climate change. While the agroecological impacts of climate change on tropical agroforests are becoming increasingly apparent, few studies investigate the impacts on farmers’ wellbeing. This study empirically analyses how a potentially warmer and drier future climate could affect the wellbeing of subsistence farmers in a homegarden agroforestry system.

We employed a space-for-time climate analogue analysis approach based on the variation in altitude proxying for changes in climate on the lower southeast slopes of Mt Kilimanjaro to examine the climate effect on provisioning ecosystem services and farmers’ wellbeing. To guide our study, we developed an interdisciplinary framework for understanding how changes in climate pressures can impact farmers within tropical agroforests by considering effects on the system’s social and ecological components, ecosystem services, and farmers’ wellbeing. A mixed-method approach was used to statistically analyse the variation in farming households’ wellbeing in the homegardens and qualitatively understand the underlying mechanisms.

Overall, the change in climate conditions reduced the homegarden’s natural capital stock, e.g., livestock fodder, and productivity, negatively affecting farmers’ wellbeing. For example, farmers under the warmer and drier climate conditions were less likely to consume the three daily meals required for a good life ($OR = 0.441, P < 0.05$). Farmers who supplemented their homegarden crop production using dryland agriculture were less vulnerable to climate effects. However, this strategy relies on farmers’ sustained access to expensive productive assets, i.e., agrochemicals and farmland, which could become challenging under climate change. Our findings are significant because 1) they indicate that farmers’ wellbeing could decline under climate change, and 2) they evidence that tropical agroforestry systems can still be vulnerable to climate effects despite their advocacy in climate adaptation scholarship. We suggest that policymakers utilise current climate financing oppertunities to assist farmers in adapting their homegarden to climate change, for example, by establishing climate-resilient fodder and crops.

1. Introduction

1.1. Background

‘Subsistence’ farmers can fall along a continuum ranging from purely subsistence to being more commercial-orientated (Morton 2007) by selling surplus crops. Tropical agroforestry systems (TAFS) – the integration of trees in agricultural landscapes (in the tropics) (Schroth et al., 2004) – support the wellbeing of subsistence farmers through provisions of crops and income (Hashini Galhena et al., 2013). Wellbeing – the qualities needed for a good life (Diener and Suh 1997) – is multidimensional (Alkire and Jahan 2018). Wellbeing is best captured through its multiple objective dimensions (measurable components linked to an individual’s quality of life (Western and Tomaszewski

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2016)), e.g., living standards, and subjective dimensions that hold internal, intrinsic, and instrumental value, e.g., cultural value and social relationships (Alkire 2007; Schaafsma et al., 2022). The concept of wellbeing can also comprise 'outcomes', which are internal elements constituting a person's wellbeing, e.g., health and nutrition, and 'inputs' that involve the resources/means needed to achieve these outcomes (Dasgupta 2001). Farmers' income from TAFS crops constitutes an input because it funds their household's education, food, and living standards (Kumar and Nair 2004; Hashini Galhena et al., 2013). Similarly, the consumption of a diverse range of TAFS crops (inputs) influences subsistence farmers' nutrition (Whitney et al., 2018).

Livelihood assets – *human and non-human resources* (Rakodi 1999) – represent inputs to wellbeing. This is because assets, such as land, labour, and knowledge, enable households to function and formulate strategies, e.g., farming, that generate produce, e.g., crops and income, which facilitate wellbeing outcomes (Dorward et al., 2001; Siegel 2005). TAFS indirectly influence the wellbeing of farmers through their livelihood assets. For instance, canopy shading provides environments for farmer-to-farmer exchanges where social capital is reinforced and agricultural knowledge (human capital) is exchanged (Pandit et al., 2014; Díaz-Reviriego et al., 2016). Likewise, the supply of fodder allows livestock keeping (financial capital) (Luedeling et al., 2016), while the reinvestment of crop income funds farmers' access to agricultural inputs (physical capital) (Hashini Galhena et al., 2013). Hence, we conceive well-being as multidimensional, encompassing both objective and subjective outcomes mediated by inputs.

Due to the wider ecosystem services of TAFS, which include the provision of diverse crops and products for risk management (van Noordwijk et al., 2023), supporting livestock-keeping (Nyong et al., 2020), microclimate buffering effects (van Noordwijk et al., 2021), and the maintenance of soil quality and water (Gusli et al., 2020; Muchane et al., 2020), proponents maintain that TAFS offer an ideal adaptation to climate change strategy for subsistence farmers (Thorlakson and Neufeldt 2012; Lasco et al., 2014; Sileshi et al., 2023; van Noordwijk et al., 2023). In addition, the governments of over 63 countries now recognise agroforestry as an adaptation to climate change strategy (Rosenstock et al., 2018), with some developing countries enacting policies to increase the number of farmers practising agroforestry (Kitalyi et al., 2014). The IPCC (2022) has also recently highlighted agroforestry as a measure that could improve farmers' climate resilience. Indeed, this is empirically supported by studies that compare TAFS, including homegardens, montane-based TAFS and multi-strata systems, to non-tree-based gardens and farms (Linger 2014; Pandey et al., 2015; Simelton et al., 2015; Quandt et al., 2017). However, studies often do not describe the exact TAFS studied, which limits the broader validity of climate resilience statements, and mostly focus on identifying relative differences in resilience between farms, overlooking exactly how the climate can affect TAFS. These knowledge gaps were highlighted in two recent reviews, which found that little empirical research has studied how climate change may affect farmers' wellbeing in TAFS (Watts et al., 2022) or whether TAFS can protect farmers under more adverse climate conditions expected over longer timescales (Quandt et al., 2023).

Furthermore, while the potential climate resilience benefits of TAFS are well articulated in the literature, agroforestry scholars have acknowledged that these systems will still be exposed to elevated temperatures and changes in humidity and rainfall under climate change (Luedeling et al., 2014; Mbow et al., 2014a). In tropical regions, the agroclimatic and environmental conditions largely determine how TAFS function (Atangana et al., 2014; Dagar and Tewari 2017), which implies that TAFS could be climate-sensitive. Moreover, there is still debate over whether important tree-soil-crop interactions facilitated by TAFS actually support farmers' crop yields due to the elevated risk of resource competition (Bayala et al., 2019), and these risks could intensify under environmental conditions of lower soil and water resource availability from changes in temperature and rainfall (Abdulai et al., 2018; Blaser et al., 2018). Subsequently, commentators have expressed that TAFS, their ecosystem services, and the farmers may still be vulnerable to climate change (Ghosh-Jerath et al., 2021; Allakonon et al., 2022), despite the viewpoint amongst proponents that TAFS increase climate resilience (Sileshi et al., 2023; van Noordwijk et al., 2023). Indeed, growing evidence has highlighted the negative agroecological impacts of climate change on TAFS (Russell and Kumar 2019; Wagner et al., 2021; Watts et al., 2023). However, whether and how these impacts affect the wellbeing of farmers remains poorly understood (Watts et al., 2022).

The future climate conditions for tropical regions are relatively uncertain. These regions exhibit the lowest agreement among climate models on rainfall trajectories (Knutti and Sedláček 2013; McSweeney and Jones 2013), while the paradigm that 'wet areas will become wetter and dry areas drier' is becoming increasingly challenged (Feng and Zhang 2015; Greve and Seneviratne 2015). Tropical regions are projected to be around 3.5 °C warmer by 2080–2100 (Lee et al., 2021), with more severe warming (+4 °C) in tropical Africa (Serdeczny et al., 2017). Such warming could be coupled with increased drying (Siyum 2020), including in East Africa according to some climate models (e.g., CanESM2) (Laprise et al., 2013) and climate change studies (Williams and Funk 2011), with the drying occurring the most during the long rainy growing season (Cook and Vizy 2012; Vizy and Cook 2012). Although some climate models forecast increased rainfall in East Africa (e.g., Shongwe et al., 2011), this contrasts with current trends, introducing uncertainty into current estimates (Rowell et al., 2015). A potentially warmer and drier climate would represent a worst-case scenario for natural resource-dependent farmers, for whom adaptation measures must remain robust. Thus, evidence is needed to understand whether and how such changes in climate conditions could affect farmers' wellbeing in TAFS.

Our study investigates how warmer and drier climate conditions affect the wellbeing of subsistence farmers in homegardens, a TAFS involving the intermixing and vertical layering of trees with other plants and crops (Atangana et al., 2014). Following our approach to investigate the agroecological impacts of climate change on the homegardens (Watts et al., 2023), we approach our wellbeing study by adopting a space-for-time climate analogue analysis (CAA) using Mt Kilimanjaro's agroecological zones of the midland (900–1200 m asl) and highland (1200–1800 m asl) altitudes. Compared to our agroecological study, which focused on past banana yield, the current study analyses primary data gathered on other crop yield and income sources, productive livelihood capital assets, and wellbeing components to assess the potential wellbeing impacts. Our objectives are.

1. Identify how changes in climate conditions affect the provision of crops and income from homegardens.
2. Assess current livelihood capital assets between the two agroecological zones, and any potential changes under drought conditions.
3. Examine, if any, the differences in wellbeing outcomes between the two agroecological zones, and any potential changes under drought conditions.

1.2. Climate analogue analysis

CAA involves examining empirical measurements taken from different locations within an area of interest which are exposed to different climate conditions (Veloz et al., 2012). Specifically, different locations are sampled wherein at least one location, the climate conditions resemble the current climate (baseline), while in the other sampled location(s), the conditions resemble projected climate conditions. This space-for-time approach allows plausible changes in the climate to be put into empirically measurable contexts to predict the effects of climate change on the variables of interest (Ford et al., 2010). Sampling locations must be carefully selected so that their current climate conditions resemble a plausible future scenario to facilitate a meaningful comparative analysis between the different climate settings (Bos et al., 2015). In agroforestry research, CAA provides an alternative to model simulations, which can struggle to simulate climate effects on these complex systems (Luedeling et al., 2014).

Mountains in tropical regions offer ideal study sites for CAA due to their abrupt change in climate conditions with elevation (Wang et al., 2016). For example, downslope locations provide warmer and drier climate conditions that can resemble the environmental conditions expected under climate projections (Tito et al., 2020). While CAA is often used to predict the effects of climate change on ecosystems (Nottingham et al., 2015; Tito et al., 2018), CAA can also be used to study the potential climate effects on communities dependent on natural resources (Ford et al., 2010). These communities must be carefully sampled to ensure their socio-economic contexts are comparable (Bos et al., 2015).

2. Materials and methods

2.1. Study area and site justification

Our study was conducted in the Chagga homegarden of the Moshi Rural district on the southeast slopes of Mount Kilimanjaro (Fig. 1). The climate encompasses a bimodal rainfall regime involving rainfall from March–May and October–November. Up to 1800 m asl before dense forest vegetation influences the microclimate, temperatures decrease, and precipitation increases linearly with elevation (Hemp 2006). Based on our analysis of Appelhans et al.'s (2016) climate data used in our agroecological study, Moshi Rural's highland agroecological zone experiences a median annual temperature of 18.6 °C, while the midlands experience 22.4 °C (+3.8 °C difference) (see Appendix A.1). The highlands also receive a median rainfall of 2027 mm/year compared to 1222 mm/year for the midlands (−40% difference) (Appendix A.2).

The homegardens span the district's midland and highland agroecological zones. Below 900 m asl (the lowland agroecological zone), open dryland agriculture is practised. The homegardens are traditional, densely planted 'banana forests' with a scattered upper tree layer resulting from the transformation of the natural forest over numerous centuries by the Chagga tribe. This system integrates multipurpose trees and shrubs with food crops and stall-fed livestock under several multi-layered vegetation levels (Fernandes et al., 1984). The midlands are mainly characterised by *Croton-Olea* submontane forests and homegarden plantations of coffee and banana, which transition into *Agauria-Ocotea* montane forests in the highlands. Soils across the two zones are composed of similar soil parent material (Dawson 1992).

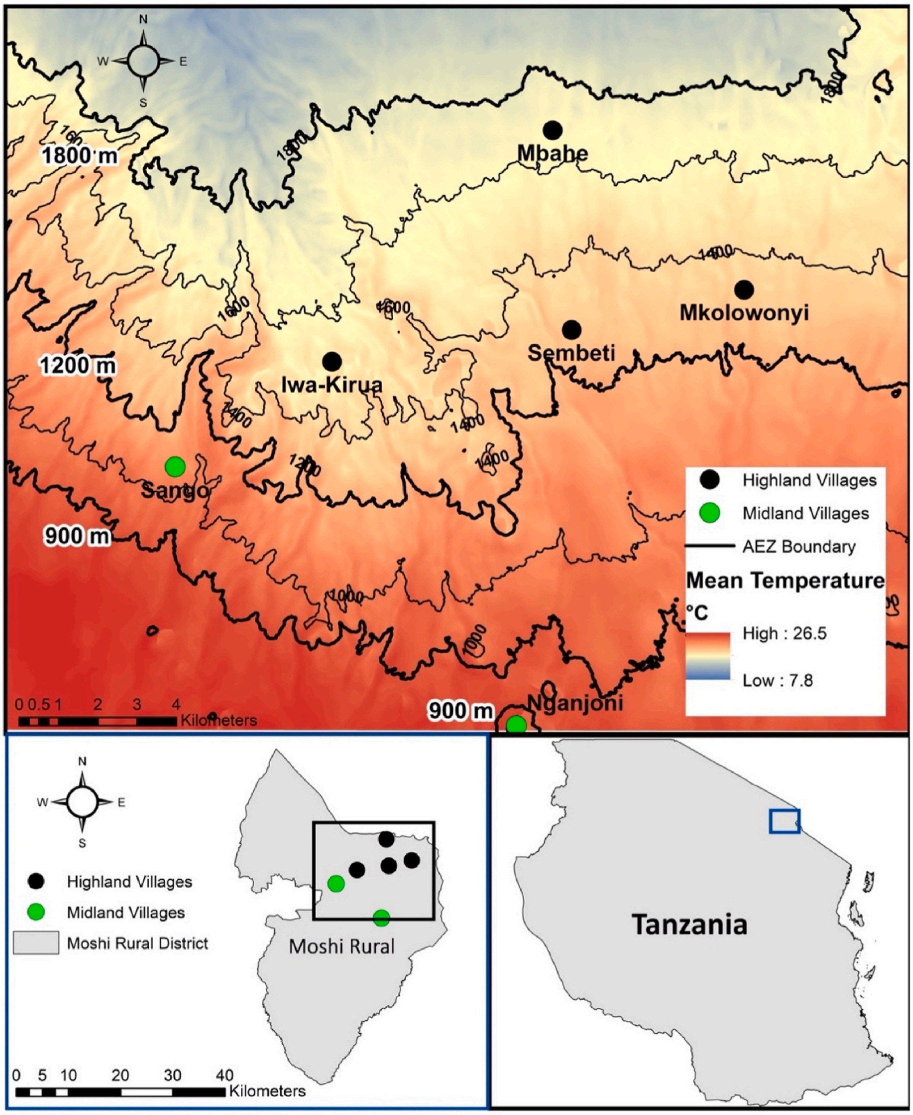

Fig. 1. Location of village sites within Moshi Rural's agroecological zones and change in annual temperature. Temperature represents the climate of 2013 and is sourced from Appelhans et al. (2016).

Moshi Rural has an estimated population of 466,737 (HH 2017), of which 99.1% of households are involved in agriculture (URT, 2012). Most are subsistence farmers who are reliant on the mountain's natural resources and rain-fed agriculture (Masao et al., 2022). Agricultural challenges are prevalent due to poverty, climate change, population pressures, and diminishing natural resources (Soini 2005; Masao et al., 2022). The main crops cultivated are maize and beans in the lowlands, while in the midlands and highlands, it is bananas and coffee, as well as vegetables, fruits, maize, and beans. Crop production is predominantly subsistence-orientated, with coffee and bananas providing some crop income for farmers (Ichinose et al., 2020). Farmers also practice livestock keeping for acquiring manure (organic fertilisers) and household income.

A consideration of Moshi Rural's climate conditions and socio-agronomic and ecological characteristics indicates that the district supports our CAA study approach. In addition to the potential changes in climate outlined in section 1.1, downscaled climate projections suggest that Moshi Rural could become warmer (+3.3–6.0 °C) and drier (up to −65% precipitation) over the current century (Luhunga et al., 2018; Rahn et al., 2018). The change in climate conditions across Moshi Rural's midland and highland agroecological zones supporting homegarden agroforestry reasonably accord with these climate projections. Furthermore, the high dependence of subsistence farmers on natural resources highlights that Moshi Rural's farmers are eligible for our CAA study (see section 1.2). Lastly, having farmland composed of identical soil parent material is advantageous for CAA studies interested in the climate effects on ecological functions and outputs (Becker et al., 2015), and thus, the potential climate effects on provisioning ecosystem services.

2.2. Conceptual framework

We developed an interdisciplinary conceptual framework for our study (Fig. 2). Our framework integrates the concept of ecosystem service co-production between humans and the natural environment (Jones et al., 2016) with the idea of productive livelihood assets from the Sustainable Livelihoods Framework (Carney 1998), how environmental change can impact ecosystem service production from the Framework for Ecosystem Service Provision (Rounsevell et al., 2010), and how this impact on ecosystem services influences human wellbeing from the Drivers, Pressures, States, Welfare and Response (DPSWR) framework (Cooper 2013). The components and ideas from these frameworks were thoroughly examined regarding our study objectives and the conceptualisation of farmers' wellbeing in section 1.1. Next, we carefully combined these components and ideas to offset each framework's weaknesses. Following Jabareen (2009), we empirically validated and refined our framework by completing a qualitative scoping study (described in section 2.3.1).

Our framework adopts the overarching structure of DPSWR to describe the homegardens as a socio-ecological system (Fig. 2), defined broadly as a system of interconnected and interacting social and ecological variables that produce outcomes for farmers. Drivers external to the homegardens (e.g., climate change) create internal pressures (e.g., increasing temperatures) that affect its natural capital (NC) stock, defined as the biotic and abiotic elements of the natural environment (Maseyk et al., 2017; Bateman and Mace 2020). The combination of NC stock with farmers' productive non-natural livelihood assets co-produce crops for consumption and/or selling (Jones et al., 2016). For example, household labour (human capital), farming knowledge (human), manure sourced from livestock (financial) and farming equipment (physical) interact together with stocks of soil nutrients, moisture, and trees (shading) to co-produce bananas. As such, a change in natural and/or non-natural capital will impact farmers' crop production and income. This income enables farmers to maintain access to these productive assets. However, farmers' household income can also be supplemented by their financial assets, such as livestock and remittances. Farmers' crop yield and income will then influence their household wellbeing outcomes (Hashini Galhena et al., 2013). Farmers may respond to impacts on their wellbeing by adapting their crop production system, although their endowment of livelihood assets will mediate their ability to respond (Adger et al., 2003; Osbahr et al., 2010).

Our qualitative scoping study (section 2.3.1) found that some farmers supplemented their homegarden crop production and income with crops (maize and beans) cultivated from (mostly) rented farmland

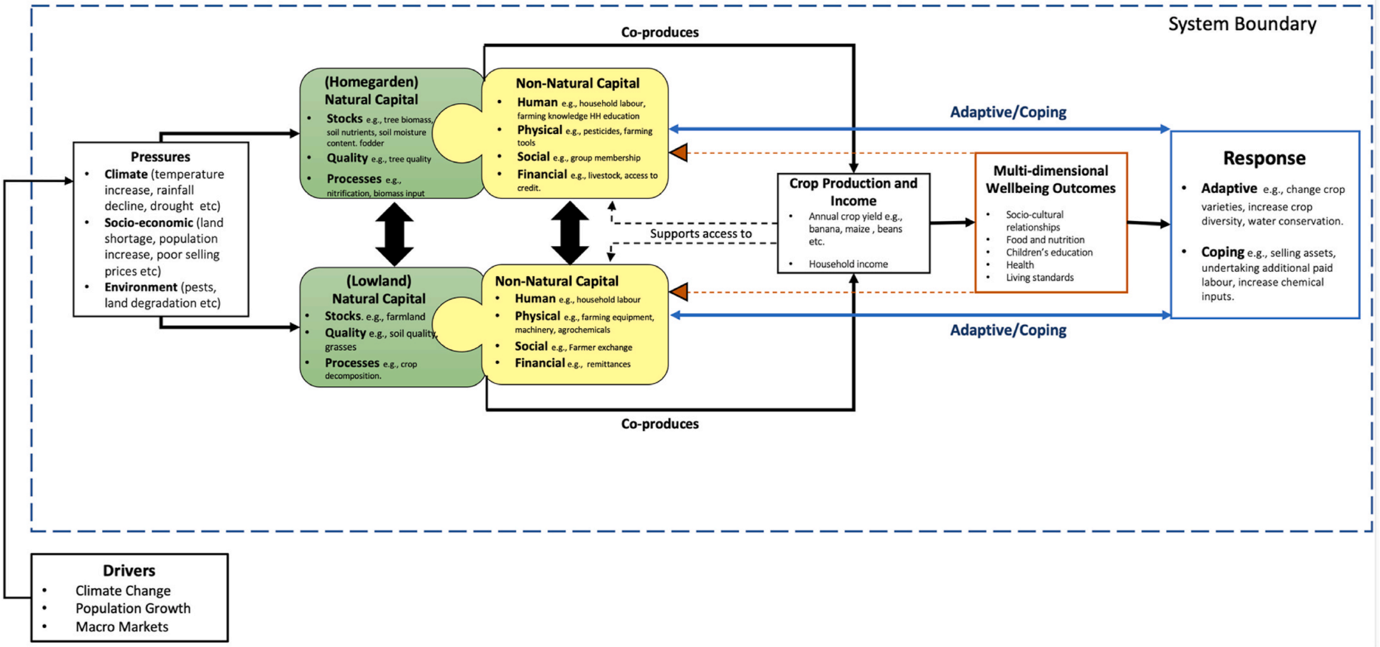

Fig. 2. Conceptual framework used to assess how climate change could impact the wellbeing of subsistence farmers in homegardens. Dotted arrows denote feedback, and the full arrows represent the main causal direction. Thick double-ended black arrows between the homegarden and lowlands demonstrate interzonal movements of farmers' capital assets. The examples listed in the components are contextualised from the scoping study (section 2.3.1).

in the lowlands. According to the findings of our scoping study, this additional produce from the lowlands can also influence farmers' wellbeing in the homegardens. Therefore, the role of the lowlands is also considered in our framework since it is possible that lowland produce might influence how the climate conditions in the homegardens affect farmers' wellbeing outcomes.

2.3. Data collection

We used a mixed methods approach that involved the qualitative data collection methods of key informant interviews (KIIs) and focus group discussions (FGDs) and the quantitative data collection method of a household survey to quantify farmers' wellbeing across our CAA zones supporting homegarden agroforestry (midlands and highlands) and then provide qualitative explanations for the differences (Creswell and Creswell 2011). Due to the COVID-19 pandemic, we could not follow up our survey with further qualitative research. Therefore, we re-examined our qualitative scoping study data.

2.3.1. Qualitative scoping study

We collected qualitative data from Nganjoni, Sembeti, Mkolowonyi, and Iwa-Kirua villages. These villages cover a range of climate conditions across both agroecological zones (Fig. 1) and were sampled based on discussions with our local collaborator, Kilimanjaro Environment and Development Actors (KEDA). We conducted KIIs with agricultural officers, foresters, and village heads to gain background information on farming communities and the pressures affecting these communities. FGDs were then held with subsistence farmers at the village level and contained themed questions to (i) conceptualise their crop production system, (ii) identify the resources needed for co-producing crops, (iii) understand the relationship between their crops and wellbeing outcomes, and (iv) recognise how different pressures affect their crop production system and wellbeing. To gain a detailed understanding of farmers' crop production system, wellbeing, and how they were affected by different pressures, we employed seasonal calendars, wellbeing ranking, and participatory timeline exercises during FGDs, respectively (Schreckenberg et al., 2016) (Fig. 3). The ranking exercise involved participants self-defining indicators of their wellbeing, before ranking the dimensions by their perceived importance (Appendix B.1). This exercise developed bottom-up wellbeing indicators which were used as dependent wellbeing variables in our later quantitative analysis. For example, good food diversity (nutrition) involves regularly consuming meat and/or fish. A combined purposive and snowball sampling approach was used to gather our focus group participants. Separate groups were held for men and women.

In total, we completed 11 focus groups with 83 participants and seven KIIs (three village heads, three agricultural officers, and one forest extension officer). Both methods were administered across two fieldwork trips in November 2019 and March 2020, using KEDA's Swahili-speaking translators. All responses were digitally recorded.

2.3.2. Quantitative survey

Using the indicators displayed in Fig. 2, we developed a cross-sectional household survey that quantified farmers' livelihood assets (e.g., labour and agrochemicals), annual crop yield, total agricultural income, and wellbeing outcomes across sampled villages in the midlands and highlands, for the year of 2020. In addition, our survey gathered recalled measurements of the same household's annual crop yield and income, productive livelihood assets, and wellbeing outcomes for 2013 and 2017, representing non-drought and drought years, respectively. The productive assets measured in 2013 and 2017 were farmers' number of cattle, agrochemical usage (kg), and the size of their lowland farms (ha). Our scoping study found that these livelihood assets were necessary for producing crops but could be vulnerable to climate pressures. The wellbeing outcomes measured included the frequency of meals (nutrition), food diversity (nutrition), and healthcare expenditure (USD) (health). Living standards indicators were unlikely to vary over time, while farmers' socio-cultural relationships remained unchanged. Issues during the collection of children's education data meant that it could not be used. Such before-during-after drought approaches can help to highlight the climate impacts on TAFS (Vincent et al., 2009; Gateau-Rey et al., 2018) and, in our study, corroborate differences in wellbeing

Fig. 3. Participatory activities conducted during FGDs. A) seasonal calendars (conceptualising farmers' crop production system), B) wellbeing elicitation and matching, and C) participatory timelines (to understand how pressures affected crops and wellbeing).

discerned through our CAA approach. We acknowledge the risk of imprecision from using participant recall. However, we examined farmers' recall ability during the participatory timeline exercise, and in our agroecological study (see Watts et al., 2023), and found that their recall was dependable. Furthermore, studies have shown that farmers' recall is reliable (Chapman et al., 2016) for even up to ten years (Howard 2011).

In total, 261 households were sampled across six villages spanning the midland and highland agroecological zones (Table 1). These villages were selected based on their spatial distribution at different elevation points across the climate gradient and their comparable socio-economic contexts to facilitate our CAA approach (Bos et al., 2015). Eight villages were initially recommended by KEDA. KEDA works with farming communities and, therefore, know local contexts well. Villages were inspected during the scoping study to determine if subsistence farming was the livelihood practised, similar crops and livestock were farmed, and comparable farm management practices were used. We also explored whether the villages had unique socio-economic factors. This led to the removal of two villages. One village near the national park was impacted by tourism activities, while another village accommodated businessmen and (ex)government employees from which farmers could receive financial support via community groups and government aid. Some households in Nganjoni village used irrigation, which we collected data on to account for during analysis. Another village (Sembeti) was located relatively nearer to a local market. However, farmers' main income source (banana) is derived primarily from buyers coming to their homegarden, reducing this advantage.

To construct our sampling frame, we mapped each subsistence farming household in each sampled village and their socio-demographic characteristics in February 2021. Next, we applied stratified random proportionate sampling to capture different subgroups of farmers, e.g., wealth, age, and household head gender. The survey was cross-checked for any translation issues and piloted in early March 2021 to establish the validity of the questions across the different villages (Newing 2010). From March until late April 2021, the survey was administered face-to-face using electronic tablets. Due to logistical and resource constraints, we only interviewed the household head (where possible). In rural Sub-Saharan Africa, household-level decisions and management related to agriculture and the health of household members are mostly determined by the household head (Nthambi et al., 2021). Therefore, we deemed the household head as the ideal source of information on climate effects on crop production and household wellbeing.

2.4. Data analysis

2.4.1. Statistical analysis

Regression analysis assessed differences in the farmers' livelihood assets and wellbeing outcomes between the two sampled agroecological zones (AEZ) – AEZ constituting our independent variable to analogue the climate change effect - whilst controlling for the effect of different household characteristics. Given the breadth of our livelihood asset and wellbeing outcome dependent variables studied (see Tables 3 and 5) and their characteristics, i.e., numeric, binary, and count; we used various regression models, including multiple linear, binomial, generalised Poisson, or negative-binomial models. All relevant model assumptions were checked. Prior to analysis, the data were checked for outliers, and two midland and eight highland households were removed. Due to our remaining relatively small sample size for a household survey (n = 251), we used $P < 0.1$ as an initial statistical significance threshold to alleviate type II errors following comparable studies of identical sample sizes and statistical analysis (Dave et al., 2017).

Regarding our examination of farmers' livelihood assets in Table 3, we found that the numeric data representing farmers' agrochemicals, remittances, lowland land size, and crop income were zero-inflated. Therefore, we employed Hurdle models using R's MAST package (McDavid et al., 2021) to avoid biased estimates (Boulton 2016). In addition to our CAA independent variable (AEZ), we included control variables of the household head gender, the average age of household members, the number of active working household members, and a local contextual wealth variable. Our wealth variable was developed based on the number of cattle a household owned and whether hired labour was used and was cross-checked with farmers during the FGDs. Such household-level sociodemographic characteristics have also been shown to impact the accumulation of livelihood assets in rural settings (Winters et al., 2009; Chowa and Masa 2015) and thus were included in our model. Table 2's description of the survey sample describes these sociodemographic variables. A generic model to analyse farmers' livelihood assets (Y_i) is specified in equation (1), where the effect of our analogue variable (AEZ) (Z_i) is examined alongside our control variables (X_i). Our error structure will alter depending on the asset examined, i.e., a binomial error structure for assets measured on a binary scale.

$$Y_i = \beta_0 + \beta_1 Z_i + \beta_2 X_i + \varepsilon_i \tag{1}$$

To visualise any important trends in livelihood assets across the midlands and highlands, we developed a livelihoods assets index (see Appendix C). These indexes visually depict differences in assets between different locational groups of households (Nasrnia and Ashktorab 2021). Moreover, it is known that having access to certain assets can enable households to access other livelihood assets; for example, financial and social capital can increase access to land, knowledge, and physical inputs (Mofya-Mukuka et al., 2017; Bray and Neilson 2018). Therefore, we employed factor analysis, a multivariate statistical technique that highlights a covariation amongst variables, to explore whether any trends in farmers' assets across the different climate conditions could also be linked with any inter-asset dependences (Filmer and Pritchett 2001) (Appendix D).

Regarding our wellbeing outcome variables, we applied Hagenaars et al.'s (1994) equivalence scale to our household healthcare expenditure data to account for the different numbers of adults and children in households. We specified our wellbeing models based on the relationships and effects theorised in our conceptual framework and emerging quantitative findings, e.g., the unfolding importance of lowland farms for midland households (see section 3.3). A list of the model variables and their rationale is given in Appendix B, Table B.3. Our wellbeing models can be specified as in equation (2), where the effect of our independent variables of AEZ (Z_i) and lowland size (L_i), their interaction, and the homegarden productivity (P_i) alongside control variables (X_i), are considered. Model interactions and control variables were retained if the loglikelihood significantly improved ($P < 0.1$).

$$Y_i = \beta_0 + \beta_1 Z_i + \beta_2 L_i + (\beta_1 Z_i \times \beta_2 L_i) + \beta_3 P_i + \beta_4 X_i + \varepsilon_i \tag{2}$$

We used multilevel regression analysis to examine the variation in farmers' livelihood assets and wellbeing outcomes before, during, and after 2017's drought event using survey respondent's recall data (section 2.3.2). Multilevel models consider data dependencies through 'random effects', which involve random slopes or intercepts for different clusters (Finch et al., 2019). Clusters can be assigned at the individual (household) level, allowing random effects employed in models that analyse trends over time to consider individual household trends (Garcia and Marder 2017). Individual trends may change at different rates, extents, and directions to other individuals, for example. In our present study, such random effects allow our models to account for and adjust for any uncaptured individual traits of farmers' households, or villages, that could have also influenced their wellbeing over time when

Table 1
Summary of six sampled villages[a].

Village	Elevation range (m asl)	Median elevation (m asl)	Estimated mean annual temperature (°C)	Estimated mean annual rainfall (mm/yr)	AEZ	Relative size (N subsistence farming households)	N of households sampled in the survey	Access (roads)	Access to main markets	Ability to irrigate	Main livelihood
Mbahe (Highland)	1621–1800	1685	16.8	2395	Highlands	95 (Small)	40	Poor, difficult to reach.	Poor	No	Subsistence Farming
Iwa-Kirua (Highland)	1272–1442	1400	19.4	1834	Highlands	145 (Large)	40	Good, a tarmac road was recently built but required money to capitalise on via public transport, which most farmers do not have.	Poor	No	Subsistence Farming
Sembeti (Highland)	1267–1358	1310	20.2	1657	Highlands	125 (Medium)	40	Medium, tarmac road within bike ride distance. But both journeys require $	Good – Marangu market. However, it requires walking uphill for several hours.	No	Subsistence Farming
Mkolowonyi (Highland)	1258–1399	1334	20.0	1704	Highlands	100 (Small)	40	Poor, difficult to reach.	Poor	No	Subsistence Farming
Sango (Midland)	900–1190	1027	22.8	1101	Midlands	129 (Medium)	61	Poor, roads are muddy and unusable when wet.	Poor	No	Subsistence Farming
Nganjoni (Midland)	900–1024	980	23.2	1008	Midlands	135 (Large)	40	Poor, roads are muddy and unusable when wet.	Poor	Yes, via a canal. However, the canal is opened only once a week. Only households below the canal can irrigate	Subsistence Farming

[a] As Sango village covered the entire elevation range of the midland, an additional 21 households were sampled. The village's temperatures and rainfalls were estimated using the relationship between climate variables and altitude established in Watts et al. (2023).

Table 2
Sociodemographics of farmers' households in the household survey.

Midland (n = 100)			Highland (n = 161)		
Relative Wealth Category (Ordinal) (N)					
Poor	Medium	High	Poor	Medium	High
35% (35)	42% (42)	23% (23)	40% (64)	38% (61)	22% (36)
Gender of Household Head (Binary) (N)					
Male	Female		Male	Female	
70% (70)	30% (30)		73% (116)	27% (44)	
Number of household members (Count) (mean/standard deviation)					
3.54/1.63			3.73/1.83		
Number of active household members (Count) (mean/standard deviation)					
2.04/0.82			2.17/1.04		
The average age of adults in the household (Numeric) (mean/standard deviation)					
49/13			49/14		

producing estimates for our 'fixed effects' (the coefficients of variables our study is interested in) for the overall survey sample. Consequently, our models encompassed two or three levels, depending on likelihood ratio tests. Time (2013, 2017 and 2020) represented level 1 (each recalled measure nested within each household), the individual household level 2, and the village (within which households were sampled) level 3. A standard covariance structure was used to accommodate our unequally spaced time intervals studied (Finch et al., 2019).

The cattle data we analysed was transformed to fit a Gaussian distribution by adding a value of one and performing a log transformation (Harrison et al., 2018). Linear modelling on transformed hierarchical count data can outperform generalised Poisson models by reducing type 1 error (Ives 2015). Farmers' agrochemical metric was estimated by standardising and summing the current and recalled values for pesticide and chemical fertiliser usage. To meet assumptions, the numeric data on agrochemical usage, annual healthcare expenditure (USD), and size of lowland land (ha) were transformed using Peterson's (2021) 'bestNormalise' R package. Temporal trends in our dependent variables and how trends varied depending on independent variables, e.g., wealth and AEZ, etc (see Appendix E, Table E.1 for their description and rationale), were first explored to inform model interactions and growth trends. Independent variables and interactions were sequentially added to the unconditional means model and retained if the loglikelihood and AIC significantly improved ($P < 0.1$). A multilevel model examining the effect of our variables of interest to our study including year (T_i), AEZ (Z_i), lowland land size (L_i), and their interaction, and control variables (X_i), can be specified as follows in equation (3), where V_s denotes any random effects, which can apply at one, two, or three levels:

$$Y_i = \beta_0 + \beta_1 T_i + \beta_2 Z_i + (\beta_1 T_i \times \beta_2 Z_i) + \beta_3 L_i + (\beta_1 T_i \times \beta_3 L_i) + \beta_4 X_i + V_{si} + \varepsilon_i \tag{3}$$

Our multilevel models were fitted using the lme4 package in R (Bates et al., 2015). Model assumptions were checked using the DHARMa R package for residual diagnostics for multilevel regression models (Hartig 2017). If heteroscedasticity was detected, robust standard error measures were applied using Pustejovsky's (2022) 'ClubSandwich' R package.

2.4.2. *Descriptive statistics*

Data frequencies (%) and point range plots were used to explore differences in NC stock, crop yield, and income under different climate conditions. As our survey cannot quantify NC stock, e.g., soil moisture content, respondents instead commented on perceived differences in NC under drought (2017) and non-drought conditions (2013) relative to 2020 to indicate how NC could alter under differing climate conditions. These differences in NC stocks were also examined using Chi-square tests.

2.4.3. *Qualitative analysis*

FGDs and KIIs were translated and transcribed from Swahili into English using KEDA's translators, and the transcripts were uploaded into NVivo software for analysis. To validate and refine our framework (section 2.2), we developed a priori codes according to the ideas borrowed and integrated from each reviewed framework before applying a grounded theory approach to explain any relationships not captured by the existing frameworks. To qualitatively explain our quantitative results, we used deductive analysis using codes corresponding to Fig. 2's components and relationships.

3. Results

3.1. *Household sociodemographics, crops, and income sources*

The sociodemographic characteristics of surveyed households are relatively identical across the midland and highland agroecological zones (Table 2). The majority of households in our sample are of medium (n = 103, 39%) and low relative wealth (n = 99, 38%), while more households are headed by men (n = 186, 72%) than women (n = 74, 28%). Overall, the average age of household members in our survey sample is relatively old (49 years).

Banana was the most common homegarden crop grown, followed by avocado and coffee in the highlands and maize and beans in the midlands (Appendix F, Table F.1). Bananas, avocados, mangos, and coffee were often marketed; however, bananas generate the most household income. Maize and beans were the dominant lowland crops, with maize often sold (63% of households). Livestock also generates income for farmers, but less than crops. On average, banana production generates more annual income per farm in the highlands (USD 133.16) than in the midlands (USD 57.72) for households cultivating bananas. In the lowlands, maize provides the highest annual income, particularly for midland households (on average USD 114.18 compared to USD 33 for highland households). Highland households also sell fewer of their lowland crops (30%) than midland households (52%).

3.2. *The effect of climate conditions on provisions of crops*

Overall, the warmer and drier climate conditions under drought reduced NC stock in the homegardens (section 3.2.1) and the yields of the main homegarden crops (section 3.2.2.1). The yields of banana and maize crops in the homegarden also exhibited a quadratic relationship with the increasingly warmer and drier climate conditions downslope (Fig. 5).

3.2.1. *Natural capital stock*

NC stock in the homegardens was lower under drought climate conditions (2017) compared to 2020 (Fig. 4). Fodder grasses declined the most and more severely in the relatively warmer midlands (56% compared to 36%). Farmers in FGDs in midland villages recurrently complained about the reduced availability of fodder grasses under an increasingly warmer and drier climate, supporting survey respondents' viewpoints (Appendix G, Fig. G.1A). Homegarden soils were also poorer under drought conditions with 51% and 63% of survey respondents noting poorer soil quality and 65% and 70% of respondents noting a

Table 3
Summary of the regression results comparing households' livelihood assets under different climate conditions.

Livelihood Asset (Dependent Variable)	Description	Midland AEZ ref (warmer and drier climate) (N = 98) N/% or mean/SD	Highland AEZ (N = 153) N/% or mean/ SD	Odds ratio (if binary) or estimate (if numeric) of AEZ effect and associated 95% confidence intervals
Human Capital (HC)				
Average number of years of education in the household	Years (Numeric)	6.674/2.314	6.774/2.248	0.162 (−0.391–0.715)
Availability of household labour	Total number of hours per year working on the farm from household members (Numeric)	2030.667/1453.784	2067/ 1504.403	−0.092 (−0.314–0.13)
Whether labourers are hired	Yes/No (Binary)	48/49%	66/43%	0.715 (0.306–1.653)
Ability to hire labour	1 = 0 labourers	50/51%	87/57%	–
	2 = 1–2 labourers	22/22%	35/29%	
	3 = 3–4 labourers	21/21%	22/14%	
	4 = 5+ labourers	5/5%	9/6%	
Financial Capital (FC)				
Whether remittances are received	Yes/No (Binary)	61/62%	64/42%	1.333 (0.775–2.316)
Amount of remittances received	Tsh per year per household (Numeric)	56.85 /113.89	68.62 /122.50	13.59 (−44.51–71.43)
Access to credit	Yes/No (Binary)	22/22%	39/25%	1.211 (0.659–2.265)
Number of livestock owned	Total number of cattle, pigs and goats owned (Count)	3.9/3.5	4.183/3.701	1.112 (0.887–1.392)
Livestock income	Total annual income from livestock production per household in USD (Numeric)	129.96 /128.68	149.83 /147.55	28.34 (−23.68–79.81)
Banana income	Total annual income from banana production per household in USD (Numeric)	57.34 129.84	134.75 237.47	89.56** (18.85–158.53)
Homegarden crop income	Total annual income from homegarden crop production per household in USD (Numeric)	89.51 /153.89	161.34 /247.15	79.31** (17.63–139.40)
Lowland crop income	Total annual income from lowland crop production (if relevant) per household in USD (Numeric)	71.86 /136.08	21.22 /65.13	−69.71* (−140.35 – 2.28)
Total crop income	Total annual income from all crops per household in USD (Numeric)	165.93 /243.71	185.35 /260.67	27.29 (−40.17–94.22)
Social Capital (SC)				
Association with institutional/social groups	Yes/No (Binary)	98/100%	153/100%	–
Membership in coffee cooperatives	Yes/No (Binary)	9/9%	38/25%	3.223***(1.513–7.531)
Association with government programs	Yes/No (Binary)	9/9%	15/10%	1.024 (0.426–2.582)
Physical Capital (PC)				
Access to farming machinery, e.g. power tilla	Yes/No (Binary)	69/70%	48/31%	0.116****(0.056–0.224)
Whether chemical fertiliser is used	Yes/No (Binary)	94/96%	93/61%	0.052**** (0.015–0.141)
Amount of fertiliser	Total amount of chemical fertiliser used annually per household (kg) (Numeric)	69.714/51.630	33.222/450.6	−22.664****(-35.351 to -9.977)
Whether pesticide is used	Yes/No (Binary)	82/84%	60/39%	0.086**** (0.04–0.172)
Amount of pesticides	Total amount of pesticide used annually per household (litres) (Numeric)	1.166/1.450	0.698/1.273	0.348 (−0.162–0.858)
Natural Capital (NC)				
Size of homegarden	Total area of the homegarden plot per household (ha) (Numeric)	0.552/0.483	0.394/0.286	−0.404*** (−0.65 to - 0.158)
Whether a lowland farm is used	Yes/No (Binary)	75/77%	81/53%	0.313****(0.167–0.568)
Size of lowland farm (if used)	Total area of lowland farm per household (ha) (Numeric)	0.447/0.424	0.268/0.407	−0.118* (−0.236 to -0.0004)
Crop diversity	Total number of crops cultivated (Count (up to 7))	3.112/1.068	2.922/1.218	0.931 (0.804–1.078)
Whether irrigation is used	Yes/No (Binary)	34/35%	4/3%	0.046****(0.013–0.126)

*denotes significance at <0.1, ** denotes significance < 0.05 p-value, *** < 0.01 p-value and **** < 0.001 p-value. The midlands AEZ is used as a reference category. Odds ratios are reported for binomial regression and 'estimates for linear and hurdle regression. 95% confidence intervals are reported for all models.

decline in soil moisture in the highlands and midlands, respectively (Fig. 4). Focus group and the survey respondents both agreed that lower annual rainfall and warmer temperatures mostly decreased homegarden soil moisture and quality (Appendix G, Fig. G.1A). Overall, NC stock in 2013 (non-drought) appeared higher than in 2017 (Fig. 4), implying that the variation in NC could be climate-related. Chi-square tests confirmed that NC stock significantly differed across the pre-drought and drought years, except for soil quality in the highlands ($P = 0.143$).

3.2.2. *Crop yield*

The climate gradient and homegarden crop yield were correlated for bananas ($P < 0.001$) and maize ($P < 0.05$). Irrigation had no significant effect on crop yield. Nonlinear relationships characterised the variation in certain crop yields (Fig. 5). Banana yield, for example, increases up to

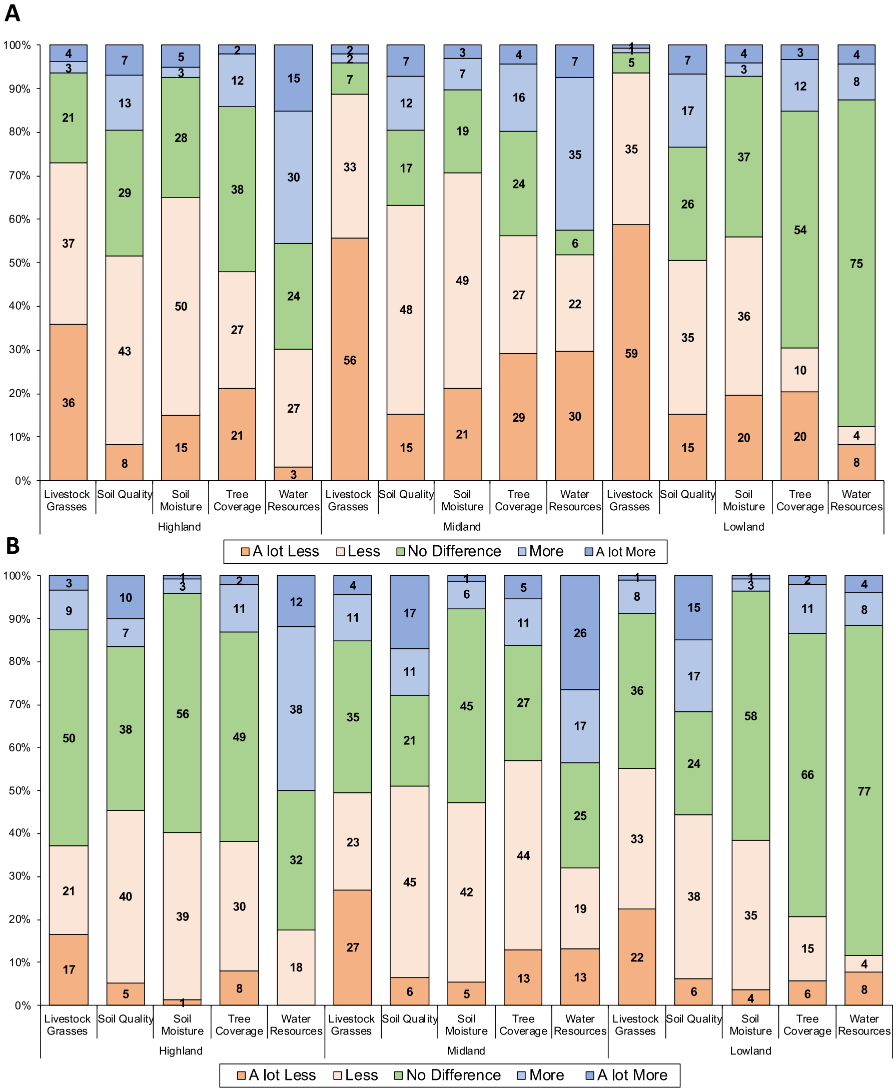

Fig. 4. Changes in NC stocks for (A) 2017 and (B) 2013. Figures represent the proportion of survey respondents (%) who perceived changes in NC stock relative to 2020 for the drought (2017) and pre-drought (2013) periods. Columns are categorised by agroecological zone to highlight differences across climate conditions.

1325 m asl and declines after 1450 m asl. According to farmers in FGDs, temperatures too warm can accelerate the development of bananas, creating smaller and thinner produce, although temperatures too cold will hinder banana plant productivity. Similarly, farmers agreed that maize yield decreases with increasing elevation because cooler temperatures also limit maize plant productivity. At the same time, heavier rainfall also damages maize, suggesting that climate change might increase farmers' homegarden maize yield.

3.2.2.1. Changes in crop yield and income. Following the trends in NC stock, crop yield generally decreased under the drought climate conditions (Fig. 6). FGDs revealed that the gradual declines in coffee yield are due to increasingly drier climate conditions, more pests, and low selling prices, which discouraged production. The variations in crop income primarily reflected crop yield, excluding bananas (Appendix H, Fig. H1). It was found that the regional market used for buying and selling bananas meant that changes in banana yield could inversely affect the market price, enabling farmers to increase their banana income.

3.3. Livelihood assets under different climate conditions

The climate conditions had a mixed statistically significant effect on 12 livelihood assets, mostly belonging to NC, PC, and FC (section 3.3.1). In addition, certain livelihood assets declined under drought (cattle), and others remained unchanged (lowlands farm size) or increased (agrochemical usage) despite the adverse climate conditions (section 3.3.2).

3.3.1. Differences in livelihood assets between agroecological zones

Households in the highlands had lower odds of accessing rented lowland farms than households in the warmer and drier midlands (OR = 0.313, $P < 0.001$) and used smaller lowland plots ($P < 0.1$) (Table 3).

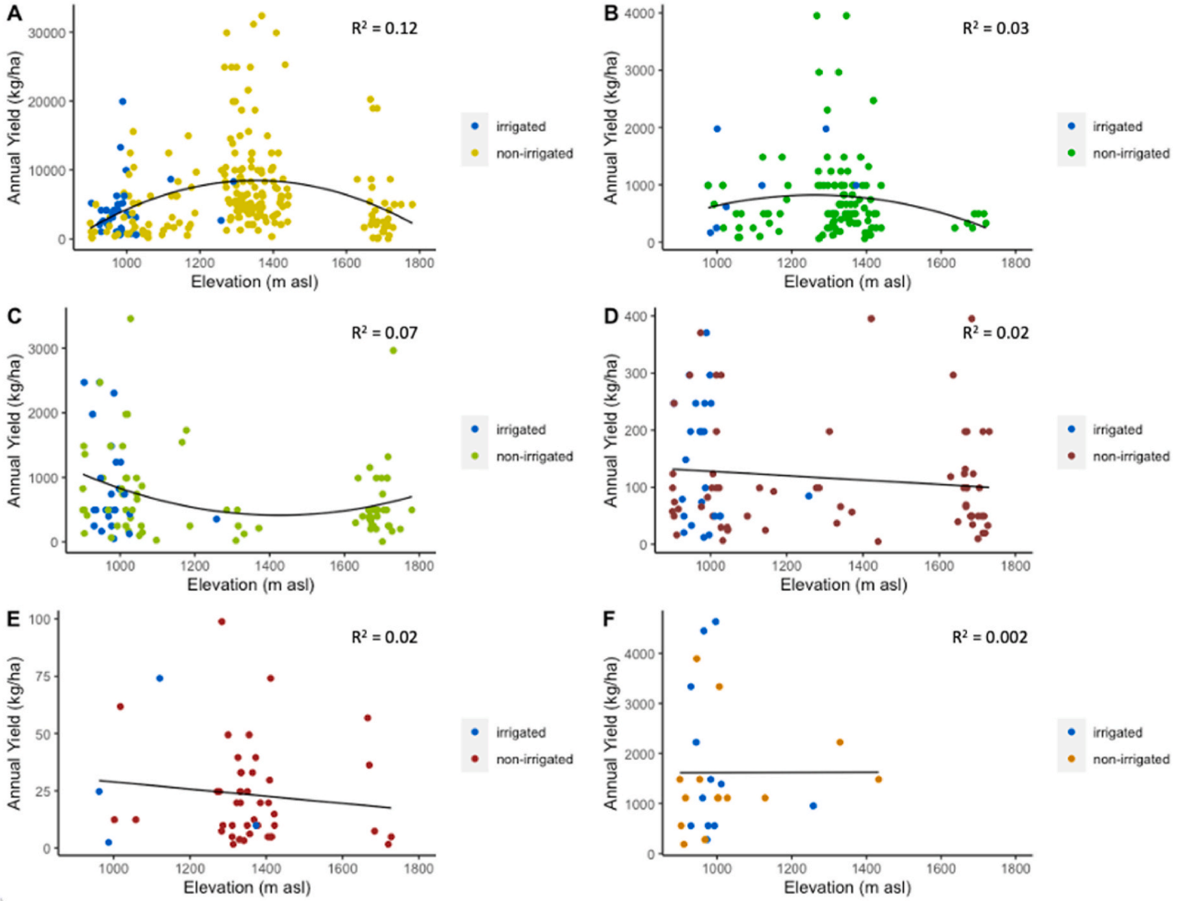

Fig. 5. Changes in annual homegarden crop yields (2020) with increasing elevation for (A) Banana, (B), Avocado, (C) Maize, (D) Beans, (E) Coffee, and (F) Mango.

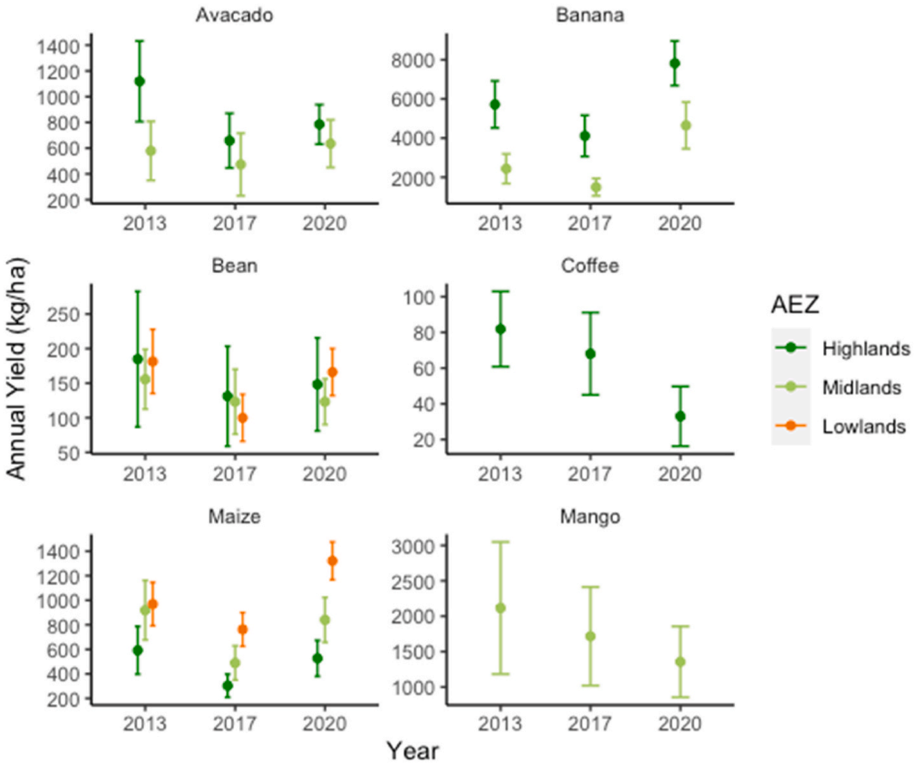

Fig. 6. Changes in annual crop yields for the main homegarden crops across the three studied periods. Error bars correspond to the 95% confidence intervals calculated from current and recalled crop yields in our household survey dataset.

Regarding PC, highland households were less likely to use farming machinery ($OR = 0.116$, $P < 0.001$), pesticides ($OR = 0.052$, $P < 0.001$) or chemical fertilisers ($OR = 0.052$, $P < 0.001$) than households under the warmer and drier climate. Highland households also used significantly less chemical fertiliser ($P < 0.001$). Concerning FC, households under the warmer and drier climate conditions (midlands) received less annual income from their banana production ($P < 0.05$) and total homegarden crop production ($P < 0.05$). However, their annual income from their lowland crop production was significantly higher ($P < 0.1$).

In support of Table 3's results, our livelihood indices indicate that midland households under the warmer and drier climate conditions are more endowed with livelihood assets than highland households regardless of wealth (Appendix C, Fig. C.2). Key disparities were in NC - likely from a higher proportion of these households cultivating crops in the lowlands - and PC. Alongside the results of section 3.1, the statistical evidence implies that households farming under warmer and drier climate conditions may depend comparatively more on their lowland crop production. Households cultivating homegarden crops under the highland's current cooler and wetter climate exhibited a comparatively higher homegarden crop yield (Fig. 6) and income, despite using fewer inputs (Table 3), denoting that homegardens under the warmer and drier climate conditions are less productive. The non-significant difference in total crop income implies that households in the less productive midland homegardens can counteract their income deficit via their lowland crop production. Indeed, the importance of lowland crops was especially emphasised in midland FGDs, where respondents expressed that their lowland crops were very 'powerful' for them. Such emphasis was not replicated in highland FGDs involving respondents who also cultivated lowland crops.

Fig. 7 shows that farmers' total crop income, labour (HC), agrochemicals (PC), farming machinery (PC), and lowland farm size (NC) are positively correlated. During FGDs, farmers explained that their crop income helps fund their lowland farmland rent and the required agrochemical input to produce lowland crops. Table 3 showed that cultivating in the lowlands and on larger farms was more common amongst households producing crops under the warmer and drier climate conditions. Considered alongside Fig. 7, the evidence suggests that the higher PC and NC of households under the midland's warmer and drier climate conditions are associated with their more common lowland-homegarden crop production strategy.

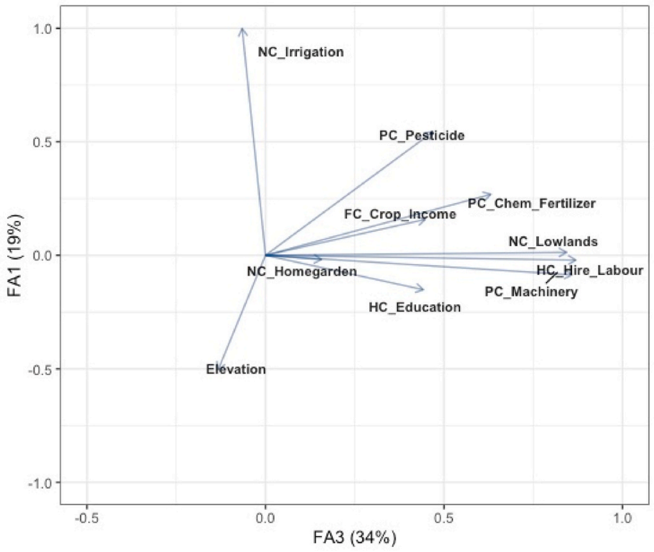

Fig. 7. Biplot of the factor analysis exploring associations between elevation and livelihood assets. The first factor (FA1) represents a negative association between increased elevation and irrigation and agrochemicals because their arrows move in opposing directions, and a weak association between elevation and other livelihood assets. The third factor (FA3) represents a positive association with crop income and most other livelihood assets, as these arrows face the same direction and exhibit small angles.

3.3.2. *Changes in livelihood assets under changing climate conditions*

3.3.2.1. Cattle. Households under warmer and drier climate conditions (midlands) experienced a greater decline in their number of cattle during drought than highland households before numbers increased thereafter ($P < 0.01$) (Table 4). Participants in midland FGDs emphasised that climate change reduced their ability to keep cattle due to the climate pressures reducing the available stock of fodder grasses, matching the trends outlined in section 3.2.1. Such grasses were essential because cattle could not survive on only tree fodder.

> "During drought, the livestock grasses die, so there is a failure to feed the animals. Farmers are not able to go to the shop to buy any food for their livestock …… it is not everyone who is able to buy food for the shops to support their animals."

- Male, Nganjoni (midland)-

Other potential explanations from FGDs concerned the increased selling of livestock to meet household needs, given the poorer crop harvests during 2017. Households using lowland farms were able to retain more cattle under drought conditions ($P < 0.1$) (Table 4). According to FGDs, the lowlands provide additional livestock fodder from crop residues, alleviating grazing pressures in the homegardens.

3.3.2.2. Lowland farmland. Farmers' lowland land size remained unchanged ($P = 0.240$) (Table 4). The higher income from bananas during drought, alongside the cited increases in livestock sales in FGDs, could have offset other losses in income, allowing farmers to continue renting lowland farmland.

3.3.2.3. Agrochemicals. The farmers' supply of agrochemicals increased over time ($P < 0.001$) (Table 4). Highland households were able to increase their supply of agrochemicals more rapidly over time ($P < 0.05$), which could be due to the highland's relatively greater financial productivity (see section 3.3.1). FGDs indicated that these increases were a response to climate-related environmental change with more pests and declining soil quality meaning that sustaining yields required more agrochemical input. However, this was costly, which sometimes mandated selling livestock.

> "Now, if we are cultivating without applying chemical fertiliser, we do not see results. Previously, we were cultivating without using this artificial fertiliser … using manure from the cow, and your crops grew well. Now, if you apply manure, you cannot get anything … if you do not apply UREA (chemical fertiliser)."

- Female, Nganjoni (midland)-

3.4. *Wellbeing outcomes under different climate conditions*

In general, households in the midland's warmer and drier climate conditions had poorer well-being outcomes than the cooler and wetter highlands (section 3.4.1). In addition, farmers' household nutrition declined under drought conditions, although their household healthcare expenditure increased over time, including during the drought (section 3.4.2).

Table 4
Changes in farmers' livelihood assets and wellbeing outcomes over time from our mixed-effect models.

	Livelihood assets			Wellbeing outcomes		
Dependent Variable	Cattle FC (numeric) N observations = 519	Lowland Size NC (numeric) N observations = 456	Agrochemicals PC (numeric) N observations = 567	Daily Meals (binary) N observations = 720	Food Diversity (binary) N observations = 720	Healthcare Expenditure (tsh per year – numeric) N observations = 718
Effects	Estimate (95% CI)	Estimate (95% CI)	Estimate (95% CI)	Odds Ratio (95% CI)	Odds Ratio (95% CI)	Estimate (95% CI)
Time (level 1)						
Intercept	0.876****	−21.245	−0.599****	3.59****	8.563****	−0.069
Year (numeric)	0.298 (−0.071–0.668)	0.010 (−0.007–0.027)	0.096**** (0.062–0.130)	0.168 (0.085–0.333)****	0.043 (0.012–0.151)***	0.058 (0.035–0.081)****
Year^2 (numeric)	−0.069 (−0.164–0.027)	–	–	1.201 (1.106–1.303)****	1.451 (1.246–1.689)****	–
Household (level 2)						
AEZ (binary: highland = ref)	−0.122** (−0.237 to –0.007)	0.231 (−0.054–0.516)	0.333** (0.002–0.663)	0.497 (0.077–3.192)	1.830 (0.254–13.199)	−0.171 (−0.533–0.198)
Lowland size (ha – numeric)	0.059** (0.012–0.106)	–	0.317** (0.122–0.511)	0.708 (0.288–1.743)	2.579 (0.683–9.738)	0.047 (−0.041–0.131)
Lowland ownership (Yes/No)	–	0.236 (−0.228–0.700)	–	–	–	–
AEZ*Year	−0.896*** (−1.453 to –0.339)	–	−0.045** (−0.081 to –0.008)	–	–	–
AEZ*Year^2	0.230*** (0.086–0.374)	–	–	–	–	–
Lowland Size*Year	0.296* (−0.037-0.630)	–	–	1.581 (0.987–2.533)*	0.184 (0.045–0.748)**	–
Lowland Size*Year^2	−0.077* (−0.157-0.004)	–	–	0.951 (0.899–1.006)*	1.236 (1.041–1.468)**	–
Mid wealth (poorest = ref)	–	0.495**** (0.246–0.744)	0.317*** (0.123–0.512)	3.071 (1.236–7.632)**	4.888 (1.290–18.527)**	–
High wealth	–	0.607**** (0.304–0.911)	0.314** (0.018–0.610)	4.325 (1.227–15.249)**	7.868 (1.138–54.376)**	–
Gender of household head (Male = ref)	−0.201**** (−0.312 to –0.089)	−0.375** (−0.681 to –0.068)	−0.286*** (−0.473 to –0.099)	–	–	–
Remittances (Yes/No)	0.149*** (0.043–0.254)	0.402* (−0.029-0.833)	–	–	–	–
Healthcare card (Yes/No)	–	–	–	–	–	−0.191 (−0.484–0.105)
Healthcare card*Year	–	–	–	–	–	−0.064 (−0.119 to −0.010)**
Random effects (ICC)						
Year	0.35	–	–	–	–	–
Household (cluster)	0.40	0.72	0.49	0.82	0.98	0.43
Village (cluster)	–	–	0.09	0.03	–	0.04
Model fit indicators						
AIC	829.48	998.657	1225.819	675.5	543.07	1812.84
LogLik	−399.738	−489.323	−601.909	−326.7	−261.5	−897.42

*denotes significance at *<0.1*, ***<0.05*, ****<0.01*, *****<0.001*. The binary climate independent variable is proxied by the AEZ, with the warmer and drier midlands representing the climate change effect. N corresponds to the total number of observations. Given that some households never had certain livelihood assets, these households were not included in the model. Due to heteroscedasticity, robust standard errors were applied to FC, NC, and PC models. Random intercepts for households and slopes for years were included in the FC model, while only random intercepts were applied to the remaining models.

3.4.1. Differences in household wellbeing outcomes between agroecological zones

Total annual household income from homegarden crops and livestock was found to explain farmers' wellbeing outcomes best. Crop yield and crop income were positively associated ($P < 0.001$), indicating that farmers' homegarden crop yield is still accounted for in our numeric 'production' independent variable, as per the component in Fig. 2. Homegarden productivity increased the odds of consuming ≥ 3 daily meals (OR = 1.016, $P < 0.05$) (Table 5). Households under the warmer and drier climate conditions were less likely to consume ≥ 3 daily meals than highland households (OR = 0.441, $P < 0.05$), although farming in the lowlands alleviated this deficit (OR = 7.142, $P < 0.05$). In FGDs, farmers linked their crop production to their health outcomes through their crop income, providing their household healthcare access. Homegarden productivity increased healthcare expenditure ($P < 0.1$). Subsequently, households under the less productive midland climate conditions had lower healthcare expenditures than highland households ($P < 0.05$). However, again, lowland farming helped to alleviate this expenditure deficit ($P < 0.1$). Households under the midland's warmer and drier climate conditions were also less likely to have improved toilet facilities (OR = 0.421, $P < 0.05$). However, the homegarden productivity and lowland independent variables were not significant. Such improvements in living standards typically exceeded farmers' annual income, meaning that improvements were often gradual. The lack of improved toilet facilities could reflect midland farmers' lesser ability to save under the warmer and drier climate conditions.

3.4.2. Changes in wellbeing under changing climate conditions

3.4.2.1. Nutrition. The odds of households consuming ≥ 3 daily meals decreased under the drought conditions (OR = 0.168, $P < 0.001$) and increased thereafter (OR = 1.201, $P < 0.001$) (Table 4), emulating the trends in farmers' crop yield (Fig. 6). Households that cultivated in the lowlands were more likely to consume ≥ 3 daily meals under drought conditions (OR = 1.581, $P < 0.01$), probably due to greater food availability. The odds of eating meat and/or fish also decreased during drought (OR = 0.043, $P < 0.001$) before increasing post-drought (OR = 1.246, $P < 0.001$) (Table 4). A reduction in the diversity of foods

Table 5
Differences in household wellbeing outcomes across different climate conditions.

Dimension of wellbeing	Nutrition		Living Standards		Health
Indicator/Dependent Variable	**Daily meals** (Binomial: ≥3 daily meals)	**Food diversity** (Binomial: Meat or fish consumed)	**Sanitation** (Binomial: Unimproved or Improved toilet)	**Housing** (Binomial: Natural or improved floor material)	**Expenditure on healthcare** (Numeric: USD per year)
Effects	Odds Ratio (95% CI)	Odds Ratio (95% CI)	Odds Ratio (95% CI)	Odds Ratio (95% CI)	Estimate (95% CI)
Intercept	1.72 (1.018–2.916)**	1.521 (0.898–2.595)	0.927 (0.564–1.517)	2.023 (1.196–3.474)	0.078 (−0.148–0.304)
AEZ (Binary: highland = ref)	0.441 (0.199–0.956)**	1.124 (0.489–2.625)	0.421 (0.199–0.862)**	0.804 (0.422–1.536)	−0.392 (−0.717 to –0.067)**
Lowlands size (Numeric: ha)	0.789 (0.319–2.126)	0.666 (0.241–2.067)	0.772 (0.295–1.799)	0.949 (0.387–2.581)	−0.023 (−0.407–0.361)
AEZ*Lowlands	7.142 (1.437–39.902)**	1.713 (0.353–9.787)	2.732 (0.752–10.639)	–	0.488 (−0.090-1.066)*
Homegarden productivity (Numeric: per 10 USD per household)	1.016 (1.002–1.030)**	1.003 (0.990–1.020)	1.005 (0.994–1.017)	1.001 (0.988–1.018)	0.005 (−0.001-0.010)*
Mid wealth (poorest = ref)	–	3.057 (1.537–6.281)***	1.414 (0.780–2.577)	1.827 (0.941–3.601)*	–
High wealth	–	3.762 (1.441–10.895)***	2.078 (0.752–10.639)*	5.376 (1.849–18.679)***	–
Gender of household head (Male = Ref)	0.551 (0.309–0.981)**	–	–	–	
Healthcare card (Yes/No)	–	–	–	–	−0.558 (−0.853 to -0.262)****
AIC	320.42	275.97	348.71	275.95	
Log-likelihood	−154.211	−130.984	−167.356	−131.975	
Wald Chi-square/F-Statistic	−21.434****	−16.413**	−13.053**	−14.431**	3.944****

*denotes significance at *<0.1, **<0.05, ***<0.01, ****<0.001*. The f statistic is used for the health linear regression model instead of the Wald Chi-square value.

consumed during drought was recurrently highlighted in FGDs; respondents mentioned sacrificing eating different purchased foods to conserve their own crops and income.

> "You may finish your week without eating meat (during drought). You just eat vegetables and some fruit. You might be able to eat meat one time per week."

- Female, Mkolowonyi (highlands)-

Interestingly, households farming in the lowlands were less likely to eat meat and/or fish during drought (OR = 0.184, $P < 0.01$). One explanation may involve farmers preservation of their maize and bean crops (mainly grown in the lowlands) during drought-induced food scarcity, which households may consume instead of selling for funding access to other foods.

3.4.2.2. Health. Healthcare expenditure increased over time ($P < 0.001$) (Table 4). This contrasts with farmers' lived experiences voiced during FGDs where they conveyed a greater financial dependence on neighbours to fund healthcare during such hardship. It is possible that the higher healthcare expenditure observed during the drought year may be related to the increased occurrence of illness due to food shortages (the average number of farming days lost from illness was highest under drought (19)), alongside the further ageing of our relatively old survey sample (45% of households currently have at least one member ≥ 65 years), increasing household healthcare needs.

> "You will find that due to drought in our farms, either the children are sick, or I am sick, and we have to go to the hospital where I need to provide money … if you need medicine, you have to provide the cash."

- Female, Sembeti (highlands)-

3.4.3. Responses to wellbeing impacts

Common household responses to wellbeing impacts have already been highlighted in section 3.3.2. For example, selling livestock and increasing agrochemical inputs. However, these actions resemble short-term coping responses, which could ultimately hamper farmers' homegarden crop production. Few households (n = 35) employed adaptive responses, including changing crop types, increasing crop diversity, and water conservation techniques, mainly due to financial barriers (n = 97). During FGDs, many farmers conceded that few response options were feasible due to their limited financial capital, despite repeatedly experiencing climate pressures and impacts on their wellbeing.

4. Discussion

Overall, our study found that a potentially warmer and drier future climate could reduce farmers' crop yield, income, and wellbeing outcomes in the homegardens. However, these impacts may possibly prompt an increase in farmers' livelihood assets. By incorporating a social dimension into a research approach used to predict the ecological impacts of climate change, this study presents a novel assessment of the potential impacts on subsistence farmers' wellbeing within a TAFS. The spatial and temporal trends in our quantitative results and triangulation with qualitative evidence indicate that the recorded differences in provisioning ecosystem services and wellbeing under different climate conditions are mainly climate-related. Our results are also supported by the trends found in most climate change and TAFS studies (predominantly negative) (Watts et al., 2022) and complement the current interdisciplinary literature highlighting the adverse effects of climate change on trees, soil, crops, income, livelihood assets, and wellbeing in TAFS (Agwu et al., 2018; Córdova et al., 2019; Ghosh-Jerath et al., 2021).

4.1. The potential effects of climate change on provisions of crops and income

Overall, climate change could reduce the NC stock and productivity of homegardens, supporting our agroecological study findings (Watts et al., 2023). Following our conceptual framework, this erosion of NC implies that TAFS ecosystem services could be vulnerable to climate change, complementing other current TAFS studies (Tamayo-Chim et al., 2012; Arnold et al., 2018; Lakshmi et al., 2021). Provisions of high-value homegarden crops, e.g., bananas, were the most climate-sensitive, creating a crop yield and income deficit between the climatically different agroecological zones. Indeed, warmer and drier climate conditions can hinder crop yield within TAFS (Lott et al., 2009;

Abdulai et al., 2018; Gateau-Rey et al., 2018). Our analysis suggested that households that also cultivated lowland crops reduced this deficit.

Our examination of crop income data implies a complex outlook for farmers' future income due to a possible inverse relationship between banana yield and selling prices. The outlook for banana yield is also complex; yields could temporarily increase under warmer temperatures (Ramirez et al., 2011) and from reductions in banana fungal diseases under drier climate conditions (Nyombi 2010; van Asten et al., 2011), although only for homegarden farms currently located in the coolest and wettest environments. A potential future scenario could entail a lower banana yield but with the farmer's income sustained. This could support the production of other crops since banana income can facilitate farmers' access to productive assets. However, banana yield may reach a threshold whereby both household subsistence and income needs cannot be simultaneously met, although a potential increase in maize yield could occur under climate change, providing an additional food source for farmers. Indeed, TAFS can support farmers' climate resilience through their high crop diversity, reducing dependence on singular crops (Sileshi et al., 2023).

4.2. The potential effects of climate change on farmers' livelihood assets

Farmers' households in the warmer and drier midland climate had more livelihood assets than highland households, with the key disparities in NC and PC assets likely linked with midland farmers' lowland crop production stratergy. The climate conditions may have influenced these differences, e.g., through the midland households' greater dependence on lowland agriculture due to a less productive homegarden. However, we acknowledge that their crop production strategy could also be influenced by non-climate factors, such as their closer proximity to the lowlands.

We found that farmers' productive livelihood assets decreased (cattle), increased (agrochemicals), and remained unchanged (lowland farms) under drought conditions. The extent of any changes differed by agroecological zone, suggesting that differences in temperature may have played a role. Cattle numbers, for example, declined from decreases in fodder under the midland's warmer climate conditions. Córdova et al. (2019) have detailed similar climate effects on fodder and livestock numbers in TAFS in Ecuador. Homegardens are TAFS abundant in fodder, making them ideal for keeping livestock (Mathukia et al., 2016). This suggests that livestock kept in other TAFS could also be vulnerable to climate effects. Livestock supports the functioning of silvopastoral and agropastoral agroforestry systems (Pathak and Dagar 2000), and provide income, fertiliser, and livelihood diversification, which together support farmers' climate resilience (Sileshi et al., 2023; van Noordwijk et al., 2023). Our findings imply that climate change could reduce these ecosystem services and farmers' resilience.

Changes in farmers' productive assets may also be interconnected, e.g., selling cattle to finance access to agrochemicals and farmland, construing a dynamic situation whereby farmers must make trade-offs between assets. Selling livestock for short-term gain risks further eroding the homegardens productivity, which over time could feedback to amplify declines in productive assets through future losses in crop income. Additionally, maintaining sources of organic fertiliser will become increasingly important as homegarden soil quality declines (section 3.2.1). Furthermore, farmers' perceived need for increasing agrochemical inputs in a traditionally organic system to sustain crop yields perhaps signifies a decline in the climate resilience of these low-input agroecological systems (Mbow et al., 2014b). However, increasing agrochemical input may not sustain the homegarden productivity as productivity remained lower under the midlands' warmer and drier climate conditions despite the greater input. Our recorded increases in productive assets parallel other works in Tanzania, where farmers reluctantly increased their farmland and labour in response to declining soil fertility associated with climate change (Nelson and Stathers 2009).

4.3. The potential effects of climate change on farmers' wellbeing outcomes

In general, the wellbeing outcomes of farmers' households were lower in the less productive homegardens located under the warmer and drier climate conditions, especially for households without lowland crops. Considering Moshi's downscaled projections (Luhunga et al., 2018; Rahn et al., 2018), our study suggests climate change could reduce farmers' wellbeing in the Chagga homegardens.

Consistent with the current literature, we found that climate change will likely negatively affect the wellbeing of subsistence farmers through their nutrition (Dickerson et al., 2022). However, the perceived most important dimension of wellbeing (socio-cultural relationships) remained unaffected. According to Allison et al. (2009), farmers prioritise different elements of their wellbeing during hardship. Reductions in food intake are a common compromise that farmers make (Ubisi et al., 2017; Awiti 2022), and is perhaps evident in our study. The recorded impact on household food intake is important because poor nutrition negatively impacts health, which can then feedback to reduce HC, e.g., labour, as other studies have documented (Thompson et al., 2010; Chandra et al., 2017). Alongside reductions in livestock numbers, reduced HC could further compound the effects of climate change on farmers' homegarden crop production. While feedback creating socio-ecological impacts has been documented in TAFS climate change studies (Landreth and Saito 2014), few studies have considered how feedback can impact farmers' wellbeing (Watts et al., 2022). Uncertainty over farmers' future crop income and financial-related response barriers implies that farmers may struggle to adequately respond to the wellbeing impacts.

Growing literature maintains that TAFS can protect vulnerable subsistence farmers against climate change (Verchot et al., 2007; van Noordwijk et al., 2021; Quandt et al., 2023; Sileshi et al., 2023), supporting an expansion of TAFS in low-mid income countries. Our study demonstrates that subsistence farmers in homegarden TAFS can still be vulnerable to climate effects. Climate adaptation decision-makers in low-mid income countries should seek to facilitate adaptive responses within farmers' homegardens to improve the resilience of these systems. Capitalising on recent climate financing commitments by countries like Tanzania for supporting farmers' climate adaptation (GCF, 2021), financial resources could be sourced to alleviate adaptation barriers and reduce coping responses that may hamper the productivity of the homegardens over time, e.g., selling assets. Climate financing could also be used to source more climate-resilient forms of fodder grasses and subsidise fodder, especially for farmers without a supply of lowland fodder, and when climatically appropriate, encourage maize production in the homegardens. Such measures should help to protect farmers' livestock against climate change and manage risks of crop failure, enabling farmers to gain the associated climate resilience benefits (Sileshi et al., 2023; van Noordwijk et al., 2023).

While we cannot assume the direct generalisability of our study findings, our results are broadly relevant for highlighting the risk to farmers' wellbeing under climate change in other homegardens, especially homegardens where farmers' crop yield and income influence their wellbeing outcomes. This includes homegardens located in Bangladesh (Bloem et al., 1996; Talukder et al., 2000), Sri Lanka (Landreth and Saito 2014), Uganda (Whitney et al., 2018), Mexico (Blanckaert et al., 2004; de la Cerda and Mukul 2008), and Zimbabwe (Maroyi 2009), with the latter countries likely to become warmer and drier according to recent climate projections (Lee et al., 2021). In Uganda, farmers' homegarden banana production largely influences their households' nutrition outcomes (Whitney et al., 2018). Since East African banana varieties respond similarly to climate effects (van Asten et al., 2011), our findings imply that the nutrition of these households may also worsen. Given the uniqueness of the integrated homegarden-lowland production system, it is less clear how our results regarding farmers' assets may generalise. However, our evidence demonstrates that livestock in other TAFS, including in TAFS less abundant in stocks of fodder, could be vulnerable to climate change.

4.4. Reflections on climate analogue analysis approach

Our analysis of the evidence indicates that our findings are mainly climate-related. However, non-climate factors associated with our study village locations that could influence our findings warrant reflection. For example, the distance to markets varied between villages, with Sembeti (highland) being the closest (Marangu market). For both midland villages, the closest market is in the lowlands (Himo market). Although banana buyers come to farmers' homegardens, income from other crop sales and better access to agricultural inputs could have influenced farmers' homegarden management, possibly in Sembeti. Different levels of accessibility to villages and road quality can also impact farmers' crop production (Bos et al., 2015). Although Mbahe and Mkolowonyi villages (highlands) may have had poor road access (Table 1), roads to both midland villages can become inaccessible during heavy rainfall. Since 2020 was a wetter-than-average year (Wagner et al., 2021), the crop yield in the midland villages may have been further constrained. Considering this variation in village and market accessibility, crop varieties could also vary. For instance, multiple varieties of bananas are grown in the homegarden. However, as mentioned, East African banana varieties respond similarly to climate effects (van Asten et al., 2011), suggesting this is not a major limitation. Different land use histories between analogue sites may also influence crop yield (Bos et al., 2015). However, this was probably less influential in our study since the homegardens have evolved from centuries of the Chagga's cultural interaction with the forest, meaning that indigenous knowledge has had ample time to shape the agricultural landscape. Similarly, potential variations in off-farm work and income should be minimal, as this was carefully considered during site selections.

There are also general limitations to our study design. For example, our survey may not reflect the perceptions of the entire household because responses will be biased towards the perspectives of the household head. Perceptions of climate change can sometimes vary between household members who may undertake different household roles, e.g., women. Quandt (2019), for example, reports that women in East Africa perceive drought to be less severe than men, which, if replicated in our study, could have biased our survey responses towards more severe perceptions of the climate change effects given the preponderance of male household heads in our sample (Table 2). Also, the recorded impacts on farmers' food diversity under drought could have been exaggerated by changing government policies, such as the temporary closure of trading borders with Kenya, increasing the cost of food. We also did not closely study the effects of climate on the lowlands because these farms exhibit different land cover and climate characteristics from the homegardens, restricting comparability. Consequently, our study cannot demonstrate the climate resilience of homegardens relative to open-field agriculture. As with CAA studies, our study cannot consider all non-climate factors that could influence the homegarden's pathways over time (Ford et al., 2010); for example, new climate-sensitive technologies that benefit farmers' crop production could emerge. Our projected impacts should be interpreted with these limitations in mind.

Next, our CAA study could not consider the climate effects of increased rainfall variability or the individual effects of temperature and precipitation. However, our study did capture the main climate pressures affecting the homegardens (decreased annual rainfall and warmer temperatures (Appendix G, Fig. G.1)). Future work could use Mount Kilimanjaro's E to W rainfall gradient to unravel the individual effects of temperature and precipitation. Lastly, we used agroecological zones to capture an overall change in climate conditions and facilitate a more intelligible empirical analysis. However, we recognise that the climate conditions will also vary between villages; for example, Mbahe's high altitude means that this village is significantly cooler (around -6.2 °C) and wetter (around +1340 mm/yr) than both midland villages. Considering the constraints of cold and wet conditions on homegarden crop yield (section 3.2.2), this suggests that our estimated impacts could be conservative. Finally, we recognise that the climate difference of around +4 °C and 40% decline in precipitation between the midlands and highlands does not precisely replicate some climate projections (e.g., Luhunga et al., 2018; Rahn et al., 2018). However, our study mainly aims to evidence how a plausible future climate could affect farmers' wellbeing in TAFS, given the current limited knowledge, and how this potential climate scenario would constitute a worst-case for subsistence farmers, and thus where robust adaptation measures would be important.

5. Conclusion

Our study assessed the potential impact of climate change on subsistence farmers' wellbeing in homegardens using a CAA approach. Overall, we found that climate change could reduce farmers' homegarden crop yield, including for major crops like bananas, and their income. This requires some farmers to offset these losses by practising dryland crop production. The declines in homegarden productivity could be compounded by reductions in farmers' livestock numbers and organic fertiliser from diminishing fodder stocks under increasingly warmer and drier climate conditions.

The reduction in homegarden productivity is expected to negatively impact farmers' wellbeing, primarily through poorer nutrition outcomes. Climate change is, therefore, a potential risk to the nutrition of farmers in homegardens located elsewhere, particularly in East Africa. The climate impacts on farmers' wellbeing might be buffered by supplementing the homegardens with dryland crops. However, this strategy mandates sustaining access to productive assets like farmland, which could become increasingly scarce and costly over time with climate change.

To help protect farmers' crop production and wellbeing from climate change, we suggest that different countries' sources of climate financing should be used to assist farmers in adapting their homegarden into a more resilient 'state', potentially by establishing more climate-resilient sources of fodder.

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CRediT authorship contribution statement

Martin Watts: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Craig Hutton:** Writing – review & editing, Supervision, Conceptualization. **Abel Paul:** Data curation. **Natalie Suckall:** Writing – review & editing, Supervision, Conceptualization. **Kelvin S.-H. Peh:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Martin Watts reports financial support was provided by Economic and Social Research Council. Martin Watts reports a relationship with Economic and Social Research Council that includes: funding grants.

Data availability

The dataset is currently under embargo until December 2024 within the University of Southampton's repository. The dataset will be available for use following December 2024.

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Appendix. Supplementary data

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