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Climate change scenarios in Zambia: modeling farmers' adaptation

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Abstract

Background: At the center of the Sustainable Development Goals (SDG) by the United Nations is climate change. Analyzing adaptation processes is fundamental to enhance resilience in the poorest parts of the world. The analysis harmonizes top-down and bottom-up approaches by integrating general circulation models into the method of mathematical optimization. The article designs a quantitative farm planning model for rural Zambia and focuses on optimal allocation of land, labor and cultivation methods. Our research takes advantage of recent survey data of 277 Zambian households from 2018. The model simulates a baseline scenario, 2 climate change scenarios and 7 variations of farmers' land availability, labor capacity and off-farm work possibility. This results in 21 possible future outcomes and farmer adaptations.

Results: Climate change negatively affects future livelihoods at the study site. A dry climate decreases a farmer's wealth by around 30% and a wet climate by nearly 20%. However, simulations show households are able to sustain their livelihood through adaptation processes at the farm level. Farmers' variation in land size for crop cultivation indicates the strongest livelihood impacts in response to climate change. Increasing the land for cultivation is the best response, whereas a reduction of labor supply at the farm leads to households being more vulnerable to a changing climate. Off-farm employments reveal significant potential for climate change adaptation. An increase in work opportunities at a refugee camp nearby has a significant positive effect on rural livelihoods, without reducing the households' farm production. The refugee camp, however, may imply future land competition.

Conclusions: The study concludes climate change has a serious impact on farm yields and requires land and labor adjustments to prevent losses in wealth. Altering the cropping mix, reallocating planting times or changing farming techniques are meaningful instruments to respond to climate change at the study site. Agricultural intensification can increase the productivity per hectare and the mix of on- and off-farm work indicates income diversification as possible response to climate change. The analysis is specified to a rural farm context in Zambia, but is applicable to similar settings in sub-Saharan Africa and useful for local policy implementations towards climate change adaptation.

Keywords: Climate change, Adaptation, Mathematical optimization, Farm decision, Zambia, Refugee camp

Background

The United Nations highlight climate change as a major issue of the 2030 Agenda for Sustainable Development. In particular, Sustainable Development Goal (SDG) 13, climate action, calls for urgent action to combat climate change and its impacts [82]. Over the past 3 decades, global temperature has been steadily increasing [42]. The changing climate poses serious challenges to human livelihoods due to changes in rainfall patterns, seasonality and biodiversity [68, 79, 84], implying strong links to land transformation, agricultural productivity and food production [33, 42, 44]. Particularly, the poorest and most vulnerable countries and communities in the Global South have a weak adaptive capacity [21, 63, 68],

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characterized by limited asset endowment, few income opportunities [60, 62], high dependence on agriculture [9, 20, 23, 56] and food insecurity [22, 27].

Investigating climate change adaptation processes is fundamental to enhance resilience in the poorest parts of the world [4, 82]. According to Lobell and Burke [50], climate change requires humanity to adapt its activities to new challenges. In particular, adaptation strategies aim at long term changes of actions to sustain livelihoods [11, 20, 75]. The FAO [30] identifies adaptation as one of the main measures to reduce long term impacts of climate change. Similarly, Burnham and Ma [15] define adaptation as the process of adjusting livelihoods to predicted impacts from a changing climate.

The article investigates a case study region in rural Zambia, whose conditions provide a suitable context to study the impacts of climate change on farmers' livelihoods and adaptation processes. Rainfall and temperature predictions for the year 2050 show that climate change heavily affects weather conditions and the resilience of rural households by degrading asset endowments and creating uncertainties for already vulnerable livelihoods [87]. Food insecurity [59] and poverty [17] is already severe in Zambia. According to the Global Hunger Index, Zambia suffers from alarming hunger levels and ranks 113th out of 117 countries [85]. Furthermore, livelihoods of the country's rural population depend largely on agriculture [17, 46]. The climate change risk analysis by USAID [83] shows that temperature is projected to increase in the next decades. This results in a higher hot-day-frequency, lower cold-day-frequency, an increase in rainfall intensity and frequency, and finally more extreme weather events, such as droughts and floods. Similarly, the International Center for Tropical Agriculture [19] expects future rainfall increases in northern Zambia. The country needs to plan for different climate change scenarios, particularly in the agricultural sector, where rainfall changes are expected to have the greatest impact [19]. The Zambian government is already aware of the climate change risks to its population. The Ministry of National Development Planning provides a "national policy on climate change", embedded in the "revised Sixth National Development Plan" on Zambia's sustainable development. The policy seeks to implement adaptation and risk reduction, for example by promoting early warning systems, improving infrastructure and fostering resilience on the governmental community level against climate change [71].

Researchers historically use top-down approaches to analyze adaptation to climate change at the global or national scale [86]. Investigations base on economic and risk analysis and assess impacts ex-ante using quantitative models, mostly general circulation models [16, 57, 70, 76]. For example, Girard et al. [35] use a top-down approach by simulating the response of a climate system to a future scenario with climate driving effects, such as greenhouse gases. The authors seek to achieve local climate projections via a downscaling technique, resulting in the top-down scheme. This way, top-down approaches provide decision-makers with assessments of the future by downscaling global development scenarios to the regional level [35]. However, researchers using this method often neglect the complexity of the social environment of actors which are exposed to the changing climate [26]. Models reveal limited capacity to capture specific adaptation processes due to their downscaling uncertainties and partly simplified impact assessments [29, 35, 86].

Contrary, bottom-up approaches consider the social, economic, political and environmental circumstances of critical actors at the local scale to analyze adaptation to climate change [10, 11, 49]. These approaches take advantage of the adaptive capacity of local communities [3, 7]. Models analyze the decision-making process for climate change adaptation of critical actors ex-post using qualitative methods, such as key informant interviews or group discussions [8, 14, 39, 51, 61, 73], often combined with econometric analyses [6, 13, 52, 64]. In addition, there are ex-ante studies with a bottom-up approach using choice experiments to analyze farmers' adaptation intention under hypothetical climate change scenarios [5, 69]. Some studies focus on household drivers [48, 56], motivators [8, 11] and/or barriers of adaptation [47, 66]. Literature highlights the perception by critical actors as starting point to analyze practical strategies to combat climate change [48, 51]. Local communities memorize climatic trends, especially those years dominated by extreme climatic conditions and other significant events [4, 56]. However, bottom-up approaches contradict the reliability of empirical data on climate change impacts, as individuals may under- or overestimate the occurrence of climatic events and the impact on their livelihoods [9, 89].

This paper harmonizes the top-down and bottom-up approaches using the methodology of mathematical optimization. The quantitative method focuses on rational decision-making rather than subjective ex-post perceptions by actors [41, 65] and is applicable for rural livelihoods [36] and agricultural analysis [18]. We design a farm planning model on the local level, simulate ex-ante climate change scenarios and investigate farmers' optimal resource allocation in a rural Zambian setting. In particular, the paper raises the following 2 questions: (1) What is the optimal reallocation of land and labor factors in response to climate change? (2) How is the household's cultivation pattern affected by climate change? To answer these questions, the article applies a mathematical optimization approach and takes advantage of recent survey data of 277 Zambian households from April 2018. Our research contributes to scientific literature by simulating a baseline scenario, 2 climate change scenarios and 7 variations in farm assets. First, the model evaluates baseline, dry and wet climate scenarios. Second, the scenarios are connected to 7 asset variations with respect to farmers' land availability, labor capacity and off-farm work possibility. This results in 21 possible future outcomes and farmer adaptations, including the consideration of different cultivation methods. The scientific analysis points to specific actions, which require (political) attention to adapt to climate change in rural Zambia.

Materials and methods

Study site

The study site, Mantapala, situates in Zambia's Nchelenge District, marking the boundary to the Democratic Republic of Congo (Fig. 1). It locates very remotely in a forest area, about 20 km to the nearest small town, Nchelenge, and over 1,000 km to the capital, Lusaka. A gravel road is the only way in and out, indicating the poor local infrastructure. Geographically, Mantapala locates at an altitude of approximately 807 m above sea level. It covers an area of 13,000 hectares. Climatically, it is tropical with 3 seasons: Winter (May–August), dry (September–October) and rainy season (November–April). Average monthly temperature is 24 °C, but daily fluctuations can be large with lows of 11 °C in the winter and highs of 34 °C in the dry season. Rainfall follows a seasonal pattern, with peaks of 2,700 mm in rainy months and close to 0 mm during dry months [37].

The case study setting is a rural community of 277 households (1,673 residents) from 8 villages. Each village comprises about 10 to 80 households. The community faces difficult living conditions marked by severe poverty and food insecurity [38]. Agriculture plays an important role in the district [77]. Households' livelihoods depend primarily on subsistence agriculture and forest resources (nearly 90% of Mantapala's Gross Domestic Product). Farmers mainly grow low-yield cassava and maize next to some groundnuts, beans, sweet potato, rice and millet on up to 3 hectares of land. Firewood and charcoal are the main sources of energy, as most households live without electricity. In addition, limited fish stocks from a river and some streams provide a source for food. There are also households keeping small livestock. The average household size in Mantapala is 6 people and about half are of working age [37]. Table 1 provides further sample characteristics of the study area (based on a household survey from April 2018; more information on the sample, see below). A remarkable study site feature is the Mantapala refugee settlement, which locates within the rural community (average distance of households to the camp is 4.8 km; 10-km radius around the camp). The settlement was established for Congolese refugees in early 2018. Around 8,000 hectares of the study site relate to the settlement, which accommodates about

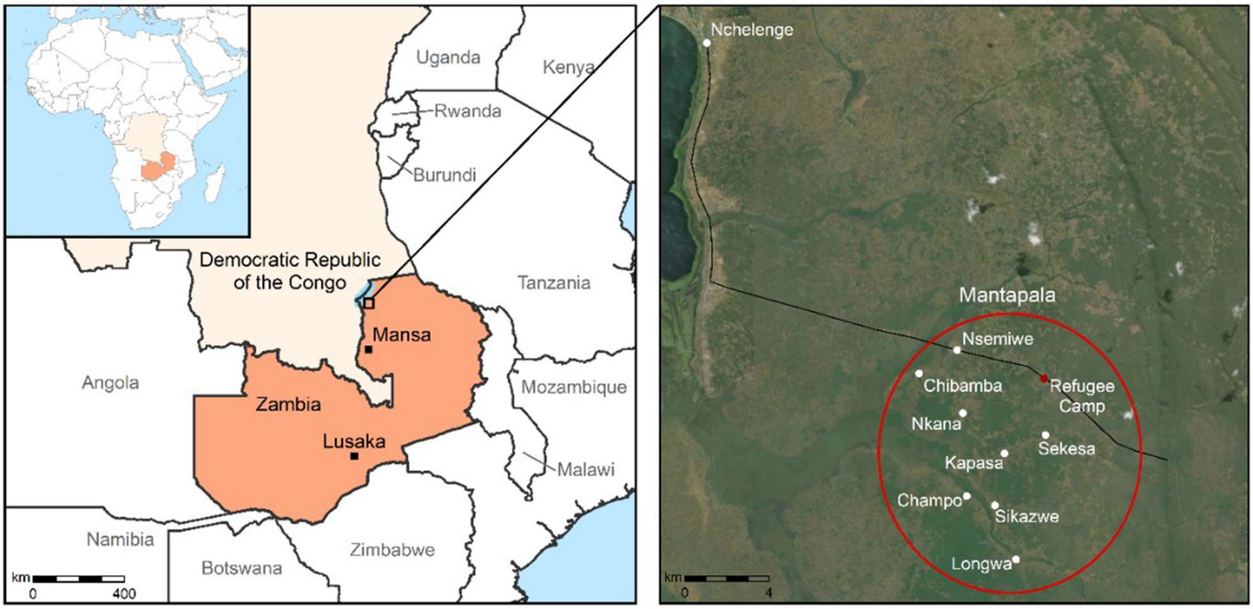


Fig. 1 Mantapala in the Luapula Province, Zambia [38]

Table 1 Sample characteristics of the study area (based on [38])

Sample characteristics	Unit	Obs	Mean	SD
Individual characteristics				
Age of respondent	years	277	42.6	14.6
Education of respondent	years	277	6.7	3.0
Gender	%, female	277	20.2	40.2
Religion	%, protestant	277	74.4	43.7
Member of a community group	%, yes	277	35.4	47.9
Household characteristics				
Size	members	277	6.0	2.4
Distance to camp	km	277	4.8	1.6
Savings	ZMK[a]	277	260.6	413.1
Months of enough food	months	277	10.4	2.6
Social contacts	number	277	1.7	0.9
Agricultural characteristics				
Land size	hectare	277	6.7	5.6
Livestock possession	TLU	277	0.6	1.2
Top 3 reasons for leaving land uncultivated				
Labor shortage	%, yes	277	33.9	47.4
Waiting for recovery from slash and burn	%, yes	277	17.3	37.9
Not enough money	%, yes	277	16.3	37.0
Natural resource characteristics				
Fish catch	%, yes	277	30.3	46.0
Firewood collection	%, yes	277	84.8	35.9
Host-refugee contact characteristics				
Contact with refugees	%, yes	277	93.1	25.3
Contact via joint employment	%, yes	277	52.0	50.1
Contact via trade opportunities	%, yes	277	49.8	50.1

Obs observation, *SD* standard deviation, *TLU* tropical livestock unit

[a] 1 US$ = 10 Zambian Kwacha (ZMK) (March 2018)

15,231 Congolese [81]. According to Gronau and Ruesink [38] the host–refugee ratio is approximately 1 to 10. Zambia manages the settlement according to the Comprehensive Refugee Response Framework (CRRF) by United Nations, which basically aims for refugee integration [38]. Interestingly, the refugee settlement provides various off-farm employments to local residents (e.g., administration, construction, guarding), leading to more than half of the hosts already having contact with the camp via employment opportunities. Current developments show host households are even employing refugees as farm workers to assist on their fields, which enables crop cultivation of larger areas (the mean land size is around 6 hectares per household). Interestingly, the sample analysis reveals labor shortages by hosts as the main reason for leaving land uncultivated in the study area; reported by 1 out of 3 households. Additional reasons are "waiting for recovery from slash and burn" and "not having enough money". Finally, the camp's market, with over 200 traders, enables business interactions [38].

Sample size and data acquisition

The paper uses a recent data set of a household survey of 277 households collected in April 2018. Field research was part of the "Food Security in Rural Zambia (FoSeZa)" project funded by the German Federal Ministry of Food and Agriculture. The data set includes a census from the 8 villages of the Mantapala society. A structured questionnaire was conducted with the respective head of the household. It included questions regarding the household's socio-demographics, social capital, economic activities, income sources, savings, consumption and expenditures, use of natural resources, livestock breeding, food security and contact with refugees. It also comprised a section on households' agricultural production and land uses. The time period of the survey was 12 months between April 2017 and March 2018. Parameters for the model calibration are primarily from the questionnaire. In addition, the data set is supplemented by secondary data on crop calendars [32], labor time, crop prices, crop yields, crop production costs [74] and off-farm wages [36]. The analysis also accounts for crop yield sensitivity to climate change [87] and different climate change scenarios [43]. Finally, the secondary data set includes kilocalorie parameters for foods [54] and human kilocalorie requirements [31].

The farm model specification

We apply a mathematical optimization approach involving a farmer's rational decision-making process as a function of climate change uncertainties and asset endowment variations. Basically, an optimization method seeks to maximize/minimize an outcome/objective subject to capacity constraints/limitations (see [41, 65]). The paper applies the optimization approach to the conditions of a representative farmer at the Zambian study site. Our model is multi-period, which makes its decisions at the beginning of the time horizon. A period t represents a year and each period t has subperiods s, representing months. We simulate a time horizon of 5 periods. This timeline is run for 3 future scenarios: 1 applied to the conditions of the year 2018 (baseline scenario) and 2 are taking place in the year 2050 (dry and wet scenario). Basically, the model utilizes the FoSeZa data set for parameters regarding household characteristics, asset availabilities and food preferences. Information regarding the crop production and farm inputs is derived from Siegel and Alwang [74], which complements the model calibration. For the dry and wet scenarios, adjustments are made to crop yields following projections by Wineman and Crawford [87]. We implement 7 staple crop types n for farmers' production decisions. The model decides between the cultivation of maize, cassava, groundnut, millet, sweet potato, beans and/or rice. It also makes choices between fertilizing (yes/no), use of altered planting types (early/late/common) and seed types (local/hybrid). The availability of fertilizers, plant varieties and seeds relate to the conditions of the study site. It is derived from observations and the household survey. Local seed types represent the usual cultivation, leaving out fertilizer application and hybrid seeds. Crop yields and expenditures vary by production decisions. Fertilizer application, available for maize cultivation, produces higher outputs but is more time and cost intensive. Cheaper local seeds produce lower yields, while expensive hybrid seeds (available for maize, groundnuts and rice) generate higher yields. Late or early planting methods, applicable for maize and beans, also generate lower yields, but are off-season and prevent bottlenecks of labor capacity. As a result, the farm model chooses between 12 different cultivation methods i to produce crop types n (see Table 2). Furthermore, on- and off-farm works reflect the spatial distribution of activities. On-farm refers to the income generated with own produced crops, while off-farm defines income generated at the refugee settlement.

Table 2 Overview of cultivation possibilities

Cultivation: *i*	Crop: *n*	Fertilizer: binary	Planting: early/late/common	Seed type: local/hybrid
1	1 = Maize	No	Early	Local
2	1 = Maize	No	Late	Local
3	1 = Maize	Yes	Early	Hybrid
4	1 = Maize	Yes	Late	Hybrid
5	2 = Groundnut	No	Common	Local
6	2 = Groundnut	No	Common	Hybrid
7	3 = Cassava	No	Common	Local
8	4 = Millet	No	Common	Local
9	5 = Sweet Potato	No	Common	Local
10	6 = Beans	No	Early	Local
11	6 = Beans	No	Late	Local
12	7 = Rice	No	Common	Hybrid

Climatic conditions and households' asset endowments are essential simulation factors. According to scientific literature, households' assets, i.e., the land, labor and capital endowment, influence decisions to climate change adaptation [2, 27, 87]. We examine a baseline scenario, 2 climate change scenarios and 7 possible responses per scenario available, relating to farmers land availability, labor capacity and off-farm work possibility. The farm model implies a smallholder's rational decision-making process, taking into account the limited resource endowment and climate change vulnerability context. A system of mathematical equations, variables, parameters and indices defines the household's decision process. Table 3 gives an overview of variables (in capital letters) and Table 4 of the parameters (in small letters). The General Algebraic Modeling System (GAMS) Software is used to construct and solve the farm model.

The farm model maximizes the livelihood outcome over all periods. The livelihood outcome (profit) is defined as the difference of the budget B_t of the current period t and the purchases of farm inputs (P_t) and food (PM_t). Equation 1 defines the model's *Objective Function*:

Table 3 Overview of decision variables

Variable	Unit	Definition
$X_{i,t}$	$[kg]$	Production of cultivation type i in period t
$F_{n,t}$	$[kg]$	Production of crop n in period t
$FST_{n,t}$	$[kg]$	Stored crop n in period t
$FE_{n,t}$	$[kg]$	Consumption of self-produced crop n in period t
$FS_{n,t}$	$[kg]$	Sales of crop n in period t
$FP_{n,t}$	$[kg]$	Purchases of crop n in period t
B_t	$[ZMK]$	Budget in period t
P_t	$[ZMK]$	Farm input purchases for crop production in period t
PM_t	$[ZMK]$	Food purchases in period t
SV_t	$[ZMK]$	Savings generated in period t
$A_{k,s,t}$	*Binary*	1 if adult k in month s and period t is working on-farm, 0 otherwise
$Y_{i,t}$	*Binary*	1 if cultivation type i in period t is produced, 0 otherwise

Table 4 Overview of parameters

Parameter	Unit	Definition
$labor_{i,s}$	$days/hectare$	Labor input for cultivation i in month s per hectare
$yield_{i,t}$	$kg/hectare$	Yield of cultivation i in period t per hectare
cl	$days/month$	Availability of on-farm labor days per adult per month
cla	$hectare$	Availability of farm land for crop production
cm	$percent$	Share of available off-farm work to the total number of adults
r_n	$kg\ rotted/total\ production$	Ratio of rotted crop n
$kfix_i$	ZMK	Fix costs of cultivation i
$kvar_i$	$ZMK/hectare$	Variable costs of cultivation i per hectare
$kcal_n$	$kcal/kg$	Kilocalorie of crop n per kg
$child$	$Number$	Children per household
$minkcal$	$kcal/year$	Kilocalorie requirement per household member per year
h_n	$kg\ of\ crop\ n/total\ consumption$	Habit to eat crop n
$bmin$	ZMK	Minimum budget needs per household per year
pr_n	ZMK/kg	Retail price of crop n per kg
pp_n	ZMK/kg	Purchase price of crop n per kg
w	$ZMK/month$	Off-farm wage per month
K	$Number$	Number of adults

$$MAX \sum\nolimits_{t=1}^{T} B_t - P_t - PM_t \tag{1}$$

The model implies 2 activity options to gain budget for a period t. Either via on-farm work (selling of crop $FS_{n,t}$ to the price pr_n) or via off-farm employment at wage w. The model makes a flexible decision about the number of adult household members k to attend in income generating activities $A_{k,s,t}$ in month s of period t. Savings SV_{t-1} from the last period are added to the budget of period t, while it reduces by the minimum budget $bmin$, which the model leaves as a basic livelihood security. Equation 2 is the *Budget Function*:

$$\begin{aligned} B_t =& SV_{t-1} + \sum_{n=1}^{N} FS_{n,t} * pr_n \\ &+ \sum_{k=1}^{K}\sum_{s=1}^{S}\left(\left(1 - A_{k,s,t}\right) * w\right) - bmin \forall t \end{aligned} \tag{2}$$

Purchases for cultivation processes i in period t cover fix costs $kfix_i$ and variable costs $kvar_i$. Equation 3 describes the *Input Good Function*:

$$P_t = \sum_{i=1}^{I}\left(Y_{i,t} * kfix_i + X_{i,t} * \frac{kvar_i}{yield_{i,t}}\right)\forall t \tag{3}$$

The total market purchases in period t, PM_t, are calculated by multiplying the purchases of crop n in period t, $FP_{n,t}$, with the purchase price parameter for this crop, pp_n, and summing this up for all purchased crops. Equation 4 defines the resulting *Food Market Function*:

$$PM_t = \sum_{n=1}^{N} FP_{n,t} * pp_n \forall t \tag{4}$$

Equation 5, the *Purchase Limitation Function*, limits the purchases to the available budget and savings of period t.

$$B_t \geq P_t + PM_t + SV_t \forall t \tag{5}$$

The model also features a *Crop Cultivation Condition*. Equation 6 accumulates cultivation type i's production in period t, reduced by an individual crop rotting ratio r_i into the variable $F_{n,t}$. Therefore, the $F_{n,t}$ variable harmonizes the cultivation practice i and the crop type n.

$$\sum_{i=1}^{I} X_{i,t} * (1 - r_i) = \sum_{n=1}^{N} F_{n,t} \forall n, t \tag{6}$$

Moreover, the farm model decides on the purpose of the produced ($F_{n,t}$) and stored crop ($FST_{n,t-1}$) in period t. It distinguishes between consumption ($FE_{n,t}$), sales ($FS_{n,t}$) and/or storage ($FST_{n,t}$) for the next period. Equation 7 describes the *Crop Usage Condition*:

$$F_{n,t} + FST_{n,t-1} = FE_{n,t} + FS_{n,t} + FST_{n,t} \forall n, t \tag{7}$$

Equation 8 focusses on *Household's Kilocalorie Requirement*. Household members ($K + child$) consume at least a minimum amount of kilocalories $minkcal$. The model fulfills the requirement either via own production or via market purchases, which is multiplied by the food specific kilocalorie characteristic $kcal_n$. A special model feature is a consumption habit parameter h_n, defined as the ratio of the food type n, which is usually consumed by households at the study site. The habit parameter ensures that households' food portfolio follows the usual consumption pattern.

$$(FE_{n,t} + FP_{n,t)} * kcal_n \geq (K + children) * minkcal * h_n \forall n, t \tag{8}$$

The farm model also introduces a *Production-Purchase Condition* via Eq. 9. The representative household must at least produce the same amount of crop type n as it purchases to prevent a one-sided burden on either the supply or demand side. Equation 9 ensures that subsistence farming behavior is maintained at the study site. It prevents farmers from specializing only on the most profitable crop (harmonization of the profit maximization behavior) leading to an unbalanced market and a shortage of nutritional important crops in the rural community.

$$F_{n,t} \geq FP_{n,t} \forall n, t \tag{9}$$

Finally, we set 3 essential limitations to households' asset endowment, namely, labor capacity, land availability and off-farm opportunity. Equation 10 is the *Labor Constraint Farm Function*. The right-hand side defines the labor availability for crop production. The on-farm labor input cannot exceed the monthly labor availability cl. The left-hand side defines the labor input needed for crop cultivation $X_{i,t}$. It describes the labor needs for production in period t and subperiod s, which depend on crop yields ($yield_{i,t}$) and labor efforts ($labor_{i,s}$). Equation 11 is the *Land Constraint Farm Function*. The availability of farm land cla limits the production on the right-hand side. The left-hand side describes the land demand for the crop cultivation in period t. Finally, the *Labor Constraint Off-Farm Function* (Eq. 12) sets a limitation to off-farm employments at the refugee camp to the representative household. The right-hand side defines the market capacity by multiplying the cumulated number of household adults $\sum_{k=1}^{K} k$ with the share of available off-farm employment possibilities. The left-hand side limits the labor supply of the representative household at the refugee camp.

$$\sum_{i=1}^{I} \frac{labor_{i,s}}{yield_{i,t}} * X_{i,t} \leq \sum_{k=1}^{K} A_{k,s,t} * cl \forall s, t \tag{10}$$

$$\sum_{i=1}^{I} \frac{X_{i,t}}{yield_{i,t}} \leq cla \forall t \tag{11}$$

$$\sum_{k=1}^{K} \left(1 - A_{k,s,t}\right) \leq \mathrm{K} * cm \forall s, t \tag{12}$$

Climate change scenarios and asset response variations

The analysis investigates farmers' optimal adaptation decisions to a baseline scenario, 2 climate change scenarios and 7 possible asset variations. Climatically, a dry and wet climate change scenario are assumed for the year 2050, which are based on the outcomes of 2 model simulations performed by Wineman and Crawford [87]. They are pictured by altered and uncertain crop yields in contrast to a stable and well-known outcome in the baseline scenario for the year 2018. Asset-related, we consider households' baseline endowment, but also a low and a high variation on labor and land allocations. This reveals 21 model modifications and possible simulation outcomes as a response to climate change. The model thus provides ex-ante households' adaptation decisions to climate predictions by revealing possible response mechanisms on land and labor allocations.

Climate change is incorporated into the model via its impact on farmers' crop yields. Wineman and Crawford [87] predict in their study how crop yields in Zambia will vary in 2 different model simulations. The authors incorporate country-wide weather data, including 1 weather station in Luapula province. Furthermore, the study covers 10 additional sites with rainfall patterns similar to the study region (see [45]). Anticipated crop variations by Wineman and Crawford [87] are thus applied to the baseline scenario to create the paper's 2 future climate change scenarios: a dry and a wet scenario. The authors calculate yield estimates and crop sensitivity to temperature, rainfall (total amount) and variation in rainfall (fluctuation during the year) using a statistical yield function. Yield estimations base on 2 different climate scenarios predicted by IPCC [43], using the general circulation models HadCM3 (see [58]) and CCSM (see [28]). The climate projections of the HadCM3 model define the dry scenario, while projections of the CCSM model refer to the wet scenario. In general, the climate models predict a higher temperature and more variability in the rainfall pattern to different degrees by 2050. Specifically, the dry climate scenario predicts a strong increase in the variability of the monthly rainfall pattern over the crop-growing season (November to March) for the study area (see Table 5). Contrary, the wet climate scenario defines higher future precipitation rates. Both model scenarios indicate an increase in mean temperature by around 10 percent. Table 5 also shows most crop yields suffer from climate change, but for cassava and groundnut it is a positive effect [87]. In addition, the model assumes that crops, which are more sensitive to climate change have higher uncertainties in their yields throughout the periods. For this reason, we consider a yield variation along the simulated periods in the dry and wet

Table 5 Climate predictions and crop yield changes in 2050 compared to baseline year 2018 [87]

Change in %	Dry climate scenario	Wet climate scenario
Rainfall	-0.75	+6.93
Mean temperature	+10.52	+9.43
Variation in rain	+9.32	+3.67
Maize yield	- 4.79	-2.77
Groundnut yield	+4.00	+5.68
Cassava yield	+5.61	+8.68
Millet yield	-22.41	-21.74
Sweet potato yield	-1.06	-1.06
Bean yield	-10.32	-7.97
Rice yield	-18.92	-17.72

Table 6 Households' asset response variations

Response	Low	Baseline	High
Labor availability (adults)	2	3	4
Land availability (hectare)	1.18	2.95	5.9
Off-farm work opportunity (adults per household)	no supply	1 out of 3	unrestricted

scenario. A set of possible yield scenarios is assumed, following a normal distribution within the yields' variation with a standard derivation dependent on the sensitivity of the crop to the climate. Realizations for $yield_{i,t}$ as representatives of this set are then drawn randomly.

The model tests for households' land and labor allocations as response to climate change. The asset endowment variations focus on the (1) labor capacity, (2) land availability for farm production and (3) market supply of off-farm employment opportunities. Asset endowment modifications distinguish between a baseline, low and high parameter availability (Table 6). Regarding households' land and labor availability, we derive the first (low capacity), second (baseline capacity) and third (high capacity) quartile from the household sample. The baseline situation represents the status quo 2018, with 3 adults available for on- and off-farm works (20 days/adult/month) and 2.95 hectare of land cultivated. The model accounts for fallow periods. For the off-farm employment at the refugee camp, a low capacity implies no work opportunities, the baseline capacity enables 1 person per household to attend in off-farm work and a high capacity unrestricted off-farm employment by a household. Employment values are not defined by the refugee camp but instead given by the baseline assumption of one person per household working in the settlement. The two boundary values of no supply and unrestricted supply are tested via model simulations.

Results and discussion

The farm model indicates negative impacts of climate change on future livelihoods in rural Zambia. Model results reveal a wealth reduction by comparing the outcome of the baseline scenario with the wet and dry scenarios. Figure 2 provides an overview of the climate change scenarios, asset modifications and livelihood outcome changes over time. By investigating the slopes of the developments, it is possible to interpret how much worse off farmers will be in the dry or wet scenario. Regarding a baseline factor endowment, a household decreases its wealth by 27 percent (approximately 17,705 ZMK) after facing 5 periods of a dry climate in comparison to the baseline scenario. Similarly, the wet climate affects the farmer by a reduced livelihood outcome in period 5 by 19 percent (around 12,398 ZMK). Interestingly, the model reveals positive outcomes for all scenarios over the 5 periods. The slopes are positive as the savings from the last period are added to the profits of the current period. In all scenarios, the farmers are thus able to improve their livelihood outcome. Only in the baseline scenario with a low land endowment, we observe a slightly negative development in the first period. The constantly positive slope is explained by the model assumptions: Farmers' activities are limited to crop cultivation and off-farm employment at the refugee site, while other typical activities at the study site (e.g., fishing, firewood collection, charcoal production, livestock breeding) are not included. Furthermore, the expenditures are limited here. In the model, farmers have expenditures solely on food and other expenses, such as housing, clothes, mobiles and/or school fees [37], are neglected. The savings accumulation has thus to be analyzed with caution. The profits gained in a specific period fluctuate strongly in face of climate change, making households more vulnerable to shocks and uncertainties. Nonetheless, a household facing climate change is able to sustain its livelihood through adaptation processes at the farm level. The highest effect on the household´s resilience is the land endowment, because the steepest curve is found with a household facing a high land endowment and the flattest shows a scenario of a low land endowment (the most vulnerable).

The diversity of cultivation methods increases significantly in the climate change scenarios (see Fig. 3). Thereby, a stronger variety in terms of hybrid versus local seed type uses or planting dates is found. According to Fig. 4, baseline scenario results reveal farmers are able to focus on cash crops, such as rice, next to staple crops (namely, maize, cassava, groundnuts, sweet potato and beans). However, climate change, especially dry conditions,

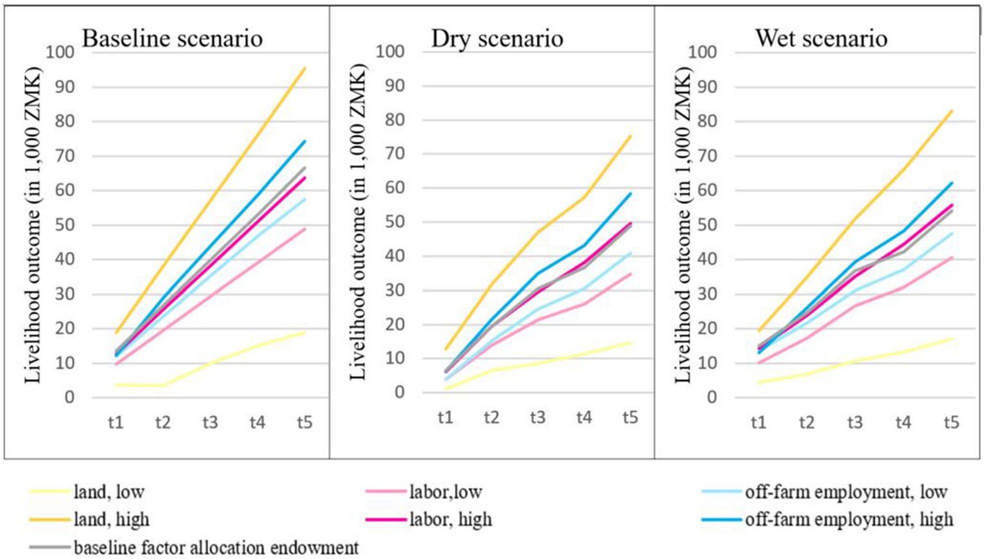


Fig. 2 Climate change scenarios and farmers' response options

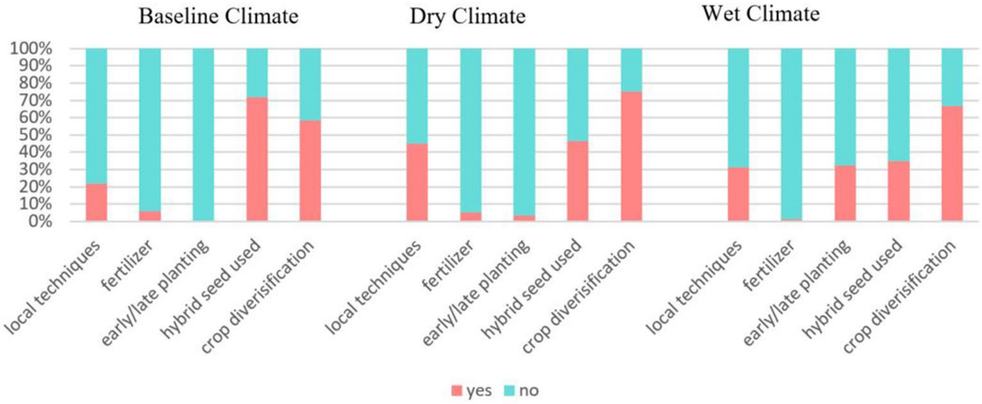


Fig. 3 Share of cultivation processes in the baseline asset endowment for climate modifications

negatively affects crop yields and leads to reallocations in farm production. The models' consideration of seasonality and varying returns of inputs, such as land and labor, make it sensitive to crop diversification (measured as the share of cultivated/used seed types divided by total seed types available). Simulations show that altering the cropping mix is a meaningful response to climate change at the study site. In particular, sweet potato and maize cultivation substitute rice. Simulation results are consistent with the related literature, indicating that altering the cropping mix is an adaptation strategy to climate change (see [9, 61, 78]).

The model tests for possible land and labor modifications to compensate wealth losses due to climate change at the study site. In the following, the paper focuses on 3 additional key outcomes of the farm model: (1) Farmers' variation in land size for crop cultivation shows the strongest livelihood impacts in response to climate change. (2) A reduction of labor supply at the farm makes households more vulnerable to a changing climate. (3) Off-farm employments reveal significant potential for climate change adaptation, especially in times of less on-farm work.

First, smallholders' land endowment has the greatest influence on wealth. Model outcomes emphasize that increasing land cultivation generates the highest profit growth and is the best response to climate change. If more land is available, households' total crop production increases (see Fig. 4). (a) It enables farmers to reinvest

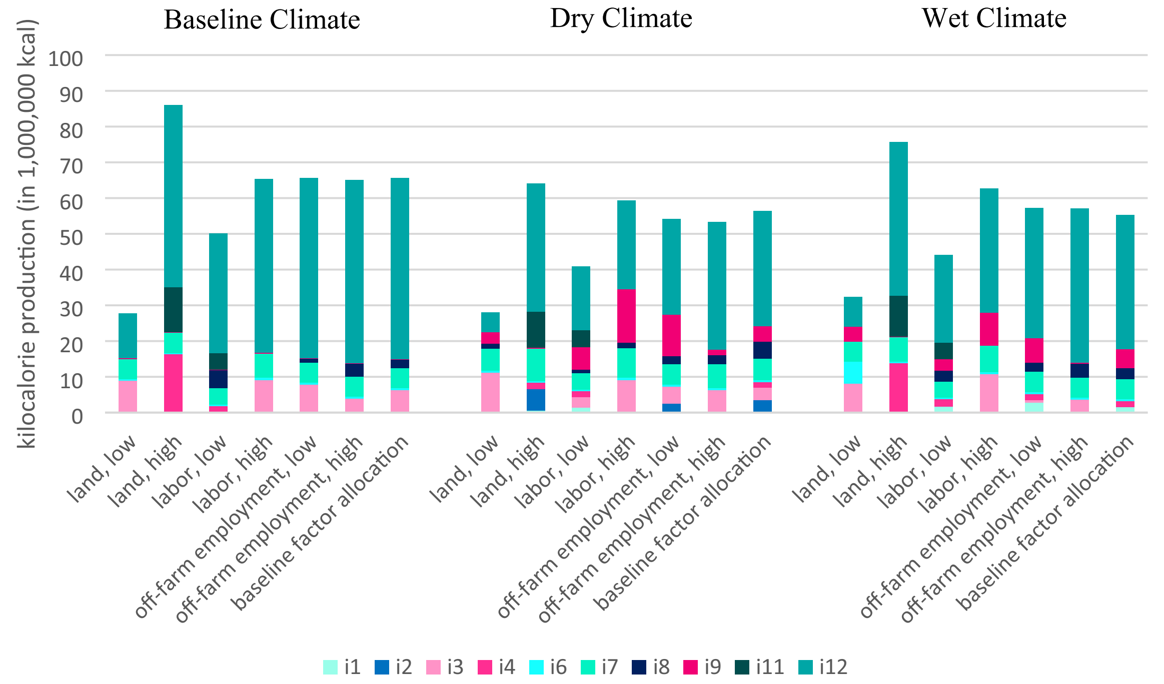


Fig. 4 Cumulated production of crops for climate and factor modifications

profits in more beneficial hybrid seed types (i.e., maize, rice). This result is in line with relevant literature confirming the utilization of improved seeds as an adaptation strategy to climate change (see [9, 27, 40, 55]). However, the refugee camp is an important issue in this context. In the short run, increasing host farmers' land utilization for crop production is a possible adjustment to climate change in the study area as land is not scarce and no source of conflict yet, i.e., between refugees and hosts (see [38]). Additional labor by refugees can support agriculture to increase production, as the main reason for not cultivating all available farmland is a lack of labor in certain months in Mantapala. The employment cooperation is on a temporary basis via cash payments without being integrated part of the hiring host household. However, given that refugee households in Mantapala may receive land parcels from the government of the Republic of Zambia (see [80]) land scarcity increases for the number of people living in the area in the future. (b) The application of early/late planting methods allows to spread the workload throughout the year, enabling the household to use its land in full capacity. According to scientific analyses (see [1, 4, 12, 78]), changing planting patterns is an important response to climate change. For instance, Bewket [9] highlights farmers in the highlands of Ethiopia change their planting dates by up to 2 months to compensate negative effects of shifted rain and temperature patterns. (c) Higher food production leads to households becoming less dependent on food purchases (decline). Interestingly, reducing smallholders' land size for crop cultivation is the worst decision in response to climate change at the study site. Especially when the climatic conditions are dry. This outcome highlights future conflict potential with the refugee camp and a need to address this issue for conflict prevention. With low land cultivation, the crop production is declining significantly (especially for the cash crop rice), even if the productivity of kilocalorie production per hectare land is comparably high (see Fig. 5). In a sensitivity analysis with a low land endowment by farmers, we observe crop yields are mainly used for subsistence consumption. In addition, households' crop storage increases to prepare for periods of food shortage (especially for staple crops, such as maize, groundnut and millet). Households with a low land endowment seek to optimize their maize yields by fertilizer applications as a response to a changing climate, which is otherwise rather neglected. A limitation of land endowment leaves the model with labor overcapacities in various months. Labor then shifts to available employments at the refugee camp. Off-farm employments thus compensate labor overcapacities and create a meaningful cash income, which can be used for food purchases (kilocalorie intake).

Second, increasing farmers' labor capacity has an effect on wealth. This is underlined by the scaling effect in productivity (see comparison of dark and light pink bars

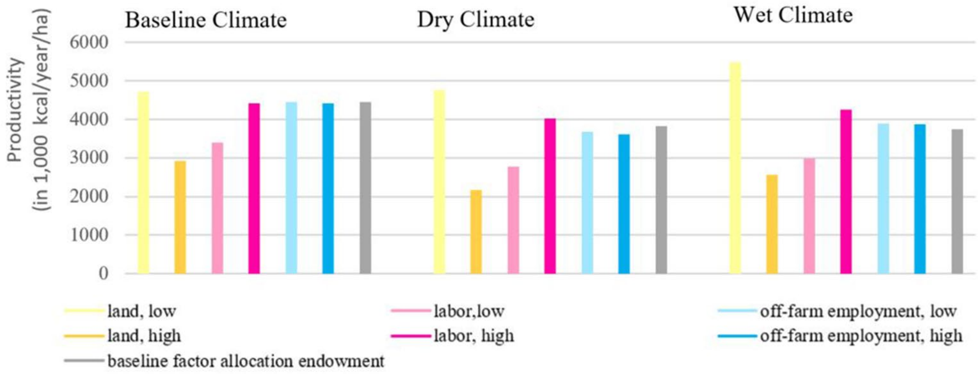


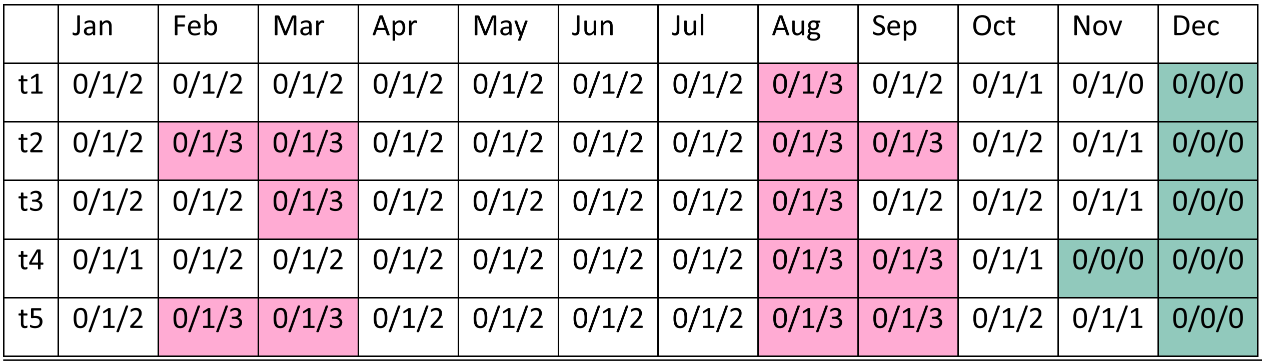
Fig. 5 Production of kilocalories per hectare per year for climate and factor modifications

in Fig. 5). However, labor availability is limited in some months of the year. The busiest months are from October to March (season of most land preparation, planting and harvesting), forming a bottleneck in farm production. In contrast, in the off-season the degree of labor overcapacity is highest. According to Siegel and Alwang [74], from June to August crops just need to be guarded with almost no labor needs for agriculture. A sensitivity test for higher labor supply at the farm as a response to climate change leads to overcapacities in those months, whereas the labor capacity is fully exhausted in the busy farming months around December, ceteris paribus (if the land endowment and off-farm opportunity is constant). Especially the dry and wet climate change scenarios reveal higher labor needs on land, affecting households' labor allocation particularly in months around December. Given these outcomes, a response to climate change is agricultural intensification. This would increase the productivity of a given land area by maximizing the farm inputs. However, intensification relates to the availability of seed and fertilizer inputs, which are heavily limited at the study site. Meaningful simulation outcomes are provided by a reduction of on-farm labor as a response to climate change, which cannot be recommended as it provides one of the worst livelihood outcomes. Missing labor capacities in the busy months of the year restrict a household in its crop production. This leads to the second lowest productivity of kilocalorie production per hectare (see Fig. 5).

Third, engagement in off-farm activities at the refugee camp is a meaningful response to climate change at the study site. A household engages in off-farm employment in every climate scenario. In general, an increase in work opportunities at the camp has a positive effect on rural livelihoods. In months of labor surplus at the farm, the model shows a labor switch to off-farm employments, but it neglects migration in busy farm months, such as December. Thereby, the household facing high off-farm work opportunities reduces its time on the farm to a minimum using high yield crops, such as hybrid maize or cassava. However, if the model has to decide between on- and off-farm works for livelihood improvement, crop production is the preferred alternative. Growing crops is more beneficial due to its use for subsistence consumption (no need for external purchase). At the same time, households use their benefit from off-farm employments for increased food purchases at the market. As a result, the model is able to increase the income of the household with off-farm work opportunities without significantly reducing the household's production of kilocalories (see Fig. 4) or productivity per hectare (see Fig. 5).

Finally, Tables 7 and 8 show the off-farm employment pattern in baseline, dry and wet climate change scenario, ceteris paribus (with a baseline land and labor endowment). It indicates the number of household members working off-farm in specific months of the year. Model outcomes reveal potential for seasonal and local labor migration: Results show labor switches (1) from on- to off-farm employment explained by high overcapacities in the less busy agricultural months and (2) from off- back to on-farm work in the farming months around December (land preparation, planting and harvesting). Here, (nearly) all available labor is used for agricultural production. In addition, the model shows that in almost all months of the year at least 1 person works/stays on-farm (red boxes are the exception). In other words, spending all the available household time throughout the year off-farm would be less beneficial. However, the mix of on- and off-farm work in the study in each scenario indicates income diversification as a possible response to climate change. This is in line with related literature (see [32, 40, 56, 78]). Alam et al. [4] also confirm that especially landless or households with limited farmland take part in seasonal or temporary migration. The results are also

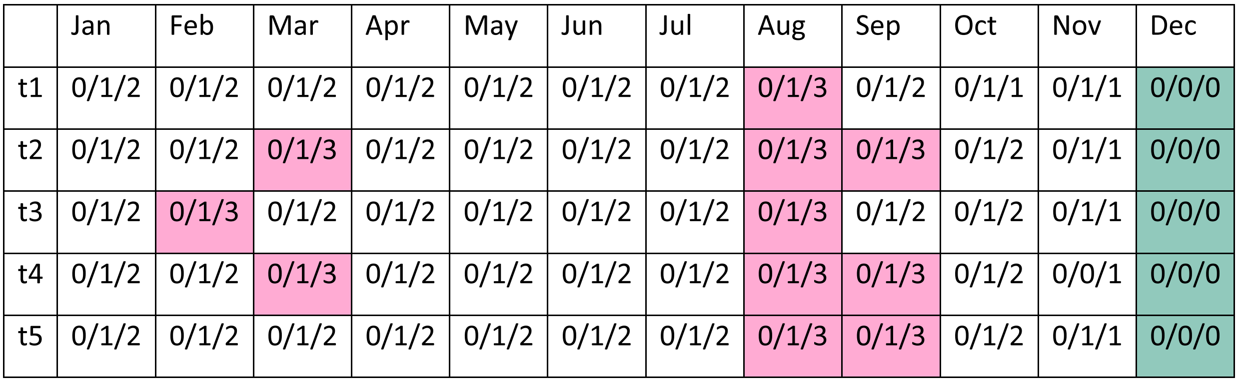
Table 7 Off-farm pattern in dry climate change scenario



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
t1	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/3	0/1/2	0/1/1	0/1/0	0/0/0
t2	0/1/2	0/1/3	0/1/3	0/1/2	0/1/2	0/1/2	0/1/2	0/1/3	0/1/3	0/1/2	0/1/1	0/0/0
t3	0/1/2	0/1/2	0/1/3	0/1/2	0/1/2	0/1/2	0/1/2	0/1/3	0/1/2	0/1/2	0/1/1	0/0/0
t4	0/1/1	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/3	0/1/3	0/1/1	0/0/0	0/0/0
t5	0/1/2	0/1/3	0/1/3	0/1/2	0/1/2	0/1/2	0/1/2	0/1/3	0/1/3	0/1/2	0/1/1	0/0/0

low/baseline/high off-farm employment, red = full employment, green = no employment

Table 8 Off-farm pattern in wet climate change scenario



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
t1	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/3	0/1/2	0/1/1	0/1/1	0/0/0
t2	0/1/2	0/1/2	0/1/3	0/1/2	0/1/2	0/1/2	0/1/2	0/1/3	0/1/3	0/1/2	0/1/1	0/0/0
t3	0/1/2	0/1/3	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/3	0/1/2	0/1/2	0/1/1	0/0/0
t4	0/1/2	0/1/2	0/1/3	0/1/2	0/1/2	0/1/2	0/1/2	0/1/3	0/1/3	0/1/2	0/0/1	0/0/0
t5	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/2	0/1/3	0/1/3	0/1/2	0/1/1	0/0/0

low/baseline/high off-farm employment, red = full employment, green = no employment

interesting for refugee settlement management plans as it reveals bottlenecks and availabilities of local labor forces.

Conclusions

SDG 13, defined by the United Nations, highlights climate change and calls for action to combat its impacts on a global but also local level. Specifically, it seeks to strengthen the resilience and adaptive capacity to climate-related hazards (SDG 13.1) and to integrate climate change measures into national policies, strategies and planning (SDG 13.2). Investigating climate change adaptation processes is fundamental to enhance resilience in the poorest parts of the world, mainly the Global South, marked by limited land and labor availability, lack of high-quality seed and fertilizer inputs, few job opportunities, agricultural dependency and food insecurity. The article investigated a case study region in rural Zambia. Rainfall and temperature predictions for the year 2050 show that climate change heavily affects weather conditions and the resilience of rural households by creating high uncertainties for already vulnerable livelihoods. The Zambian climate policy seeks to implement adaptation and risk reduction in the country, for example by promoting early warning systems, improving infrastructure and fostering resilience on the governmental and community level against climate change.

The paper used a farm planning model, simulated a baseline, dry and a wet climate change scenario and investigated farmers' optimal adaptation processes in a rural Zambian setting. In particular, it raised the following 2 research questions: (1) What is the optimal reallocation of land and labor factors in response to climate change? (2) How is the household's farming pattern affected by climate change? We applied a mathematical optimization approach, took advantage of recent census data of 277 Zambian households, defined a baseline scenario, 2 climate change scenarios and tested 7 possible future farm modifications in each case.

Results showed that climate change has a serious impact on farm yields and requires farm adjustments to prevent losses in wealth. Interestingly, climate simulations reveal that households are able to sustain their livelihood through adaptation processes at the farm. Without changing land and labor inputs, a dry and a wet climate significantly reduce farmers' income. However, altering the cropping mix is a meaningful instrument to respond to climate change at the study site. The examination of possible land and labor modifications to compensate wealth losses due to climate change revealed 3 key findings: (1) Farmers' increase in land size for crop cultivation is the best response to climate change. If more land is available, households' wealth and total crop production increase. It enables future investments in more beneficial seeds and the application of different planting methods/patterns. However, this is only feasible if land is not short in supply. (2) A reduction of labor supply at the farm makes households more vulnerable to a changing climate. A general reduction of labor capacity would limit the crop production in the busy months of preparation, planting and harvesting. Promoting farming techniques with changed planting times to smooth out the workload over the year or agricultural intensification could then increase the productivity per hectare. However, a problem in the study area can be the availability of seed inputs and fertilizer. (3) Off-farm employments reveal significant potential for climate change adaptation at the study site. Due to the significant overcapacities of labor in some months, an increase in work opportunities at a refugee camp has always a positive effect on rural livelihoods, without forcing the household to reduce their crop production or productivity. The mix of on- and off-farm work indicates income diversification as a possible response to climate change. Despite the high income-potential, subsistence agriculture should not be neglected due to limited market access. Finally, already around 50% of the farmers in the study area have some kind of trade contact with refugees and the increasing possibilities could mitigate future climate change effects.

In support of the Zambian government's adaptation and risk reduction efforts, the study points to bottlenecks in the supply of seeds and fertilizers at the local market, labor shortages, especially during the busy months of the year, and a lack of agricultural practices. Advantages of the refugee camp can be further exploited, e.g., via labor cooperation in agriculture (see [53]) and joint participation in economic support programs, such as rain-fed agriculture, gardening, small livestock and fishery (see [80]). Policy interventions such as agricultural intensification through improved seeds, technological tools, but also additional labor inputs, such as oxen are needed (see [55, 74]). In addition, policy should focus on the use of alternate seed and crop types, alternative planting/farming techniques or crop diversification (see [25, 39]), weather forecasting and education about effects of climate change (see [61]). The households' unique asset endowment and the local climate impacts are crucial to identify suitable adaptation processes.

The farm planning model incorporates crucial elements in the rural Zambian context, but still offers potential for future research. To investigate responses to climate change, studies also highlight gender and age of the household head [25, 48, 72, 88], education [4, 34], livestock ownership [25], access to credit [13, 25], market access [27], informal credits, farmer-to-farmer extensions and social networks [24, 67] to exchange about strategies as important parameters. For example, Deressa et al. [25] find a positive effect of access to credit and household head's education on changing planting times to cope with climate change. They also identify a positive effect of the household head's age and gender (being male) on the tree planting behavior. Livestock ownership affects the irrigation decision in a negative way. A limitation of the optimization methodology is the assumption of homo oeconomicus, i.e., rational decision-making (see [36]). A possible extension would be the inclusion of a utility function which also evaluates leisure (see [37]). Finally, the model separately investigates, 7 variations of farmers' land availability, labor capacity and off-farm work possibility. A combination of asset variations indicates potential for further research. The analysis is specified to a rural farm context in Zambia, but is applicable to similar settings in sub-Saharan Africa. Our research findings can be used at the policy level for local implementation, particularly for decisions related to household labor and land endowments.

Abbreviations

SDG: Sustainable development goals; IPCC: Intergovernmental panel on climate change; FAO: Food and agriculture organization of the united nations; USAID: United States agency for international development; TLU: Tropical livestock unit; ZMK: Zambian kwacha.

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Author contributions

CS and SG started the research idea. CS designed the model, did the data analysis and interpretation, developed the visualization and wrote the manuscript. BR contributed to the writing and interpretation of the article and did the submission. SG did the supervision of the research and project through which the paper was developed. All authors read and approved the final manuscript.

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Availability of data and materials

The data presented in this study are available on request from the authors.

Declarations

Ethics approval and consent to participate

Ethical clearance for field research design was granted by the University of Zambia (UNZA).

Consent for publication

Not applicable, as the manuscript does not contain data that could be used to identify survey participants.

Competing interests

The authors declare no competing interests.

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