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The potential impact of future climate change on the production of a major food and cash crop in tropical (sub)montane homegardens

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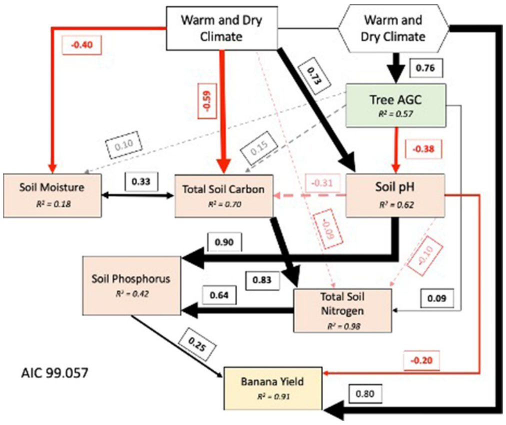
HIGHLIGHTS

- Warmer and drier climate conditions adversely affected ecological interactions in the homegardens.
- Homegarden trees have minimal effect in mediating the effects from changing climate conditions on soil and crops.
- Banana yield is mainly influenced by the climate conditions rather than soil quality in the homegardens.
- Banana yield initially benefits under warmer climate conditions before declining due to water stress.
- Declines in banana yield may be alleviated through the irrigation measures.

GRAPHICAL ABSTRACT



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ABSTRACT

Tropical agroforestry systems support the wellbeing of many smallholder farmers. These systems provide smallholders with crops for consumption and income through their ecological interactions between their tree, soil, and crop components. These interactions, however, could be vulnerable to changes in climate conditions; yet a reliable understanding of how this could happen is not well documented. The aim of this study is to understand how tree-soil-crop interactions and crop yield are affected by changes in climate conditions, which has implications for recognising how these systems could be affected by climate change. We used a space-for-time climate analogue approach, in conjunction with structural equation modelling, to empirically examine how warmer and drier climate conditions affects tree-soil-crop interactions and banana yield in Mt. Kilimanjaro's homegarden agroforest. Overall, the change in climate conditions negatively affected ecological interactions in the homegardens by destabilizing soil nutrient cycles. Banana yield, however, was mainly directly influenced by the climate. Banana yields could initially benefit from the warmer climate before later declining under water stress. Our findings imply that under increasingly warmer and drier climate conditions, homegarden agroforestry may not be a robust long-term farming practice which can protect smallholder's wellbeing unless effective irrigation measures are implemented.

Abbreviation: TAFS, Tropical Agroforestry System.

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1. Introduction

Agroforestry involves the integration or retention of trees in agricultural landscapes for socio-economic and ecological benefit (Schroth et al., 2004). Ecological interactions between trees, soils and crops in agroforests can benefit smallholder farmers' crop yields whilst minimising the need for farming inputs (Jose, 2009; Ajayi et al., 2011). Trees, for example, can improve soil fertility (Sileshi and Mafongoya, 2006; Thomazini et al., 2015), which, in-turn, increases yield and income (Cerda et al., 2014; Classen et al., 2014). In the tropics, these ecosystem services from tropical agroforestry systems (TAFS) are particularly important for smallholder farmers' wellbeing (Hashini Galhena et al., 2013). TAFS are particularly diverse agroforests, which encompass high biodiversity per unit area of farm (Dagar and Tewari, 2017). Common types of TAFS include homegardens (the intermixing and layering of trees with other plants and crops at different vertical canopy strata), multipurpose trees on woodlots (community forests providing forest products) and taungya systems (short-term crops cultivated with cleared and re-planted forest) (Atangana et al., 2014). The features and functioning of TAFS are mainly influenced by their supporting agroclimatic environmental conditions (Atangana et al., 2014), which implies that TAFS could be vulnerable to changes in climate conditions.

Climate projections for tropical regions forecast a much warmer climate (Serdeczny et al., 2017; Siyum, 2020). Compared to other world regions, rises in temperature in the tropics could be more severe (Gasparrini et al., 2017). The IPCC's recent multi-model mean projections suggest that regions including the NE South America, Central America, Western and Southern Africa and SE Asia may become drier, whilst other 'wet' tropical regions will become significantly wetter by 2100 (Lee et al., 2021). However, various studies have challenged the paradigm that wetter regions will become wetter and drier regions drier (Feng and Zhang, 2015; Greve and Seneviratne, 2015). Furthermore, tropical regions have the lowest overall agreement amongst climate models regarding their future rainfall change (Knutti and Sedláček, 2013; McSweeney and Jones, 2013). Such uncertainties are also reflected in the variance of predictions derived from downscaled assessments, including downscaled projections made for areas supporting TAFS (e.g., Platts et al., 2014; Rahn et al., 2018). Together with increasingly hotter temperatures, a potential reduction in rainfall would likely be worst-case future scenario for smallholder farmers.

Whether TAFS positively or negatively influence crop yield via tree-soil-crop interactions may depend on external climate factors including temperature and rainfall (Tscharntke et al., 2011; Luedeling et al., 2014). However, scant reliable evidence has examined how changes in climate may impact such ecological interactions in TAFS (Watts et al., 2022). Modelling-based approaches can struggle to reliably simulate already complex tree-soil-crop interactions in TAFS under changing climate conditions (Luedeling et al., 2014). Agroforestry modelling studies in the tropics also rarely corroborate their outputs (Watts et al., 2022). Empirical studies have suggested that water resource competition between on-farm trees and crops could intensify under warmer and drier climate conditions created by drought to the detriment of crop yields (Lott et al., 2009; Abdulai et al., 2018; Blaser et al., 2018). However, such resource competition under these climate conditions is speculated to be the consequence of having uncomplimentary tree-crop root structures within the systems (van Noordwijk et al., 2021). This view is supported by empirical studies performed in artificial environments, which found that droughts do not significantly impact ecological interactions and crop yields in TAFS that entail complimentary root systems (Köhler et al., 2010; Schwendenmann et al., 2010). However, artificially created drought conditions cannot precisely replicate all climate variables that drought alters (Schwendenmann et al., 2010), whilst evidence from these artificial studies is less transferable to real-world agroforestry systems (Coe et al., 2014). Consequently, little is still known about how increasingly warmer and drier climate conditions may affect TAFS. Since the wellbeing of smallholders can be influenced by their TAFS crop production, understanding how these changes in climate conditions could impact on TAFS is essential for long-term adaptation planning.

This study aims to investigate the effects of warmer and drier climate conditions on tree-soil-crop interactions in tropical (sub)montane homegardens and on banana yield. We approach this by undertaking a space-for-time climate analogue approach along Mt. Kilimanjaro's elevation gradient which spans the homegardens (900-1800 m asl). Mt. Kilimanjaro's homegardens encompass high tree species richness and diversity, which provides more complex tree-crop root systems. Homegardens can also better represent the high ecological diversity often associated with TAFS (Dagar and Tewari, 2017). Current studies on the effect of warmer and drier climate conditions on tree-soil-crop interactions in TAFS have been limited to single crop systems composed of few tree species (e.g., Abdulai et al., 2018).

Climate analogue analysis involves using measurements from different locations along an elevation gradient which are exposed to varying climate conditions (Veloz et al., 2012). The space-for-time approach is often used to predict the impacts of changes in climate conditions on ecosystems, with implications for assessing the potential impact of climate change, when alternative methods lack reliability (Leibing et al., 2013). Climate analogue analysis, therefore, provides an alternative to modelling for projecting the impacts of changing climate conditions on TAFS (Luedeling and Neufeldt, 2012; Luedeling et al., 2014).

Mountains in the tropics provide conducive environments for climate analogue analysis due to their abrupt change in climate conditions with elevation (Wang et al., 2016). Their downslope locations represent warmer and drier climate conditions which can act as 'natural laboratories' (Tito et al., 2020) and eliminate the need to create artificial climate conditions. Field experiments using elevation gradients can often reveal the effects of climate on ecosystems not easily identified using artificial settings, including detecting changes in ecosystem interactions and their subsequent effects (Tito et al., 2018, 2020). Therefore, using such an elevation gradient approach is pertinent for assessing the effects of warmer and drier climate conditions on tree-soil-crop interactions. The approach has been effectively applied to project the impacts of warmer and drier climate conditions on crop yields (Tito et al., 2018), litterfall and soil nutrient cycles (Becker et al., 2015), plant responses (Cardinaux et al., 2018) and soil decomposition processes (Nottingham et al., 2015) in tropical montane forests.

2. Material and methods

2.1. Study area

The study was carried out in Moshi Rural district's Chagga homegardens on Mt. Kilimanjaro's south-eastern slopes (Fig. 1), specifically across the areas' midland (900-1200 m asl) and highland (1200-1800 m asl) agroecological zones. The climate across the elevation gradient is characterized by a bimodal rainfall regime encompassing a shorter rainfall season from October to November and a more extended rainfall season lasting from March to May (Mpanda et al., 2016a). On average, the midlands zone experiences 1000-1200 mm annual rainfall and temperatures between 20 and 25 °C, whilst the highland receives between 1200 and 2000 mm and tends to experience temperatures of 15-20 °C (Soini, 2005).

The soils in the study area are classified as mostly Haplic Acrisol and Haplic Ferrasol (Poggio et al., 2021). The soils across the different elevations studied are composed of similar parent material (Dawson, 1992). Soils composed of the same soil parent material are particularly beneficial for comparatively analysing the effects of change in climate conditions on ecosystem processes and soil properties (Becker et al., 2015). Concerning vegetation, the midlands zone is characterized by mainly *Croton-Olea* submontane forest in conjunction with coffee-banana homegarden plantations, which gradually transition into *Agauria-Ocotea* montane forests with increasing elevation into the highlands zone. However, most of the natural forests in the cultivation belt have disappeared and only relicts are restricted to the deepest valleys (Hemp, 2006a).

The Chagga homegardens are traditional, densely planted 'banana forests' with a scattered upper tree layer. The complex multicropping system evolved over several centuries through a gradual transformation

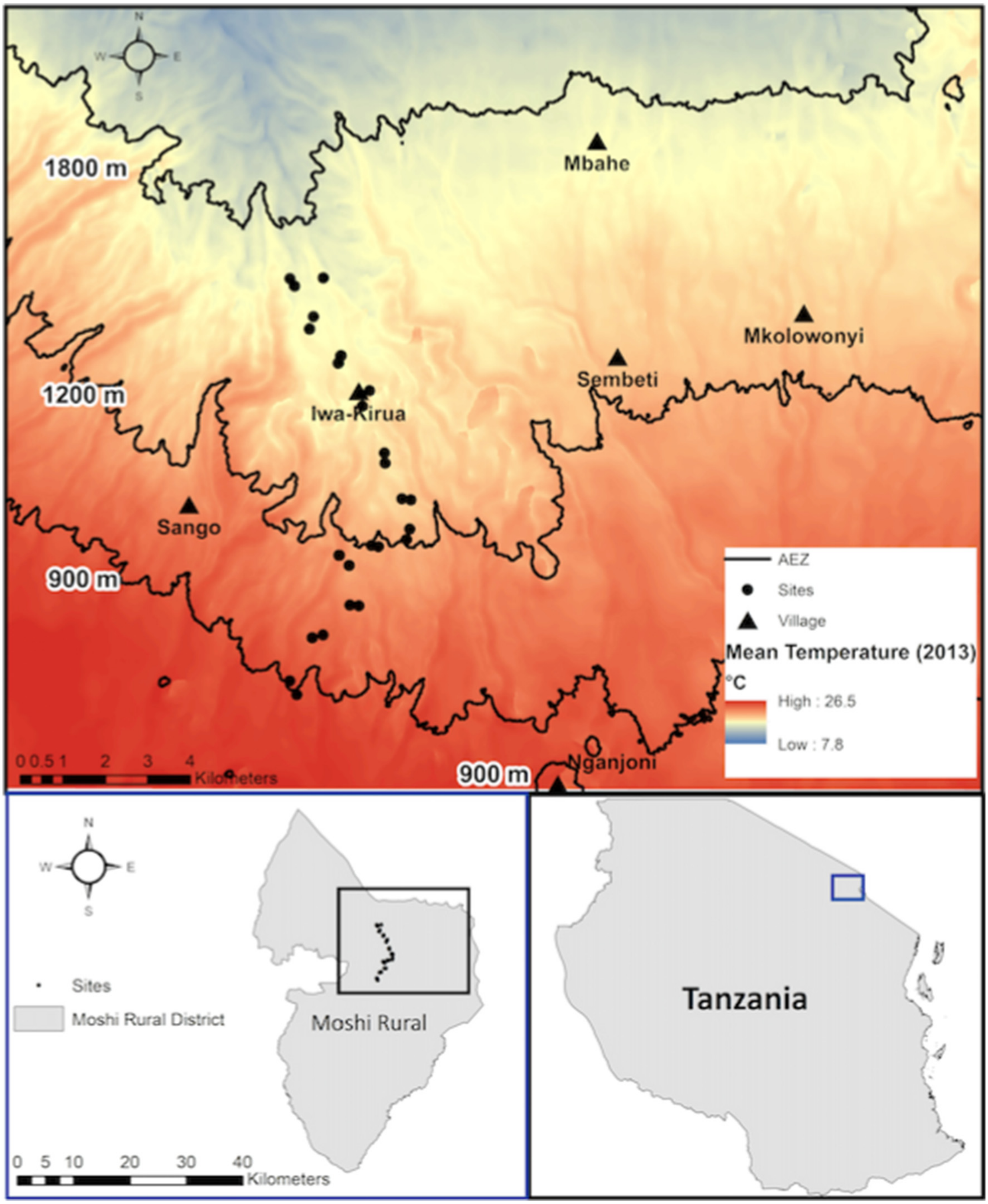

Fig. 1. Location of study sites in the homegardens following an elevation gradient and change in climate conditions (temperature) across the Moshi Rural District in Tanzania. Temperature data was sourced from Appelhans et al. (2016). This is a two-column figure.

of the natural forest on the lower slopes of Kilimanjaro. There is evidence that the first irrigated banana gardens existed already in the 12th century (Hemp et al., 2009). A Chagga homegarden integrates numerous multipurpose trees and shrubs with food crops, and stall-fed animals using four vegetation layers: Under a tree layer, which provides shadow, fodder, medicines, firewood and formerly also construction wood, bananas (the key food and cash crop produced in the homegardens) are grown and under the banana plants coffee trees, and under these vegetables (taro, beans). This multilayer system maximizes the use of limited land in a highly populated area, making sustained production possible and ensures at the same time environmental protection. The Chagga homegardens maintain a high biodiversity with over 520 species including 400 not cultivated plants (mainly forest plants) including 55 tree species (Hemp, 2006b). The agroforestry system of the Chagga homegardens is a unique feature of Kilimanjaro, stretching on the climatically most favourable zone of the southern and south-eastern slopes over an area of 1000 km^2.

2.2. Data sources and processing

Climate, tree, soil, and banana yield data from the homegardens across Moshi Rural's elevation gradient were needed to perform the climate analogue approach. As covid-related restrictions prevented most of the primary data collection, secondary data from homegarden plots distributed along a transect for the year 2013 were gathered and evaluated for this study (Fig. 1). The climate in 2013 represented a ‘normal’ year on Mt. Kilimanjaro's southern slopes, where the climate was neither excessively wet nor dry (Wagner et al., 2021). The data on trees and soils covered 50 plots along Mt. Kilimanjaro's gradient in the cultivated areas below the forest belt spanning from highland, midland and lowland. However, only data for 26 plots located within the midland ($n = 9$) and highland ($n = 17$) elevation zones were used in the empirical analysis. This is because homegarden agroforestry and banana production are not practiced in the lowlands (<900 m asl). Therefore, the secondary data collected in this zone are not relevant to our homegarden study.

We critically appraised the data on trees and soils using an evidence assessment tool developed by Mupepele et al. (2016) for ecosystem services and the data were deemed credible for this study. The climate data was derived from high-resolution maps (30 m × 30 m) in Appelhans et al. (2016), which were generated using long-term climate records from the rain gauge network of A. Hemp. This resolution was sufficient to capture the fine variation in climate conditions across the study sites. The following sections explain how the data was processed.

2.2.1. Climate data

Annual precipitation (mm/yr), air temperature (°C) and relative humidity (%) for 2013 were derived from the precipitation, relative humidity, and air temperature maps in Appelhans et al. (2016). To generate their maps, Appelhans et al. (2016) used a long-term dataset from a network of about 70 rain gauges on Mt. Kilimanjaro (Hemp, 2006c), and air temperature and above-ground air humidity collected from 52 combined temperature and relative humidity sensors spatially distributed across Mt. Kilimanjaro's southern slopes. Kriging, considering elevation, aspect, slope, sky-view factor, and normalized difference vegetation index, was used to generate the monthly relative humidity and air temperature maps, whilst kriging and machine learning techniques developed the average annual precipitation map. To derive the mean annual temperature (MAT) and average relative humidity values for 2013, raster layers for each month of that year were averaged. MAT and average relative humidity values were then extracted for each of the 26 plots.

Due to the different methods Appelhans et al. (2016) used to generate their long-term precipitation maps, it was not possible to extract 2013's mean annual precipitation (MAP) the same way. To estimate 2013's MAP, we firstly extracted the long-term averaged annual precipitation for 52 sites across Moshi Rural's elevation gradient (from lowland to montane), which included two rainfall stations located in Kilema Forest (1820 m asl, N 9640472, E 329366) and Himo Sisal Estate (850 m asl, N 9625000, E 338000). Next, the MAP for 2013 were obtained from the two rainfall stations to determine a correction factor which was then applied to all 50 plots to account for the difference in precipitation between 2013 and the long-term average (for details see Supporting Information, supplementary material 1). How the climate data used in this study varied with elevation for each homegarden site is presented in Section 3.1.1.

2.2.2. Tree data

Tree data was sourced from Mpanda et al. (2016c). The dataset included tree height, diameter at breast height and identification of trees at the species level for each tree within each site (excluding coffee shrubs) at 5 cm diameter at breast height and above. The tree dataset also included above-ground biomass (kg/ha) estimations for each study site based on Chave et al.'s (2014) allometric equation for measuring trees in the tropics. Above-ground biomass was halved to gain the tree above-ground carbon (AGC) stock. Using tree AGC in this study is important because tree growth and size in TAFS can be affected by changes in climate conditions (Feng and Li, 2007; Tamayo-Chim et al., 2012; Kumar et al., 2021). Tree AGC was also used to compute a species composition variables (% of tree biomass per plot) for legume trees species, which includes *Albizia schimperiana,* to consider the effect of N fixation in the homegardens. *Albizia* is the most frequent indigenous tree species in the homegardens of Kilimanjaro (Hemp, 2006b) and an important tree species to the homegardens for N fixation and shading (Odeny et al., 2019). Recent species distribution modelling has indicated that climate change could alter suitable areas for growing *Albizia* trees on Mt. Kilimanjaro and reduce its AGC (ibid).

As well as tree species richness, a Shannon Diversity Index (SDI) was computed for each site using Eq. (1), where *pi* represents the proportion of each individual tree species in the farm and ln represents the natural log. The Shannon Diversity Index, which accounts for tree species richness and abundance, performs well in diverse systems (Morris et al., 2014). Tree species richness and diversity variables were calculated as soil properties can be altered under TAFS varying in species richness and diversity (Mattsson et al., 2015). Any possible effect from the change in climate conditions on tree species diversity could therefore be important for assessing indirect effects on soil properties.

$$H = -\sum_{i=1}^{R} pi\,(\ln pi) \tag{1}$$

2.2.3. Soil data

The soil dataset was also derived from Mpanda et al. (2016a, 2016b, 2016c) who collected composite and cumulative soil samples (litter was removed) at the farm plot level across depths of 0-20 cm and 20-50 cm during April 2013. Samples were gathered using an inverted Y-shaped sampling design under the AfSIS protocol (UNEP, 2012). In this design, three subplots were laid out radiating at an angle of 120° and distance of 12.2 m from the centre subplot. Composite soil samples from topsoil and subsoil were collected from each of the four subplots, mixed thoroughly and 500 g of each sample was packed in zip-lock bag, and labelled. Cumulative soil mass samples from topsoil and subsoil were collected separately at the centre subplot, packed in zip-lock bags, and labelled. Composite and cumulative soil samples were processed and analysed in soil laboratory to determine physical and chemical properties.

Sensitivity analysis was performed using soil values derived from different weighted averages across soil depths and revealed that the topsoil (0-20 cm depth) was the best predictor of banana yield. This accords with banana plant's shallow root structure (Sebuwufu et al., 2004; Turner and Rosales, 2005). The soil parameters included in the dataset were gravimetric soil moisture content (%), bulk density (g/cm^3), Exchangeable Calcium (ExCa) (mg/kg), Exchangeable Potassium (K) (mg/kg), Exchangeable Sodium (mg/kg), Exchangeable Magnesium (Mg) (mg/kg), Exchangeable Actinium (Ac) (mg/kg), Exchangeable bases (Bas) (mg/kg), Iron concentration (Fe) (mgkg^{-1}), Aluminium concentration (Al) (mgkg^{-1}), Boron concentration (B) (mgkg^{-1}), Copper concentration (Cu) (mgkg^{-1}), Manganese concentration (Mn) (mgkg^{-1}), Zinc concentration (Zn) (mgkg^{-1}), Phosphorus concentration (P) (mgkg^{-1}), Sulfur concentration (S) (mgkg^{-1}), soil pH, ECd (acidity), ESP (alkalinity), total carbon (C) content (g/kg) and total nitrogen (N) content (g/kg).

2.2.4. Banana yield data

To gain banana yield estimates for each study site, we used primary data collected using a household agricultural questionnaire administered in the Fig. 1's villages. The questionnaire gathered annual banana yield (kg/ha) for 2020, 2017 and 2013, with the latter two periods using farmer recall. We assessed the reliability of farmers' recall in 2013 by comparing the trend in yield with elevation with 2020's trend (both non-drought years). This revealed an identical hump-shaped pattern indicating that 2013's yield data was reliable.

In Moshi Rural's homegarden, banana is often produced using organic fertilizer, whilst in midland villages, such as Njanjoni, farmers can also irrigate their banana plants. To discern whether fertilizer and irrigation practices may have influenced yield, we performed multiple linear regression to examine the effect on 2013's banana yield. Only irrigation was found to significantly impact banana yield ($P < 0.05$). Irrigated banana yields were subsequently filtered out from the dataset. The dataset was further refined to banana yields recorded in Sango, Iwa-Kirua and Mbahe leaving 69 yield measurements. These villages are located closest to the 26 sites transect and cover the required elevation range (see Fig. 1). Elevation was a significant predictor of banana yield ($P < 0.001$), and the relationship was found to be a hump-shaped quadratic trend. Therefore, we used the associated equation (Eq. (2)) with site elevation (x) to estimate 2013's banana yield for the 26 sites.

$$y = -0.025x^2 + 70.6x - 44595 \tag{2}$$

Various types of bananas are cultivated in the homegardens (Hemp, 2006b; Ichinose et al., 2020). During fieldwork two main banana types, locally named Mshale (genotype AA) (food and cash crop) and Jamaica (genotype AAA) (mainly cash crop), emerged as the main banana types grown in the homegardens across both elevation zones. Therefore, the general banana yield was deemed comparable across the elevation gradient given the dominance of these two cultivars. Farmers also planted more banana during April for the warm and moist environmental conditions, which accords with the soil sampling.

2.3. Statistical analysis

All statistical analysis was performed in R 4.1.3 (R Core Team, 2022). The methods included Pearson correlation plots, using Peterson et al.'s (2020) 'PerformanceAnalytics' R package version 2.0.4, linear regression modelling, using R's stats package, linear mixed effect modelling, using the lme4 package (Bates et al., 2015), and structural equation modelling (SEM), using Lefcheck's (2016) piecewise method and R package. The analysis was performed in a three-phase process to refine the tree and soil dataset to the most meaningful data to use in the SEM analysis.

2.3.1. Pearson correlation plots

Associations between climate, tree, soil, and banana variables were explored through Pearson correlation plots. Plots were designed to depict the data distribution, trendlines to identify linear and non-linear relationships, and a correlation coefficient and *P*-value. *P*-values were checked for spurious positives via Bonferroni correction. Plots were also used to identify outliers, of which site number 12 was omitted due to outliers for soil metals and phosphorus. These values were cross-checked against the expected ranges described in the literature before removal. To meet normality assumptions, all variables except for the exogenous climate variables, tree species richness, ExK, S, Fe and Al were transformed using Peterson's (2021) best normalize R package. The outputs of these plots were used to refine the number of tree and soil parameters for regression analysis (see supplementary material 2 for the details).

2.3.2. Linear and mixed-effect modelling

We used linear and linear mixed-effect regression modelling to identify how the exogenous climate variables affected tree, soil, and banana components in the homegardens. Regression analysis was also employed to examine whether and how the endogenous tree, soil and banana yield variables interacted to elucidate the indirect impacts of the change in climate conditions. The mixed-effect models used the elevation zone (midland and highland) as a random effect. However, in most models the random effect was not required or created overfitted models. Linear models were therefore mostly used.

Multicollinearity was strong amongst the climate parameters. Therefore, simple linear regression was performed to assess the direct effect of changes in climate conditions on trees, soil, and banana. Heteroscedasticity was cross-checked via model diagnostic plots and the Breusch and Pagan (1979) test. Where heteroscedasticity was evidenced, generalized least squared regression with equally weighted residuals was performed (Peres-Neto, 2022) using the nlme R package version 3.1 (Pinheiro et al., 2022). Due to the small sample size ($n = 25$), statistical significance was taken at $P < 0.1$ to avoid type II errors.

2.3.2.1. Structural equation modelling. Structural equation modelling (SEM) was carried out to examine the effects of changing climate conditions on tree-soil-crop interactions in the homegardens. SEM is a statistical modelling technique that unites numerous variables, which can function as both a predictor and response variable, within a single causal network whereby in-direct and direct (cascading) effects can be quantified (Pearl, 2012). For example, an explanatory variable in one component model can function as a response variable in another component model within the network and thereby function as an intermediate node in a causal chain to capture complex system relationships (Lam et al., 2021). Lefcheck's (2016) piecewise SEM R package and local estimation method was used to accommodate the sample size and identified non-linear relationships. The piecewise SEM method departs from traditional SEM by excluding latent variables, permitting the individual specification of each component model and relaxing assumptions of independence and normality (Lefcheck, 2016).

The SEM was developed using the refined and most meaningful tree and soil parameters. These parameters comprised tree AGC, legume composition, total soil C, total soil N, soil P concentration, pH, and soil moisture content. Multicollinearity amongst exogenous variables in SEMs can create estimate errors leading to type II errors (Grewal et al., 2004). Therefore, elevation, which explained 95 %, 98 % and 56 % of temperature, precipitation, and humidity variation respectively (see Section 3.1.1), was used to proxy the changing climate condition effect. Elevation has previously been effectively used to represent the impacts of changes in temperature and precipitation on Mt. Kilimanjaro's soils (Pabst et al., 2016).

SEM implies causal links amongst variables as unidirectional relationships are informed by priori knowledge and experiment (Grace and Keeley, 2006; Pearl, 2012). The SEM casual structure was developed based on a priori knowledge of the tree-soil-crop relationships in TAFS and how climate change could alter such relationships (see supplementary material 3 for priori knowledge details). The findings from the prior regression modelling were also drawn on during the model development. Non-linear relationships, for instance, were found between the climate (temperature and precipitation), tree AGC and banana yield variables. To accommodate these relationships whilst permitting for linear relationships between other variables, a composite climate variable was generated following Lefcheck (2021). Although not all priori regression models reported statistically significant results, some nonsignificant relationships, such as the effect of trees on soil moisture, were still included in the saturated SEM based on a priori knowledge. Shipley's (2013) AICc d-separation test was employed to determine whether the removal or addition of variables and/or pathways provided the most parsimonious model. Each model's goodness-of-fit was assessed by Shipley's test of d-separation, using Fisher's C statistics with χ^2 distribution, to establish whether the SEM specified sufficiently reflected the relationships within the data (Lefcheck, 2016).

3. Results

3.1. The effects of changing climate conditions on the homegarden

3.1.1. Change in climate conditions with elevation

There was a strong linear decrease in MAT (Fig. 2A) and a strong linear increase in MAP (Fig. 2B) and relative humidity (Fig. 2C) with increasing elevation. The average MAT across study sites was 20 °C and varied from 16.8 to 24.7 °C providing a MAT range of 7.9 °C. The average amount of MAP across study sites was 1711 mm/yr and varied from 855 to 2599 mm/yr, providing a 1744 mm/yr range. The average relative humidity was 81.7 % and ranged from 76.5 to 90.8 % (14.3 % difference).

3.1.2. The effect of the change in climate conditions on tree, soil, and banana components

Increases in both MAT and MAP initially increases tree AGC ($P > 0.001$) before decreasing AGC from approximately >1750 mm/yr MAP and approximately >20.5 °C MAT ($P > 0.001$) (Table 1). Relative humidity did not significantly affect tree AGC ($P = 0.733$). No climate parameters had a statistically significant effect on the composition of legume tree species.

Concerning soil quality properties (see Table 1), total soil C and N declined under increased MATs, whereas total soil C and N both increased

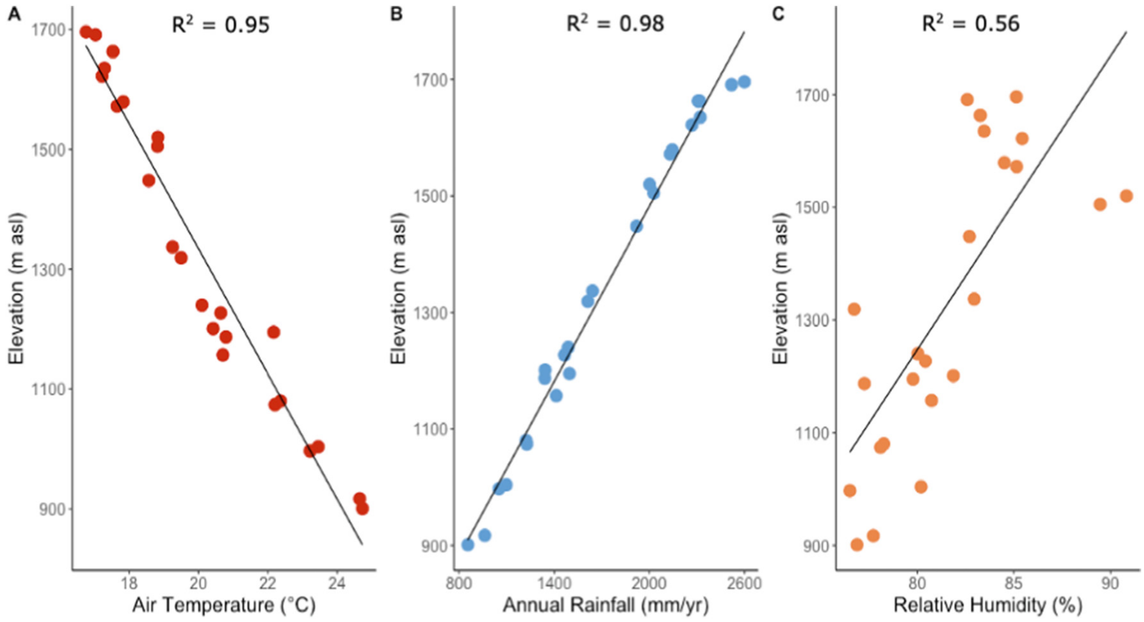

Fig. 2. Change in climate parameter with elevation for each study site (n = 25) in the Homegardens in 2013 for A) air temperature, B) annual precipitation, and C) relative humidity.

under increased MAP and relative humidity ($P > 0.001$). Soil P exhibited a significant and quadratic relationship with increased MAT ($P > 0.05$) and MAP ($P > 0.01$). Soil P initially benefits from warmer and drier climate conditions before declining under hotter MATs (approximately >20.5 ˚C) and drier MAPs (approximately <1700 mm/yr). The effect of relative humidity was not statistically significant ($P = 0.774$). Soil pH increases with increased MATs ($P > 0.01$) and decreases with increased MAP ($P > 0.001$) and relative humidity ($P > 0.01$), which suggests that a warmer and drier future climate would increase soil alkalinity. Regarding soil moisture content, soil moisture decreased under warmer MAT ($P > 0.05$), whilst moisture levels increased under wetter ($P > 0.05$) and more humid ($P > 0.05$) climate conditions, as expected.

All climate parameters significantly influenced banana yields ($P > 0.001$) (see Table 1). Both MAT and MAP exhibited a hump-shaped relationship with banana yield. Increased MAT and MAP increased banana yields, although once the climate conditions became either too warm (approximately >19 ˚C) or wet (approximately >1900 mm/yr), banana yields declined. Increased relative humidity levels benefited banana yields and were not limiting under the highest levels of humidity.

3.2. The effect of changing climate conditions on tree-soil-crop interactions and banana yields in the homegarden

Overall, 9 variations of SEM spanning an ΔAICc of 13.314 were developed and examined (see supplementary material 5). All SEMs fit the data according to Fisher's C statistic. Significant ($P < 0.1$) correlated errors, and thus a bidirectional relationship between total soil C content and soil moisture content in models 1 and 3 were found. Correlated errors improved model fit for all accommodating SEMs, justifying the inclusion. Soil C increases soil's water-holding capacity in TAFS (Phiri et al., 2003; Wu et al., 2016) and retains soil moisture, whilst soil moisture supports soil biota activity which decomposes litterfall into the soil (Abdalla and Smith, 2016). Based on Shipley's (2013) AIC model selection method for path analytic models, model ranked 1 is used to convey the SEM results (Fig. 3).

As expected, increasingly warmer and drier climate conditions had a strong and direct negative effect on total soil C (-0.59, $P < 0.01$) and soil moisture content (-0.40, $P < 0.1$), whereas the changes in climate had a strong direct positive effect on soil pH (0.73, $P < 0.001$) (Fig. 3). In contrast, the warmer climate conditions had a minimal and nonsignificant direct negative impact on total soil N (-0.09, $P = 0.166$). Consistent with Table 1's results, the change in climate conditions had a strong effect on tree AGC (0.76, $P < 0.001$), whereby a drier and warmer climate initially benefits tree AGC before reducing tree AGC.

Contrary to expectations, trees had a limited role in mediating the effect of the change in climate conditions on soils. Tree AGC had a relatively small and nonsignificant positive effect on total soil C (0.15, $P = 0.315$) and soil moisture content (0.10, $P = 0.608$). However, tree AGC significantly and negatively affects soil pH (-0.38, $P < 0.01$), increasing soil acidity. Total soil N was also increased by tree AGC ($P < 0.05$), but only marginally (0.09). Overall, these results suggest that most soil properties in the homegardens are mainly directly influenced by the change in climate conditions.

The effect of warmer and drier climate conditions on soil C and pH indirectly effected other soil nutrients supporting banana production (Fig. 3). Soil P was strongly and positively influenced by total soil N (0.64, $P < 0.01$) and soil pH (0.90, $P < 0.001$) and positively affected banana yield (0.25, $P < 0.05$). Total soil C indirectly influenced soil P and banana yield by positively influencing total soil N (0.83, $P < 0.001$), whereas soil pH both directly and indirectly influenced banana yield by having a large and positive effect on soil P (0.90, $P < 0.001$) but a negative effect on yield (-0.20, $P < 0.05$). Overall, however, the most influential predictor of banana yield was the direct effect from the change in climate conditions, which had a strong and positive effect on banana yield (0.80, $P < 0.001$). This effect was quadratic, which is consistent with Table 1's results.

4. Discussion

This study presents the first empirical field assessment of how warmer and drier climate conditions could impact tree-soil-crop interactions in a TAFS. The results have important implications for inferring how climate change in the tropics could negatively affect the productivity of TAFS through direct and indirect effects from the changes in climate conditions on soil and banana.

4.1. The effect of change in climate conditions on tree-soil-crop interactions

The optimal climate conditions supporting homegarden trees were marginally over mid-elevation. Despite receiving the greatest MAP, the

Table 1

Model outputs representing the effects of changes in climate conditions on tree above-ground carbon (AGC), legume tree species composition, total soil carbon (C), total soil nitrogen (N), soil phosphorus (P), soil pH, soil moisture content and estimated annual banana yield in the homegardens.

	Tree AGC (ORQ)		Legume composition (ORQ)		Total soil C (ORQ)		Total soil N (ORQ)		Soil P concentration (ORQ)		Soil pH		Soil moisture content (ORQ)		Banana yield (ORQ)	
	Estimate	CI (95 %)	Estimate	CI (95 %)	Estimate	CI (95 %)	Estimate	CI (95 %)	Estimate	CI (95 %)	Estimate	CI (95 %)	Estimate	CI (95 %)	Estimate	CI (95 %)
MAT	5.269****	3.169–7.368	0.514	−2.531–3.558	−0.332****	−0.438 to −0.226	−0.341****	−0.440 to −0.243	**3.55****	**1.14–6.00**	0.108***	0.045–0.170	−0.164**	−0.327 to −0.0005	3.763****	2.074–5.453
MAT^2	−0.130****	−0.181 to −0.079	−0.014	−0.088–0.06	_	_	_	_	**−0.09****	**−0.15 to −0.03**	_	_	_	_	−0.097****	−0.138 to −0.056
MAP (*100)	1.22****	0.693–1.547	0.265	−0.343–0.873	0.160****	0.113 to 0.208	0.163****	0.118 to 0.208	**0.54***	**0.16 to 1.21**	*−0.068*****	*−0.090 to −0.047*	0.081**	0.005 –0.157	1.2****	0.985–1.453
MAP^2 (*100)	−0.0003****	−0.0004 to −0.0002	−0.0001	−0.0002–0.0001	_	_	_	_	**−0.0002****	**−0.0004 to −0.00007**	_	_	_	_	−0.0003****	−0.0004 to −0.0003
Relative Humidity	0.019	−0.091–0.127	0.046	−0.056–0.149	0.171****	0.082–0.259	0.183****	0.099–0.267	−0.015	−0.119–0.090	−0.06***	−0.104 to −0.003	0.125**	0.024 –0.227	*0.127*****	*0.043–0.210*

Response variables are placed across the first row. Thicker lines denote separate simple regression outputs. Estimates in italics represent values generated through ordinary least squared regression due to homoscedasticity violation, whilst those in bold represent estimates produced by mixed-effect models. MAP estimates have been multiplied by 100 to make estimates comparable with other climate parameters. MAT/MAP alone represents a normal linear effect, whilst MAT/MAP and MAT^2/MAT^2 represent a quadratic model. The applied transformation is detailed in brackets, ORQ = Ordered Quantile Normalization (Peterson and Cavanaugh, 2019). Regression graphs depicting the relationship between climate variables and tree, soil and banana components are available in supplementary material 4.

[*] Denotes significance at <0.01.

[**] Denotes significance at <0.05.

[***] Denotes significance at <0.01.

[****] Denotes significance at <0.001.

upslope climate conditions were not the most productive, which highlights the potential benefits of warmer MATs. Trees significantly influenced soil pH and total N content but did not have a significant effect on total soil C and soil moisture content (Fig. 3). Total soil C content supported moisture content and positively impacted soil P by increasing soil N, indirectly benefiting banana yield. Homegarden trees directly benefited total soil N, possibly through atmospheric N fixation, but this increase was relatively small compared to inputs from total soil C, which is consisted with the literature (Delgado-Baquerizo et al., 2013). Soil N and P can be limited in the tropics (Schroth et al., 2002), and deficiencies in these soil nutrients limit crop productivity (Elser et al., 2007), including banana (van Asten et al., 2003). Hence, maintaining soil C in homegarden is imperative for smallholder's crop production and wellbeing.

Total soil C reduced under higher MAT and reduced MAP. This result is consistent with Russell and Kumar (2019), whose modelling of a TAFS under warmer temperatures revealed significant declines in soil C, but contrasts with Andriamananjara et al. (2019) who found that warmer temperatures increased soil microbiota activity and subsequently soil C. However, Andriamananjara et al.'s (2019) study artificially maintained constant soil moisture levels throughout, which would change under warmer MATs. Indeed, higher MATs can increase soil C content under vegetation cover from improved net primary productivity, litterfall input, microbiota activity and C turnover (Chave et al., 2010). However, sufficient precipitation and soil moisture are also required (Pabst et al., 2016). Without moisture in soils, microbial activity and decomposition are lowered which reduces C input into soil (van Straaten et al., 2010; Abera, 2013; Meisner et al., 2021), as shown in the SEM. Soil moisture and precipitation provide conducive habitats for soil biota. This has been previously shown in the Chagga homegardens where soil biota biomass has positively correlated with higher precipitation (Gunina et al., 2018), and complements the trend between soil C and MAP in this study. This evidence implies that the decline of soil C in the homegardens under warmer and drier climate conditions could be related to a decline in soil biota productivity and decomposition.

Maintaining stable soil C cycles requires constant input from aboveground biomass, i.e., trees, and productive decomposer organisms (Davidson and Janssens, 2006). Soil C cycling in the homegarden may therefore destabilize under climate scenarios entailing warmer and drier conditions because trees had minimal effect on soil C under these conditions. This could be linked with warmer MATs reducing the size and quality of litterfall from agroforestry trees limiting nutrient inputs (Esmail and Oelbermann, 2011) and may be exacerbated by the drier climate negatively effecting soil biota and litterfall decomposition (van Straaten et al., 2010). Soil C, N and P cycles are coupled in terrestrial systems (Delgado-Baquerizo et al., 2013) and soil N and P in the homegarden were shown to be strongly and positively influenced by soil C directly and indirectly. This suggests that these soil nutrient cycles could also be vulnerable to destabilization under increasingly warmer and drier climate conditions, which would have knock-on impacts on banana production. This key finding is consistent with similar works on Mt. Kilimanjaro region. Becker (2017), for example, found that under warm and dry climates (<1900 m asl) the variation in soil C and N content was determined by the climate conditions, whereas in wetter climates (>1900 m asl) tree biomass input mainly controlled soil nutrient cycles.

The strongest effect from homegarden trees was to decrease soil pH. Trees in the homegardens can increase soil acidity by providing acidic litterfall and releasing ions from their roots (Rhoades and Binkley, 1996; Koutika et al., 2014). However, the negative effect on soil pH was outweighed by the direct positive effect from the warmer and drier climate, which is likely due to changes in mineral weathering rates and soil leaching (Gelybo et al., 2018). The cascading effect of increased soil pH in the homegardens is complex. Higher soil pH appears to increase the concentration of soil P, which benefits banana yield, but increasing soil pH also exhibits a direct negative effect on banana plants which thrive in more acidic soils (Robinson and Sauco, 2010). At the same time, soil P is likely to be reduced by declines in soil C and N under a warmer and drier climate. As homegarden soils become too alkaline, the positive effect of soil pH on

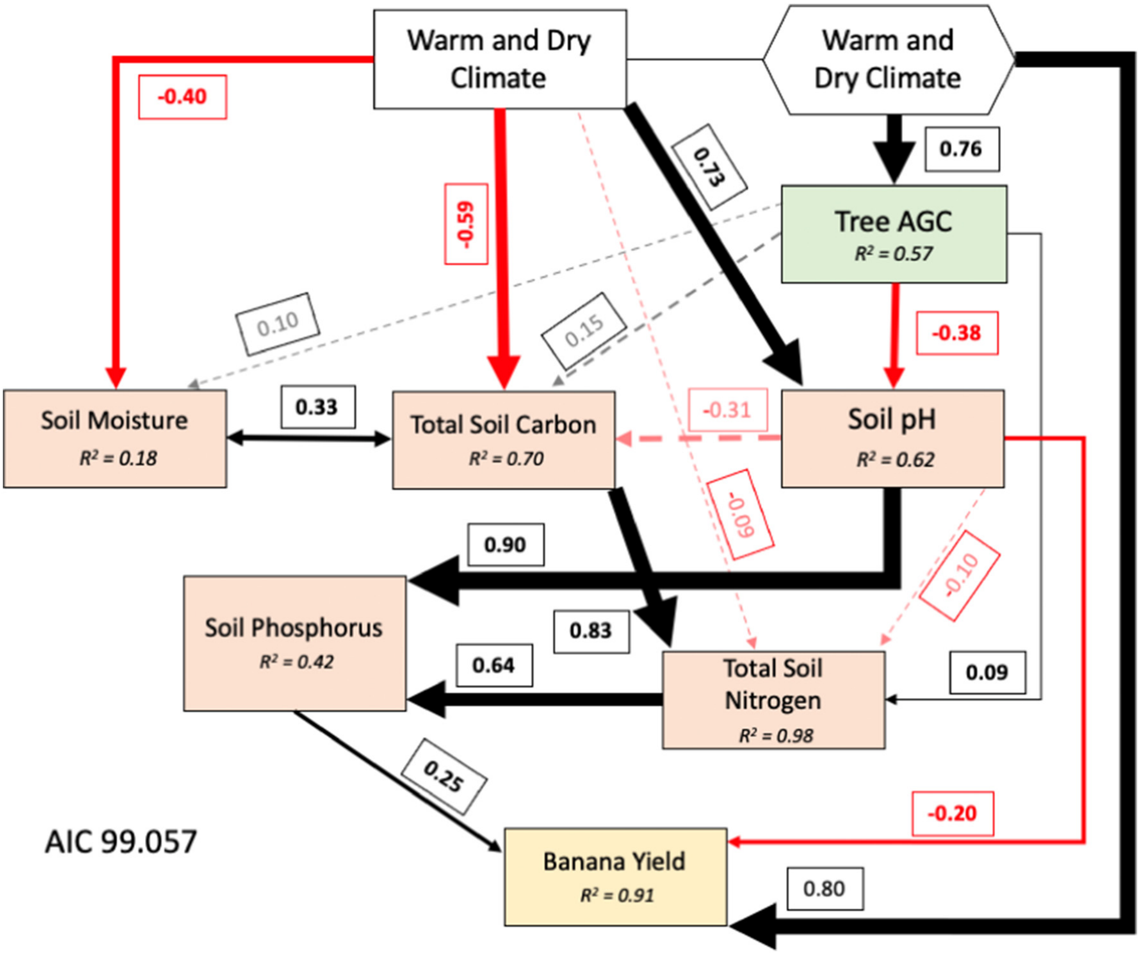

Fig. 3. Structural equation model revealing the effect of a plausible warmer and drier future climate on tree-soil-crop interactions in a tropical montane homegarden. Measured variables are shown in rectangular boxes and composite variables in hexagonal boxes. The causal relationships stemming from hexagonal boxes represent a quadratic causal effect on the response variable. Arrows indicate unidirectional causal relationships, and double-headed arrows correlated errors. Black arrows depict positive relationships and red arrows negative. Solid arrows represent statistically significant pathways, and transparent and dotted arrows nonsignificant pathways. Arrow thickness is proportional to the strength of the relationship (standardized estimate of model). Endogenous variables shaded green, brown, and yellow represent the model's tree, soil, and banana yield dimensions, respectively. The R^2 values for each component model are provided in the box of each response variable. The R code for this SEM analysis is available in supplementary material 6. This is a two-column figure.

soil P could eventually turn negative since the optimal pH for soil P availability is between 6 and 7.5 (Prasad and Chakraborty, 2019). This trend in changes in soil P is implied in our findings.

Most empirical studies maintain that climate change mediates TAFS tree-soil-crop interactions through changes in soil water. Our SEM contrasts with these studies which report that soil moisture depletes more rapidly in TAFS under warmer and drier climate conditions due to increased resource competition and water loss by trees (Lott et al., 2009; Abdulai et al., 2018; Blaser et al., 2018). Homegarden trees did not decrease soil moisture content despite the increasingly drier and warmer climate. This supports literature that maintains that agroforestry systems encompassing more complex and diverse tree root structures are less prone to water loss under climate change (e.g., van Noordwijk et al., 2021). However, our results are also contrary to studies which found that on-farm trees preserve soil water under drought conditions (e.g., Köhler et al., 2010; Schwendenmann et al., 2010). Albeit marginally, trees directly and indirectly increased soil moisture content, potentially by increasing soil water holding capacity through organic matter inputs (Phiri et al., 2003; Wu et al., 2016), canopy shading (Lin et al., 2008) and the interception of air moisture by epiphytes (Hemp, 2006b; Richards et al., 2020). These potential effects from homegarden trees failed to preserve soil moisture content under an increasingly warmer and drier climate, however. These results would infer that the homegardens climate buffering and moisture retention benefits, often highlighted by agroforestry proponents (e.g., Verchot et al., 2007; Garedew et al., 2017; Vargas Zeppetello et al., 2022), could become relatively ineffective under a plausible warmer and drier future climate scenario.

4.2. The impact of changing climate conditions on banana yield

The change in climate conditions had a significant and eventual negative effect on banana yield in the homegardens. This effect from increasing MAT on banana plant productivity is consistent with other studies conducted in the East African highlands (e.g., Sabiiti et al., 2016). In cooler areas of East Africa, banana productivity is limited, and warmer MATs from climate change could benefit yields (Ramirez et al., 2011). The colder environment in the homegardens higher elevation could have limited banana plant productivity, and increased MATs would benefit plants. High MAP upslope could also have been a limiting factor contributing to banana yields hump-shaped pattern with MAP. High MAP can increase banana fungal disease (Nyombi, 2010; van Asten et al., 2011); which are a known problem for banana plants in the Mt. Kilimanjaro region

(Ichinose et al., 2020). Therefore, a reduction in MAP may initially benefit banana yields by reducing fungal diseases. The expected increase in MAT under climate change is likely to increase rainfall demand to avoid water stress (Thornton, 2012), which, if unmet, will decrease banana plant yield (Thornton and Cramer, 2012), as our results show. Above around 19.5 °C and below approximately 1870 mm/yr precipitation could trigger water stress. Water stress causes banana plants shut their stoma to preserve water, which reduces carbon assimilation and subsequently yields (Turner et al., 2007). Yield may reduce through decreases in the number of fingers per bunch and less fruit filling (Goenaga and Irizarry, 1995; van Asten et al., 2011).

Our SEM showed that banana yield was predominantly driven directly by changes in the climate conditions rather than changes in soil. This finding implies that banana production in the homegarden could be vulnerable under climate change entailing warmer temperatures and reduced annual rainfall. According to Wairegi et al. (2010), banana yield in East Africa is mainly constrained by warm and dry climate conditions, although soil quality constraints are also common. Under warm and dry climate conditions, soil nutrient movements to, and uptake by, banana plant roots can be hindered, which decelerates plant growth and in-turn diminishes soil nutrient uptake further (van Asten et al., 2011). The relatively smaller effect of soils on banana yield could be due to banana plants' reduced ability to uptake soil nutrients whilst exposed to climate stress.

4.3. Implications of findings for homegarden agroforestry under climate change

Some climate model projections forecast a drier and much warmer climate for parts of the tropics (Gasparrini et al., 2017; Serdeczny et al., 2017; Siyum, 2020). In amalgamation with the SEM findings, this climate projection forecasts a reduction in the homegardens productivity. Climate change could increase soil nutrient deficiency by destabilizing nutrient cycles, with negative knock-on impacts on banana yield. As drought is a major abiotic stress affecting banana production worldwide, sometimes reducing yields by up to 65 % (Ravi et al., 2013; Nansamba et al., 2020), a plausible warmer and drier future climate could mean that smallholders need to shift towards producing more drought-resistance crops in homegardens.

Despite the homegardens encompassing the dense, multi-layered, and intermixing of trees with crops, on-farm trees had little effect in buffering the potential impacts of climate change on soil and bananas. The limited effect of on-farm trees under warmer and drier climate conditions on soil quality is consistent with other studies in the Kilimanjaro region (Becker, 2017). Although trees buffered against increasing soil alkalinity, a plausible warmer and drier climate change scenario may still increase soil pH. The effect of soil acidification from trees could also gradually wane as climate conditions become sub-optimal for trees. Considering this evidence, alongside the viewpoint in literature that TAFS are more climate resilience than other agricultural land use systems (Lin, 2007; Schwendenmann et al., 2010; Vaast and Somarriba, 2014; Padovan et al., 2015), it could be argued that open farming systems, such as in the foothill of Mt. Kilimanjaro, may deteriorate more rapidly under climate change.

Our results outline an interesting potential future scenario whereby smallholder farmers in homegardens may firstly benefit from climate change. Initial increases in soil P, coupled with enhanced banana plant productivity from warmer MATs, and potentially reduced fungal diseases, may initially increase banana yield. As soil quality declines, the stronger direct positive effect from climate change may help sustain banana yield. However, in later decades, banana yields may decline under the combined effects of water stress and soil nutrient deficiency. As previously mentioned, there are uncertainties associated with long-term future climate projections. Future MAP trajectories in the tropics are complex to accurately forecast (Lee et al., 2021), and some projections indicate increased rainfall in most of East Africa (e.g., Shongwe et al., 2011; Platts et al., 2014). Our analysis of the SEM results imply that increases in MAP and MAT may benefit the productivity of homegardens through improved soil decomposition processes and banana yield if water stress can be averted.

Smallholders in TAFS can respond to external drivers (Cedamon et al., 2018), including climate change (Landreth and Saito, 2014). Our findings should therefore be considered alongside the possibility that smallholders may alter their agronomic practices in response to changing climate conditions which could affect their banana yield. Based on the key finding that water stress appears to primarily negatively impact banana plant productivity, and that irrigation significantly improved banana yield in the village (Nganjoni) under the warmest and driest climate conditions (see Section 2.2.4), the adoption of irrigation measures could help to alleviate the potential effects of climate change on banana yield. However, in the Chagga Homegardens irrigation is mostly constrained to villages in lower elevations. The construction of channels to direct water flows towards highland villages and farms may therefore be required, but is probably not possible due to increasing water demand and resulting water shortages.

4.4. Study limitations

The results of our study are presented with some limitations. Firstly, human management could have influenced the modelled parameters. For example, management can also influence the variation amongst the tree variables in farms. However, strict tree cutting rules in Moshi Rural suggest that interference should be minimal, whilst human manipulation of trees in farms would be random due to likely differences in management regimes. Secondly, it was not feasible to acquire yield estimates for each banana variety in the homegardens type. Therefore, farmers' general banana yield was recorded. However, studies have shown that each East African banana variety type responds similarly to climate change (van Asten et al., 2011). Thirdly, besides *Leguminosae*, our study did not consider the effect of other types of tree species composition variables in the homegardens which may have influenced other soil parameters, such as soil pH. Fourthly, it was not possible to untangle the individual direct and indirect effects of temperature, precipitation, and humidity in the SEM. Finally, due to the constraints of suitable climate data available for this study, we were unable to consider the effects of other climatic variables which could affect crop growth in our SEM, such as solar radiation, wind speed and vapor pressure deficit.

5. Conclusion

The major objective(s) of this study were to assess the effects of warmer and drier climate conditions on tree-soil-crop interactions in tropical (sub) montane homegardens and on banana yield. Our findings revealed that the warmer and drier climate conditions are expected to reduce the productivity of the homegardens. The impacts were manifested through reductions in soil nutrients (C, N and P) and the potential destabilization of nutrient cycles. Changes in banana yield were predominantly influenced directly by the change in climate rather than alterations in tree-soil-crop interactions. Homegarden trees were found to have minimal effect in mediating the impacts of the changing climate conditions on soils and banana. Trees, however, had no negative effects on soil properties or banana yield despite the worsening climate conditions.

A deliberation of these main findings together implies that over time smallholder farmers using homegardens in areas which could experience increasingly warmer and drier climate conditions will be negatively affected by climate change. However, this may not necessarily occur immediately and could involve initial positive benefits concerning banana production. Our findings are significant because a majority of current studies and knowledge on TAFS climate resilience are based on present climate conditions. We provide evidence that under a potential warmer and drier future climate scenario TAFS could also succumb to the negative effect of climate change.

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CRediT authorship contribution statement

M.W. lead the research, wrote the paper, and gained the funding for the research project. Both K.S-H P and MW contributed to the conceptualization and methodology of the paper. M.M supplied the tree and soil data and A.H. the climate data and both M.M. and A.H. contributed to writing the paper. M.W. performed the formal analysis on the data. K.S-H P, M.M. and A.H. reviewed, edited and suggested improvements for drafts of the manuscript.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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