

The Impact of Weather Risk on Tenure Security: Evidence from smallholder farmers in Tanzania

Lisa Murken, Gregor Mager, Rahel Laudien, Kati Kraehnert[‡] and Christoph Gornott[‡]

Corresponding author

Lisa Murken

Working Group Leader, Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Telegraphenberg A31, P.O. Box 60 12 03, 14412 Potsdam, Germany, murken@pik-potsdam.de

Co-authors

Gregor Mager

Doctoral Researcher, Environmental and Development Economics, Weihenstephan-Triesdorf University of Applied Sciences, TUM Campus Straubing, Essigberg 3, 94315 Straubing, Germany, gregor.mager@tum.de

Rahel Laudien

Postdoctoral Researcher, Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Telegraphenberg A31, P.O. Box 60 12 03, 14412 Potsdam, Germany, laudien@pik-potsdam.de

Kati Kraehnert

Professor, Leibniz Institute for Economics Research (RWI)
Economic Policy Lab Climate Change, Development and Migration
Hohenzollernstrasse 1-3, 45128 Essen, Germany, kraehnert@rwi-essen.de &
Ruhr University Bochum, Faculty of Management and Economics, Bochum, Germany
Universitaetsstrasse 150, 44780 Bochum, Germany &
Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association,
Telegraphenberg A31, P.O. Box 60 12 03, 14412 Potsdam, Germany

Christoph Gornott

Professor, Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Telegraphenberg A31, P.O. Box 60 12 03, 14412 Potsdam, Germany, gornott@pik-potsdam.de &
Agroecosystem Analysis and Modelling, University of Kassel, Nordbahnhofstraße 1a, 37213 Witzenhausen, Germany

[‡] *Kraehnert and Gornott share last authorship*

doi:10.3368/le.100.4.101422-0079R1

This open access article is distributed under the terms of the CC-BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0>) and is freely available online at: <http://le.uwpress.org>

Abstract

We analyze if exposure to weather risk affects the tenure security of smallholder farmers in rural Tanzania. Drawing on a household panel survey with three waves and high-resolution weather data, our identification strategy exploits exogenous variation in precipitation across time and space. Results from household fixed effects estimations show that exposure to weather risk significantly lowers farmers' perceived tenure security, while it increases land conflicts. Moreover, weather risk influences the likelihood that farmers acquire land certificates. These findings suggest that both land formalization and land dispute resolution mechanisms are needed to cushion the impacts of weather risk.

Keywords: *Dry spells, extreme weather, land certificates, land conflicts, precipitation variability, Tanzania, tenure security*

JEL Q15, Q54, P48, O13

1. Introduction

Tenure insecurity is a major concern for smallholder farmers globally. In 2020, approximately 121 million people in Sub-Saharan Africa feared that they will lose their land or property in the next five years (Prindex, 2020). Tenure (in)security is frequently studied in the development literature, which typically analyzes the role of secure tenure for farmers to invest in their land and improve agricultural production (for reviews see Higgins et al., 2018; Lawry et al., 2017; Robinson et al., 2014; Tseng et al., 2021). However, little is known about the determinants of tenure (in)security. The tenure security of smallholder farmers is often presumed to be relatively stable over time and mainly a function of legal characteristics, such as tenure type, the presence of a formal land title, and the mode of acquisition. The role of weather for tenure security is rarely studied. Understanding the link between weather and tenure security is particularly important with progressing climate change, since weather extremes are set to increase in frequency and intensity, potentially threatening secure land tenure.

This study addresses this gap, providing new empirical evidence on the link between weather risk and the tenure security of smallholder farmers in Tanzania. Specifically, we answer the following research questions: First, does weather risk affect farmers' perceived tenure security and the occurrence of land conflicts? Second, does weather risk affect the acquisition of land certificates? Our empirical analysis builds on a household panel survey with three waves, implemented in central Tanzania between 2013 and 2018, which contains detailed information on tenure security, land conflicts, and land certificates. Using geo-referenced information on households' location, the household survey data is combined with high-resolution gridded precipitation data (0.05°) and temperature data (0.25°). Our focus is on dry spells and precipitation variability, exploiting exogenous variation in precipitation across time and space. A household fixed effects model is employed to control for unobserved time-invariant heterogeneity across households.

Results show that exposure to both dry spells and precipitation variability significantly lower farmers' perceived tenure security. At the same time, exposure to both types of weather risk increases the risk of experiencing land conflicts. Precipitation variability mainly leads to increased land conflicts between farmers and pastoralists, whereas dry spells mainly increase the risk of land conflicts within the family, with neighbors, companies, and the government. Furthermore, exposure to precipitation variability strongly decreases the likelihood that farmers acquire land certificates, while exposure to dry spells increases the likelihood that farmers acquire land certificates within 1.5 years.

An investigation into potential mechanisms reveals that income fluctuations and changes in family labor dynamics due to weather variations may impact land tenure security. In the aftermath of dry spells or erratic rainfall, households experience reduced agricultural output and income, leading to increased off-farm employment and a reduced on-farm 'guard labor' presence among family members. Consequently, this may weaken the household's ability to defend its land rights against external claims.

This article contributes to the literature in four ways. First, we provide novel empirical evidence on how different types of weather risk affect smallholder farmers' land tenure, a question that receives little scholarly attention. Exceptions include Kalkuhl et al. (2020), who study sharecropping as a choice endogenous to climate risk, and Buggle and Durante (2021), who analyze the effects of climate risk on the development of social cooperation. While a large body of literature analyzes effects of extreme weather events on conflict (e.g. Burke et al., 2015; Hsiang et al., 2013; Hsiang & Burke, 2014; Sarsons, 2015), little research focuses specifically on land conflicts.

Second, our analysis provides new empirical evidence on the determinants of farmers' tenure security, thus contributing to an under-researched field. We focus on *perceived* tenure security, which is arguably the most relevant dimension of tenure security for farmers'

behavior, since perceptions are thought to underlie human behavior (Dijksterhuis & Bargh, 2001; Jenkins et al. 2018). The small body of existing research on the determinants of perceived tenure security builds on cross-sectional survey data (Ayamga et al., 2015; Ghebru & Girmachew, 2019; Ghebru & Lambrecht, 2017; Yi et al., 2014), which often does not allow for a causal identification of effects, with the exception of Sipangule (2017). Our use of a detailed household panel survey and a household fixed effects approach allows us to control for unobserved time-constant household characteristics, a considerable improvement over cross-sectional analyses of tenure security.

Third, we add to the literature on the link between land conflicts and tenure security, which so far mainly considers concerns about land conflicts or expropriation as a measure of tenure insecurity (Jacoby et al., 2002; Linkow, 2016; Reerink & van Gelder, 2010) and well-functioning tenure systems as a remedy against land conflicts (Boone, 2014). We provide empirical evidence on both actually *experiencing* land conflicts and the perception of tenure security of smallholder farmers.

Fourth, we contribute to the debate on land formalization by analyzing how weather risk may incentivize farmers to acquire land certificates. A large body of literature studies the impact of land registration and formalization programs on tenure security, agricultural production, and other development outcomes (Ali et al., 2014, 2017; Deininger & Chamorro, 2004; Deininger & Feder, 2009; Holden et al., 2011; Kubitza et al., 2018; Place & Migot-Adholla, 1998). Yet, few studies analyze the determinants of title acquisition and we are not aware of studies that analyze the link between weather risk and the acquisition of land certificates.

The remainder of the study is organized as follows: the next section introduces the conceptual framework. Section 3 provides background on the Tanzanian context, followed by a description of the data in section 4. In section 5, we outline the empirical strategy. Section 6 presents and discusses the results. Section 7 concludes.

2. Conceptual framework: The link between weather risk and tenure security

In this study, we analyze the effect of weather risk on tenure security. Various definitions of tenure security are used in empirical research (Arnot et al., 2011). Often, a distinction is made between *de jure* tenure security, implying a legal title to land, and *de facto* tenure security, understood as the actual tenure security as determined by objective factors, such as land ownership and government policies. Van Gelder (2010) extends this to a tri-partite view, adding *perceived* tenure security, which acknowledges that informal systems can also play an important role. The FAO (2002:18) offers one of the most frequently used definitions, framing tenure security as ‘the certainty that a person’s rights to land will be recognized by others and protected in cases of specific challenges’. This definition includes components of both *de facto* and *perceived* tenure security, which can diverge if an individual’s perceived tenure security does not correspond (fully) to the factual threats or enablers of tenure security. Yet, a more comprehensive definition of *de facto* tenure security acknowledges the influence of perceptions and beliefs, as they shape actual security, as suggested by Sjaastad & Bromley (2000). If enforcement of land laws is inadequate, *de jure* tenure security may also diverge from *de facto* tenure security (Platteau, 2002).

We focus primarily on perceived tenure security and hypothesize that weather risk may affect perceived tenure security in various ways. In addition, we study the effect of weather risk on land conflicts and land formalization through the acquisition of land certificates. This stems from the understanding that perceived tenure security, land conflicts, and land formalization are intricately linked. On the one hand, farmers’ perception of the risk of land conflict (Linkow, 2016) or the risk of expropriation (Huntington & Shenoy, 2021; Reerink & van Gelder, 2010) are commonly used to define tenure security. On the other hand, weak land institutions, unclear land rights, and insecure tenure are often assumed to contribute to conflicts over land (Boone, 2014, 2017; Deininger & Castagnini, 2006). According to Coasian logic, well defined land

(property) rights reduce transaction costs and lower the risk of conflict (Coase, 1960). Land formalization is seen as a way of securing land rights, which is why tenure security is frequently defined in legal terms as having a formal, government-approved claim to land (Robinson & Diop, 2022). The evolutionary theory of land rights contends, among others, that scarcity-induced land disputes increase the demand for tenure security and, in turn, formal land titling (Platteau, 1996).

We hypothesize that direct and immediate effects of weather risk on perceived tenure security are unlikely. However, a number of intermediate channels, outlined below, are plausible, through which weather risk may affect perceived tenure security. All of these channels are induced by resource scarcity or uncertain agricultural prospects that follow from weather risk. Weather variability lowers agricultural potential, for instance through decreased water availability for crop production and livestock rearing, and can put agricultural livelihoods at risk, which may ultimately influence perceived tenure security.

First, weather risk may affect perceived tenure security in agricultural settings through a psychological channel. Adverse weather conditions, leading to resource scarcity and diminished agricultural prospects, may increase the perceived threat of losing access to one's land.

Second, weather risk is likely to induce conflicts, which, in turn, may influence perceived tenure security. The link between weather variability, climate, and conflicts is well-established. A large empirical literature documents that weather and climate significantly affect the risk of conflict, which in rural areas partially runs via agricultural production (for reviews and meta-analyses, see Hsiang et al., 2013; Hsiang & Burke, 2014; Koubi, 2019). In mixed agro-pastoral settings, dry periods or precipitation variability can spur conflicts around water and fodder access (Butler & Gates, 2012), often between pastoralists and agriculturalists (McGuirk & Nunn, 2020), which is also observed in Tanzania (Benjaminsen et al., 2009). More

generally, weather risk can also foster competition for resources and might put households in vulnerable positions, making them more prone to land conflicts within the family and with outsiders. Further, harsh weather does not always spur new conflicts, but may induce latent conflicts to surface (Dell et al., 2014). Adverse weather conditions can, for instance, affect physical boundaries that are used to demarcate land, e.g. trees and streams. When these are altered or disappear, this can invite conflicts over land.

Third, perceived tenure security may be influenced by weather risk through a reduction in ‘guard labor’. As weather risk increases and agricultural production falls, households may have to rely more on off-farm employment. This could increase perceived tenure insecurity, if fewer people – and especially the household head – are present at the homestead to defend the household’s land against outside claims. Economic theory predicts that households react to insecure property rights to land with ‘guard labor’, a substitute to productive labor in the agricultural context (Besley & Ghatak, 2010). Out-migration is also linked to tenure security, with land registration projects in low and middle-income countries often – but not always – found to increase out-migration, presumably because land is more secure and does not need to be guarded (Valsecchi, 2014).

Fourth, weather-induced resource scarcity may also cause changes in the demand for land certificates. Weather risk may reduce agricultural production and deplete households’ financial capital, thus making the acquisition of land certificates more difficult. Households’ incentives for acquiring certificates are not well understood and, despite a shift from top-down land reforms in the 1980s and 1990s to more bottom-up and participatory approaches in the 2000s, land formalization is largely viewed as externally imposed on households (Sjaastad & Cousins, 2009). Experimental evidence from Tanzania shows that the costs of acquiring a land certificate play a key role in households’ decision to apply for land certificates (Ali et al., 2016).

At the same time, land conflicts may influence the demand for land certificates, if land certificates are seen as a means of protection against land conflicts.

3. Land tenure in Tanzania

Since the start of the new millennium, Tanzania has seen intensifying competition for farmland and a rise in land conflicts (Odgaard, 2003; Walwa, 2020). In the 1990s, in the wake of a second wave of land reforms across several (African) countries, Tanzania's tenure system was reformed in an effort to recognize existing rights, while simultaneously creating an effective land market. Tanzania's land reform of 1999 is considered among the most carefully designed reforms across Africa, striking a balance between protecting vulnerable groups, such as female-headed households, while also improving efficiency and business opportunities (Pedersen, 2015). However, it is also criticized as a centralistic, bureaucratized, and legalistic reform that commoditized land and opened up the land market for investments and alienation (Boone & Nyeme, 2015).

Under the Village Land Act and the Land Act, both enacted in 1999, all land in Tanzania is classified as village land, reserve land, or general land. As of 2019, village land (which also comprises the land smallholder farm households use for farming) makes up almost 70% of all land in Tanzania (African Development Bank, 2019). A large part of village land is land held under customary tenure laws, which are protected under the Village Land Act. Such land is directly managed by village authorities or other customary institutions. Reserve land consists of spaces for wildlife and natural parks, whereas general land is all land not falling under the first two categories, for instance urban land and land leased by the government (Wily, 2003). All land is vested in the president, who has the sole authority and power to transfer land from one category to another (Rwegasira, 2012). Yet, the regulation of other land matters, such as land allocation and dispute settlement, has been gradually decentralized since mainland

Tanzania's independence in 1961. Authority in such matters now lies with village and district authorities. At the same time, customary practices that counteract village authorities are prohibited (Pedersen, 2015).

Land titling requires several steps: The Village Land Act allows villages to have their land surveyed and to devise land use plans, which must be endorsed by district councils. Once this is completed, households can apply for Certificates of Customary Rights of Occupancy (CCROs) for their land, which are granted by village land councils (Schreiber, 2017). Certificate costs vary, but are reported to be high in the absence of systematic land formalization efforts (Aikaeli & Markussen, 2022).

Implementation of the 1999 land reform and formalization process in Tanzania has been slow (Aikaeli & Markussen, 2022; Rubakula et al., 2019), among the slowest rollouts in Sub-Saharan Africa (World Bank, 2018). Since village land councils can issue CCROs autonomously, there is no central registry of all available CCROs, but a nationally integrated land management information system is planned (ibid.). Bureaucracy in issuing land certificates varies across Tanzania, since the villages have authority over issuing CCROs, but tends to be relatively homogenous within regions. Compared to other countries and in contrast to issuing of individual titles, the process of titling communal land in Tanzania has been described as comparatively fast, involving few authorities (Notess et al., 2021). By 2017, most villages had mapped their outer boundaries and about 13% had devised land use plans. Of the approximately 6 million smallholder farm households in Tanzania, an estimated 400,000 had obtained formal land titles as of 2017 (Schreiber, 2017). Titling is partially driven by government initiatives, but self-initiated acquisition of land certificates by farmers also occurs. Given the high costs of formal titling in the absence of subsidized programs, households also resort to other forms of informal documentation, which are not issued by the government (Aikaeli & Markussen, 2022). In focus group discussions carried out by researchers of Ardhi University, Tanzania, in part of

the survey villages in July 2023, lack of enforcement of existing land tenure regulations and land use plans was mentioned as a major issue impeding the proper functioning of land tenure systems in Tanzania.ⁱ

Land allocation, redistribution, and the misuse of land assigned for a specific purpose are frequent causes of disputes. Conflicts arise between farmers and pastoralists, between neighbors, between farmers and the government, between private companies, or even within households (Bergius et al., 2020; Bluwstein et al., 2018; Greco, 2015). In Tanzania, both highly mobile pastoralists and sedentary agro-pastoralist households exist. In some areas, pastoralists have not been allocated sufficient grazing land, leading them to venture into villages or reserve land to feed their livestock, particularly in dry years. This has led to violent clashes and continues to be an issue of high visibility and intense public debate in Tanzanian media and politics (Benjaminsen et al., 2009; Walwa, 2020). Land acquisitions by investors – both from the private sector and the government – have also sparked discontent and conflict over land (Bélair, 2021).

4. Data

4.1 Household panel survey data

The database for the empirical analysis is the Trans-SEC household panel survey implemented by Sokoine University of Agriculture and University of Hannover as part of the Trans-SEC project (<http://www.trans-sec.org/>). The Trans-SEC survey aims at collecting detailed data on agricultural livelihoods and food security in Tanzania. It was implemented in six villages located in two neighboring regions of central Tanzania: semi-arid Dodoma and sub-humid Morogoro region (Fig. A1 in the Appendix). These two regions jointly account for 70-80% of the farming systems in Tanzania (Graef et al., 2014). The regions and study villages

were selected to represent different cropping systems and varying degrees of market access and livestock integration. In each village, 150 households were randomly selected (out of a total population of 800-1,500 households per village) (Brüssow et al., 2019; Graef et al., 2014). The survey comprises three panel waves that were implemented in 2014, 2016, and 2018.

The sample size in the first wave comprises 899 households, of which 820 and 778 households were re-interviewed in the second and third waves, respectively. Our analyses build on a balanced panel of 778 households that were surveyed in all three waves. Sample attrition between the first and third wave was 13.5%. If households that dropped out of the panel survey over time differ systematically in their land tenure security or exposure to conflict, our results may be biased. We conduct various tests to examine the drivers of panel attrition.ⁱⁱ We conclude from those tests that attrition does not severely bias our estimates.

Households in both regions are smallholder farmers practicing primarily rain-fed agriculture as their main source of living. Livestock rearing is common in both regions, but more prevalent in semi-arid Dodoma. Besides income from agricultural production, the survey records income from renting land, receiving remittances, self-employment, wage employment, and from the extraction of natural resources. The survey has a strong emphasis on agricultural production and records plot-level information regarding land tenure, mode of land acquisition, formal status, main use of land, crop production, soil fertility, and input use in great detail. Main crops cultivated are maize, millet, sorghum, sunflower, sesame, and groundnuts. The three panel waves cover the main agricultural seasons of 2013, 2016, and 2018 (Fig. A2 in the Appendix).ⁱⁱⁱ In the survey area, the main growing season starts in January and harvest takes place in April. On average, households possess 2.62 plots. Data cleaning (explained in the Appendix) involved removing outliers in plot size, agricultural production, and income.

Our main outcome variables of interest are recorded at the plot level. Since plots are not uniquely identified across waves, we could only match parts of the plot-level sample across the

three panel waves.^{iv} In the balanced sample of households, the sample used in our main analyses, only 57% of plots (3,510 out of 6,139 plots) could be matched with confidence across all three waves. Information on the year of acquisition for all 6,139 plots reveals that 7% of plots in the sample were obtained after 2013. We conduct attrition tests to examine the factors leading to plots not matching over time.^v

Because of this rather high number of unmatched plots, we opted for using household-level variables in our main analysis and provide further analyses at the plot level as robustness test. Our choice to focus on household-level outcomes is also motivated by our interest in households' overall landholdings and tenure situation. One potential threat to our identification is that households sell or lease out land in response to weather influences. While we cannot completely rule out such effects, only few households reported selling land in response to a shock (13, 4, and 10 households in the first, second, and third panel wave, respectively).

Another potential threat to our identification could stem from inappropriate aggregation from the plot to the household level. In the study villages, almost all plots directly border the homestead. Homesteads are mostly scattered across the villages, with slightly higher concentration along roads and village centres. Each village is further divided into 9-15 sub-villages. The survey records the minutes needed to walk from the homestead to each plot. The median for this variable is zero minutes in all three waves, with average walking distances between 5.3-6.6 minutes per wave (Table A7 in the Appendix). Even when considering means, this translates into an average distance between homestead and plots of ca. 0.5km, depending on walking pace. The precipitation variables employed in our model have a resolution of ca. 5km. Overall, given the close proximity of plots to homesteads and the decentralized organization of agricultural villages in the sample, we are confident that the aggregation of the dependent variables from plot level to household level does not unduly bias the results.

The first outcome variable is perceived tenure security. For each plot, the survey records the perceived tenure security on a four-point ordinal scale, with (1) corresponding to ‘not tenure secure at all’; (2) ‘somehow tenure secure’; (3) ‘almost tenure secure’; and (4) ‘very tenure secure’. In the following, we only consider the fourth category (‘very tenure secure’) for two reasons: First, our interest is in understanding the determinants of tenure security, as compared to tenure insecurity. Second, we consider the highest and lowest category of the tenure security scale to be more accurately measured. We aggregate tenure security to the household level by creating a dummy variable taking the value one if a household owns at least one plot it considers ‘very tenure secure.’ The mean of this indicator variable increases from 0.36 in 2013 to 0.86 in 2018 (Table 2).

The second outcome variable is an indicator variable taking the value one if a household self-reports having experienced any land conflicts in the 12-month reference period preceding each panel wave.^{vi} The survey records different types of conflicts around land, including conflicts with neighbors, pastoralists, within the family, the government, and private companies. Few households report experiencing several types of conflict. The incidence of land conflicts remained relatively stable over time, with about 10% of sample households reporting conflicts in each wave. Overall, 24% of households reported experiencing any type of land conflict at least once. Figure 1 shows how the frequency of specific types of land conflicts changed over time. Notably, land conflicts with neighbors decreased and conflicts with pastoralists increased over time, while all other conflict types remained relatively stable.

[[Insert Figure 1 here]]

As the third outcome, we consider if households obtained a land certificate since the previous panel wave. We construct a dummy variable that takes the value one if household acquired a certificate for an existing plot or bought a new plot with a land certificate. A certificate does not necessarily mean a formal land title obtained from the government, but can

also take other forms of written documentation commonly used in the village. Since our focus is on the change in land certificates over time, the sample for this analysis is restricted to the second and third waves.

Table 2 presents summary statistics by wave for the dependent variables, main explanatory variables, control variables, and channels. While characteristics, such as household size, average farm size, and the number of plots farmed, remain relatively stable over time, notable increases are observed in livestock ownership, agricultural production, and – albeit at a lower rate – total net income. The moderate increase in total net income despite the considerable rise in agricultural production can be explained by price dynamics. For instance, the price of maize in 2018 was 19% lower compared to 2016, possibly due to increased maize supply.

[[Insert Table 1 here]]

[[Insert Table 2 here]]

4.2 Weather data

We focus on two weather indicators. The first is the occurrence of dry spells, defined as 15 or more consecutive dry days (CDD15). Prolonged dry periods over several successive days without precipitation are detrimental to crops and agricultural livelihoods, making it a suitable variable in studies that examine the impacts of weather on crop growth (Laudien et al., 2020; Schlenker & Roberts, 2009). Specifically, CDD15 is defined here as the number of times a dry spell of 15 or more days occurred during the previous growing season, with a dry day defined as a day with less than 0.5mm of precipitation. The previous growing season refers to the growing seasons of 2013, 2016, and 2018 that began some 9-12 months before the implementation of each panel wave.

The second weather measure is precipitation variability, which we proxy with the coefficient of variation of the daily precipitation sum (precipitation CV). Precipitation

variability is considered a main source of risk for agriculture (Aufhammer et al., 2012; Kalkuhl et al., 2020). Following Kalkuhl et al. (2020), we use the CV of precipitation and not the standard deviation, since the CV is scale-invariant.

In addition, median temperature during the previous crop growing season is used as control in all specifications, since precipitation and temperature are highly correlated.

The precipitation measures are calculated from the CHIRPS (Climate Hazards group InfraRed Precipitation with Stations) precipitation dataset (Funk et al., 2015), while the temperature measure is calculated from ERA5 (Copernicus Climate Change Service, 2017). CHIRPS has a resolution of $0.05^\circ \times 0.05^\circ$ (approximately $5\text{km} \times 5\text{km}$), which leads to 24 unique data points for the study area. CHIRPS is a state-of-the-art weather data product that blends weather station data with satellite data and provides reliable precipitation information for East Africa (Dinku et al., 2018). The resolution of ERA5 is $0.25^\circ \times 0.25^\circ$, giving six unique data points for the study region, one per village. The weather data are matched with the panel survey data, using the geo-referenced location of households for matching the precipitation data.^{vii}

5. Empirical framework

We first examine if weather risk affects farmers' perceived tenure security. We estimate a household fixed effects model of the following structural form:

$$S_{it} = \beta_1 \text{weather risk}_{it} + \delta X_{it} + \theta \text{temp}_{it} + \alpha_i + \pi + \gamma_t + \varepsilon_{it} \quad [1]$$

where the perceived tenure security S of household i at time t is estimated as a function of weather risk_{it} (the occurrence of dry spells or precipitation variability) in the previous growing season, a vector of time-varying household-level controls X , median temperature (temp) in the previous growing season, household fixed effects α_i , enumerator fixed effects

π , wave fixed effects γ_t , and an error term ε_{it} that contains unobserved and time-varying heterogeneity as well as a random individual error component. Household fixed effects capture any observed or unobserved time-invariant heterogeneity across households. Enumerator fixed effects account for possible effects stemming from the assignment of enumerators to sample households.^{viii} Wave fixed effects control for any events that affect all households in a given year in similar ways. The main coefficient of interest is β_1 , which measures the effect of weather risk on perceived tenure security. Weather risk is defined either as dry spells or as precipitation variability. Since temperature and precipitation are correlated, we control for median temperature in all specifications, as suggested in the climate econometrics literature (Auffhammer et al., 2013). We chose to cluster at the level of the precipitation data points, analogously to the literature that clusters at the level of treatment assignment in (quasi-)experimental settings (Abadie et al., 2022).^{ix} Eq. 1 is estimated with ordinary least squares (OLS) using a linear probability model, since logistic or probit regression in panels with few time periods and many cross-sectional units suffers from incidental parameter bias (Wooldridge, 2013).

Time-varying household-level controls include household size, which may influence both tenure security and land conflicts, as a larger household can pose a threat for the claims of individual members. This may result in more frequent intra-family land disputes. At the same time, a large household may find it easier to stand up to outside claims. The size of total farmland and farm fragmentation affect how easily a household can control its land holdings. Livestock ownership indicates both asset wealth and socio-economic status, which may both protect from or attract land conflicts. Summary statistics of the complete set of control variables are reported in Table 2.

In the most parsimonious model, we do not include any household-level controls in order to estimate the full effect of the respective weather risk variable on tenure security and

avoid over-controlling. We then add time-varying household-level controls. All controls constitute potential intermediate outcomes that may themselves be affected by weather conditions, thus possibly absorbing part of the effect on the main outcomes of interest. The estimated coefficients of weather risk in the full model with controls thus give an indication of the direct – not full – effect size. However, due to the likely endogeneity of most time-varying controls to the land tenure outcomes of interest, the coefficients can no longer be interpreted causally in the full model.

To estimate the effect of weather risk on land conflict, we follow a similar approach as in eq. 1, using the same controls and fixed effects.

The second research question examines if exposure to weather risk increases the likelihood that smallholder farmers acquire a land certificate. We estimate the following equation:

$$new\ title_{it} = \beta_2 weather\ risk_{it-1} + \delta X_{it} + \theta temp_{it} + \alpha_i + \pi + \gamma_t + \varepsilon_{it} \quad [2]$$

The outcome variable of interest is the acquisition of a new land certificate either for an existing plot or for a newly acquired plot since the last panel wave. The measures for weather risk, $weather\ risk_{it-1}$, are now lagged by one year (i.e., dry spells and precipitation CV two growing seasons before each interview). This accounts for the fact that land documentation often requires some time, making a certain time lag in the response likely. Although land documentation can be lengthy, within the study region, certificates can be obtained within a couple of months, since all villages in the sample have land use plans in place and their outer village boundaries are mapped. Informal written land documentation can be obtained even faster. The model is estimated for waves 2 and 3. The same sets of control variables and fixed effects are used as in eq. 1. In addition, we control for the current value of the weather risk measure, $weather\ risk_{it}$.

6. Results and discussion

6.1 Weather effects on perceived tenure security and land conflicts

Table 3 presents regression results for eq. 1, with the outcome variable being households' perceived tenure security in the previous growing season. Column 1 shows the full effect of dry spells on perceived tenure security. Exposure to dry spells during the growing season decreases households' perceived tenure security. The estimated coefficient of dry spells is significant at the 1% level and the result holds when controlling for time-varying household-level characteristics (col. 2). In columns 3 and 4, we test the effect of the precipitation CV on perceived tenure security. We find a highly significant effect on perceived tenure security: Households exposed to high precipitation variability report considerably lower perceived tenure security. When again including the full set of controls in col. 4, the coefficient of the precipitation CV on tenure security remains at similar levels.

[[Insert Table 3 here]]

Next, we analyze the effect of weather risk on land conflicts. Table 4 displays the results for all land conflicts combined (col. 1-4), for conflicts with pastoralists (col. 5-6) and other land conflicts (col. 7-8), which concern conflict parties other than pastoralists. Cols. 1-2 and 3-4 show strong positive effects of dry spells and the precipitation CV on the experience of land conflicts, both in the baseline model and when including household controls. In other words, households are considerably more likely to experience land conflicts after having been exposed to weather risk. When differentiating between conflicts with pastoralists and other land conflicts, the coefficient estimates indicate that the effect of precipitation variability can mainly be explained with increased conflicts between farmers and pastoralists, while the effect of dry spells on land conflicts is mainly driven by land conflicts other than with pastoralists.

[[Insert Table 4 here]]

6.2 Consequences of weather risk: acquisition of land certificates

In this section, we explore whether exposure to weather risk leads households to acquire a land certificate for one or several plots. Table 5 displays results for eq. 2, obtained with OLS. Columns 1-3 present the effect of dry spells on either the acquisition of a new land certificate for an existing plot or the acquisition of a new plot with a certificate. Since obtaining a new land certificate can take some months in the study area, we expect effects to materialize with a time lag. Thus, the first lag of the respective weather variable is the relevant measure. Column 1 displays results when only including lagged dry spells, col. 2 additionally controls for dry spells occurring in the current period, and col. 3 additionally includes household controls. In all three specifications, exposure to dry spells occurring about 1.5 years before the survey interview increases the likelihood of acquiring a land certificate. In contrast, the results presented in cols. 4-6, again using a stepwise approach, indicate that households exposed to precipitation variability about 1.5 years before the survey interview are considerably less likely to acquire a new land certificate. This result is in line with the large negative effects found of precipitation variability on tenure security in Table 3 and the positive influence on land conflicts (Table 4).

The positive effect of dry spells could suggest that farmers view the acquisition of land certificates as a means of protecting themselves against future land disputes. A potential explanation for the differential effects of both weather risk measures on land certificate acquisition could lie in the type of land conflict that is influenced by the respective weather event. Precipitation variability is correlated with conflicts between farmers and pastoralists, where land certificates cannot protect farmers from pastoralists' infringements on their land. On the contrary, conflicts with family members, neighbors, the government, or outside companies may be easier to address with land certificates.

[[Insert Table 5 here]]

6.3 Potential impact channels from weather to land tenure

Next, we examine potential channels from weather risk to perceived tenure security, land conflicts, and land certificate acquisitions. First, we analyze if weather risk translates into changes in agricultural production. Cols. 1 and 2 in Table 6 present results of an OLS regression of dry spells and the precipitation CV, respectively, on agricultural production (measured in kg per ha). We use the inverse hyperbolic sine transformation to transform the outcome variable, to account for the highly skewed distribution. The inverse hyperbolic sine transformation has the advantage of handling zero values, in contrast to the log transformation. Results show that dry spells and higher levels of the precipitation CV in the current season strongly decrease household's agricultural production, with both coefficients significant at the 1% level. Effects are persistent for dry spells occurring 1.5 years before the survey interview, but not for the lagged precipitation CV. The point estimates in col. 2 (-1.30) suggest a reduction in agricultural production of ca. 2.3% following a 1% increase in precipitation variability.

The drop in agricultural production after experiencing weather risk in the current growing season translates into significant decreases in net household income, which is again transformed using the inverse hyperbolic sine transformation (cols. 3 and 4 of Table 6). This is in line with a solid body of evidence documenting weather effects on income (Dell et al., 2012; Dell et al., 2014; Kotz et al. 2022). Effects on net income are not persistent over time, with the first lags of the weather risk variables being not significant at conventional levels. Part of the negative income shock following weather risk is offset by increased wage income (cols. 5 and 6), due to increased wage employment (cols. 7 and 8), which points to (partly) effective income smoothing strategies.

With regard to perceived tenure security, these effects on the households' economic situation can point to potential mechanism related to 'guard' labor. The increases in wage employment following weather risk suggest that households respond to weather risk with less

labor used for protecting their land, which could decrease perceived tenure security. At the same time, such reduced presence on the land can make the household more exposed to conflicts, if unguarded land is taken advantage of.

The negative income shock could further exacerbate tenure insecurity, as it makes households more vulnerable to outside land claims and reduces their ability to apply for (costly) land certificates. Ali et al. (2016) show that income plays an important role in the acquisition of land certificates, although other studies do not find a significant relation between income and tenure security (Sipangule, 2017; Yi et al., 2014).

[[Insert Table 6 here]]

6.4 Robustness tests

We conduct a series of robustness tests to assess the reliability of our findings. The robustness tests are split into two parts: We first carry out robustness tests at the household level and, in the second part, then analyze perceived tenure security, land conflicts, and land certificate acquisitions at the plot level.

At the household level, we first employ an alternative definition of the main outcome variable, perceived tenure security, as robustness test. Instead of using an indicator variable, we calculate the share of farmland that is considered ‘very tenure secure’ by households (see summary statistics in Table A8 in the Appendix). Results, displayed in Appendix Table A9, are very similar to baseline results. Second, we use an alternative definition of tenure security that combines the third and fourth category (‘almost tenure secure’ and ‘very tenure secure’) of the survey item from which the main outcome is constructed. We define both an indicator variable taking the value one if a household holds at least one plot it considers either ‘almost tenure secure’ or ‘very tenure secure’ and a variable representing the share of farmland perceived as either ‘almost tenure secure’ or ‘very tenure secure’ (Appendix Table A10). Results are very

similar to the baseline model when using the share variable, but not when using the indicator variable. This may be explained with the fact that by the time of the third panel wave, almost all households farmed at least one plot respondents felt either almost or very secure about, thus eliminating much of the variation (Appendix Table A8).

Note that in the baseline model, we control for median daily temperature in the previous growing season, which correlates with precipitation. Next, we test the sensitivity of our findings to using an alternative measure of temperature, maximum daily temperature, which is more likely to have an immediate effect on crops in itself (apart from its interaction with precipitation). Appendix Tables A11, A12, and A13 display results with maximum daily temperature instead of median daily temperature as control variable. Appendix Table A11 shows results for the effect of dry spells and precipitation variability on perceived tenure security. The signs of the main effects of interest remain the same as in the baseline models, although effect sizes are considerably smaller and the estimated coefficients for precipitation variability are no longer statistically significant at conventional levels. Appendix Table A12 displays results for the occurrence of land conflicts. The estimated coefficients of dry spell and precipitation variability are of comparable magnitude and have similar significance levels as the baseline results. Lastly, in Appendix Table A13 we present results for the effect of dry spells and precipitation variability with a one-year time lag on the uptake of land certificates. Again, the size of the estimated effects of dry spell and precipitation variability is smaller than in the baseline results and, partly, at lower levels of significance. Taken together, we interpret those results as supportive evidence that findings are robust to the exact definition of temperature, an important control variable.

However, threats to the validity of our findings could also arise from inappropriate aggregation of land tenure variables to the household level. In section 4.1 we explain our motivation to study tenure security primarily at the household level. We now study drivers of

tenure security at the plot-level and compare this to the household-level findings by using the matched panel of plots (3510 out of 6139) to repeat some of the main analyses at the plot level. We estimate eq.1 and 2 without household-level controls, but with plot-level fixed effects. Outcome variables are defined at the plot level, namely an indicator variable taking the value one if a plot is considered very tenure secure, an indicator variable for the experience of a land conflict on the plot and the first difference of a land certificate on a plot. The results generally confirm the household-level results, but with two important differences: the negative effect of dry spells on perceived tenure security is weaker and the precipitation CV does not have a significant impact on the acquisition of new land certificates. The first difference can potentially be explained with plot-level attrition effects and changes in the plot sample due to new plot acquisitions in between waves. The second difference may be due to the fact that the plot-level analysis cannot account for newly acquired plots with land certificates. Unconditional t-tests on the difference in means indicate that matched plots have a smaller average size compared to unmatched plots and are more likely to be documented with a land certificate. Given the high number of unmatched plots, the plot-level analysis needs to be interpreted carefully, but it generally confirms the results obtained at the household level.

6.5 Implications for land policies and programs

Our results underline the importance of better understanding short-term influences on tenure security in order to design appropriate and well-targeted land tenure interventions. This may entail establishing or improving accessible and well-functioning dispute resolution mechanisms for land conflicts, particularly in areas that are affected by weather risk, to alleviate impacts of extreme weather on households' land tenure. In Tanzania, there are specific land tribunals designated at the ward and district levels, with the High Court Land Division and the Court of Appeal forming the highest instance at national level (Rwegasira, 2012). However,

evidence indicates that this system is overburdened and prone to corruption (Massay, 2013; Rubakula et al., 2019).

In particular, our results suggest that the policy response to land conflicts and tenure insecurity should consider the type of weather risk households face in a given region, as this may influence which response – notably land formalization or the improvement of land dispute resolution – is most appropriate. The role of weather risk for tenure security is particularly concerning given the climate change context: with increasing climate change, dry spells and erratic precipitation are expected to become more likely (Kendon et al., 2019), which could result in higher tenure insecurity and more frequent land conflicts in the future.

Further, our results shed light on the importance of access to land formalization. While several studies report negative side effects of land formalization projects on smallholder farmers (for reviews, see Lawry et al., 2017; Sjaastad & Cousins, 2009), our results provide suggestive evidence that land certificates are sought by some farmers to protect themselves against previously experienced weather-driven land conflicts. However, land certificates only offer limited protection for conflicts between farmers and pastoralists, who do not threaten ownership claims to land, but rather infringe on land to graze their herds. Such conflicts are driven by precipitation variability, which requires other policy solutions for farmers (and pastoralists) affected by such conflicts. Potential solutions encompass enhanced mediation mechanisms to address conflicts between farmers and pastoralists, as well as proactive programs designed to enforce extant regulations governing resource access for both groups. This includes clear demarcation of land boundaries, land use plans, and formal acknowledgment of the resource rights pertaining to each respective group.

Generally, land certificates are not equally accessible for all socio-economic groups. Marginalized social groups may find it more difficult to gain access to certificates, while certificates are of little help against powerful and well-organized interests, e.g., the state. The

president has considerable power over land in Tanzania. In the past, even formal land certificates have not always protected rural communities from expropriation.^x In addition, the growing formalization of land tenure frequently gives rise to intra-household land disputes, often resulting from exclusionary practices disproportionately affecting women and younger men (Odgaard, 2005). In African countries, land ownership and control are typically characterized by significant inequalities across socio-demographic groups, particularly along gender lines. However, accurately quantifying the extent of these disparities remains a challenge (Doss et al., 2015). In the Trans-SEC household survey, the survey item on land tenure was, in almost all cases, reported by household heads. Hence, the data likely overlooks intra-household disputes over land that would have been reported by other members.

7. Conclusion

In this study, we provide new empirical evidence on the impact of weather risk on farming households' perceived tenure security, land conflicts, and acquisition of land certificates. Our analysis builds on a household panel survey implemented in rural Tanzania between 2013 and 2018 that contains detailed information on farmers' tenure security. We use the occurrence of dry spells and the coefficient of variation of precipitation in the previous crop growing season as measures of weather risk to study how weather affects tenure security.

Our results contribute to the literature in several ways. First, we provide novel evidence on the effect of weather on land tenure, which is, so far, mainly studied in cross-sectional settings (Kalkuhl et al., 2020). We show that exposure to weather risk decreases perceived tenure security, is associated with increased land conflicts, and even influences interest in land certificates. While both dry spells and precipitation variability increase the exposure to land conflicts, the types of land conflict vary. Precipitation variability mainly increases exposure to

land conflicts between farmers and pastoralists, while dry spells predominantly increase all other types of land conflicts, such as within the family or with neighbors.

Our second main finding is that tenure security is dynamic over time and not just influenced by plot-level characteristics but also by larger-scale weather risk. Third, we add to the debate on interactions of tenure security, land conflicts, and land documentation by showing how exogenous shocks affect the three tenure security characteristics at the same time.

Finally, we contribute to the debate on land formalization, by documenting effects of weather risk on the acquisition of land certificates. These results are mixed: while precipitation variability significantly lowers the likelihood that farmers acquire a land certificate, dry spells – with a one-year time lag – are associated with increased acquisition of certificates. This difference in impact could be explained with the different conflict types driven by the respective weather events. Other potential channels include decreases in agricultural production as a result of weather risk, which is stronger in the case of precipitation variability.

One limitation of this study is its limited geographical scope. We caution that our findings may not be generalizable to the whole of Tanzania, as the household panel survey was merely implemented in six villages. Nevertheless, those study villages were selected to cover a wide range of Tanzanian farming systems and the land tenure system is characteristic of what has been termed the ‘new’ African customary land tenure (Chimhowu, 2019), which is increasingly formalized. Consequently, our findings hold potential relevance for regions with similar climate and where agriculturalists and pastoralists interact, particularly in semi-arid areas of East Africa and the Sahel.

As a further limitation, the nature of the survey does not allow for detailed intra-household analyses, which could mask important dynamics with respect to the perception of tenure security and the benefits of land certificates within the household.

Our findings shed light on some debated questions in land policy. Secure tenure is not only important for farmers to adapt to climate change, it is itself affected by weather risk, which is set to increase with progressing climate change. Given the strong link between dry spells, precipitation variability, and tenure security, improving the tenure security of smallholder farmers will likely grow in importance with increasing climate change. Otherwise, there is a risk of tenure insecure and vulnerable households being trapped in situations of insecure land tenure for sustained periods of time. The main policy implication is that land tenure interventions, such as land registration projects or conflict resolution programs, should consider farmers' vulnerability to weather risk and target its efforts accordingly.

Acknowledgements

We are grateful for helpful comments from Svenja Fluhrer, Bisrat Haile, Luitfred Kissoly, Giulia Malevolti, Lukas Mogge, Niklas Murken, Claudio Ngassa, Ephraim Nkonya, Nelson Ochieng, Julian Röckert, participants of the LANDac Conference 2021, the Households in Conflict (HiCN) Workshop 2021, the IASC Land Commons conference, the PEGNet Conference 2022, the CSAE Conference 2023, and the participants of the AAS PhD seminar at PIK. We particularly wish to thank Anja Faße, as well as research staff at the University of Hannover and the Sokoine University of Agriculture for implementing the panel survey and for making the data available to us. The research was funded by the German National Academic Foundation and the Agrica project funded by the German Federal Ministry for Economic Cooperation and Development (BMZ). The household survey was collected as a part of the Trans-SEC project (www.trans-sec.org), which was funded by BMBF and co-financed by BMZ. We also thank the Leibniz Centre for Agricultural Landscape Research (ZALF) for coordinating the Trans-SEC project. Responsibility for the content of this paper lies solely with the authors.

References

- Abadie, A., Athey, S., Imbens, G. W., & Wooldridge, J. M. (2022). When Should You Adjust Standard Errors for Clustering? *The Quarterly Journal of Economics*, forthcoming, <https://doi.org/10.1093/qje/qjac038>
- African Development Bank (2019). *Review of land tenure systems to support the creation of an enabling environment for agricultural transformation: Report on Tanzania*. 1–64. Available at: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/Review_of_the_land_tenure_systems_-_Report_on_Tanzania.pdf
- Aikaeli, J., & Markussen, T. (2022). Titling and the value of land in Tanzania. *Journal of International Development*, 34(3), 512–531. <https://doi.org/10.1002/jid.3615>
- Ali, D. A., Collin, M., Deininger, K., Dercon, S., Sandefur, J., & Zeitlin, A. (2016). Small price incentives increase women's access to land titles in Tanzania. *Journal of Development Economics*, 123, 107–122. <https://doi.org/10.1016/j.jdeveco.2016.06.001>
- Ali, D. A., Deininger, K., & Duponchel, M. (2017). New Ways to Assess and Enhance Land Registry Sustainability: Evidence from Rwanda. *World Development*, 99, 377–394. <https://doi.org/10.1016/j.worlddev.2017.05.016>
- Ali, D. A., Deininger, K., & Goldstein, M. (2014). Environmental and gender impacts of land tenure regularization in Africa: Pilot evidence from Rwanda. *Journal of Development Economics*, 110, 262–275. <https://doi.org/10.1016/j.jdeveco.2013.12.009>
- Arnot, C., Luckert, M., & Boxall, P. (2011). What Is Tenure Security? Conceptual Implications for Empirical Analysis. *Land Economics*, 87(2), 297–311. <https://www.jstor.org/stable/41307215>
- Auffhammer, M., Ramanathan, V. & Vincent, J.R. (2012). Climate change, the monsoon, and rice yield in India. *Climatic Change* 111, 411–424. <https://doi.org/10.1007/s10584-011-0208-4>
- Auffhammer, M., Hsiang, S. M., Schlenker, W., & Sobelz, A. (2013). Using weather data and climate model output in economic analyses of climate change. *Review of Environmental Economics and Policy*, 7(2), 181–198. <https://doi.org/10.1093/reep/ret016>
- Ayamga, M., Yeboah, R., & Dzanku, F. (2015). Determinants of Farmland Tenure Security in Ghana. *Ghana Journal of Science, Technology and Development*, 2(1), 1-21. <https://doi.org/10.47881/43.967x>
- Bélaïr, J. (2021). Farmland investments in Tanzania: The impact of protected domestic markets and patronage relations. *World Development*, 139. <https://doi.org/10.1016/j.worlddev.2020.105298>
- Benjaminsen, T A, Maganga, F. P., & Abdallah, J. M. (2009). The Kilosa killings: Political ecology of a farmer-herder conflict in Tanzania. *Development and Change*, 40(3), 423–445. <https://doi.org/10.1111/j.1467-7660.2009.01558.x>
- Bergius, M., Benjaminsen, T. A., Maganga, F., & Buhaug, H. (2020). Green economy, degradation narratives, and land-use conflicts in Tanzania. *World Development*, 129, 104850. <https://doi.org/10.1016/j.worlddev.2019.104850>
- Besley, T., & Ghatak, M. (2010). Property rights and economic development. *Handbook of Development Economics*, 5(C), 4525–4595. <https://doi.org/10.1016/B978-0-444-52944->

2.00006-9

- Bluwstein, J., Lund, J. F., Askew, K., Stein, H., Noe, C., Odgaard, R., Maganga, F., & Engström, L. (2018). Between dependence and deprivation: The interlocking nature of land alienation in Tanzania. *Journal of Agrarian Change*, 18(4), 806–830. <https://doi.org/10.1111/joac.12271>
- Boone, C., & Nyeme, L. (2015). Land institutions and political ethnicity in Africa: Evidence from Tanzania. *Comparative Politics*, 48(1), 67–86. <https://doi.org/10.5129/001041515816075123>
- Boone, C. (2014). *Property and Political Order in Africa: Land Rights and the Structure of Politics*. Cambridge University Press. <https://doi.org/10.1017/CBO9781139629256>
- Boone, C. (2017). Sons of the Soil Conflict in Africa: Institutional Determinants of Ethnic Conflict Over Land. *World Development*, 96, 276–293. <https://doi.org/10.1016/J.WORLDDEV.2017.03.012>
- Brüssow, K., Gornott, C., Faße, A., & Grote, U. (2019). The link between smallholders' perception of climatic changes and adaptation in Tanzania. *Climatic Change*, 157(3), 545–563. <https://doi.org/10.1007/s10584-019-02581-9>
- Buggle, J. C., & Durante, R. (2021). Climate Risk, Cooperation and the Co-Evolution of Culture and Institutions. *The Economic Journal*, 131(637), 1947–1987. <https://doi.org/10.1093/ej/ueaa127>
- Burke, M., Hsiang, S. M., & Miguel, E. (2015). Climate and Conflict. *Annual Review of Economics*, 7(1), 577–617. <https://doi.org/10.1146/annurev-economics-080614-115430>
- Butler, C. K., & Gates, S. (2012). African range wars: Climate, conflict, and property rights. *Journal of Peace Research*, 49(1), 23–34. <https://doi.org/10.1177/0022343311426166>
- Chimhowu, A. (2019). The 'new' African customary land tenure. Characteristic, features and policy implications of a new paradigm. *Land Use Policy*, 81, 897–903. <https://doi.org/10.1016/j.landusepol.2018.04.014>
- Coase, R. H. (1960). The problems of social cost. *The Journal of Law and Economics*, 3(October), 1–44.
- Copernicus Climate Change Service (C3S) (2017). ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Available at: <https://cds.climate.copernicus.eu/cdsapp#!/home>
- Deininger, K., & Chamorro, J. S. (2004). Investment and equity effects of land regularisation: The case of Nicaragua. *Agricultural Economics*, 30(2), 101–116. <https://doi.org/10.1016/j.agecon.2002.09.004>
- Deininger, K., & Feder, G. (2009). Land registration, governance, and development: Evidence and implications for policy. *World Bank Research Observer*, 24(2), 233–266. <https://doi.org/10.1093/wbro/lkp007>
- Deininger, K., & Castagnini, R. (2006). Incidence and impact of land conflict in Uganda. *Journal of Economic Behavior and Organization*, 60(3), 321–345. <https://doi.org/10.1016/j.jebo.2004.04.008>
- Dell, M., Jones, B. F., & Olken, B. A. (2012). Temperature Shocks and Economic Growth: Evidence from the Last Half Century. *American Economic Journal: Macroeconomics*, 4(3), 66–95. <https://doi.org/10.1257/mac.4.3.66>

- Dell, M., Jones, B. F., & Olken, B. A. (2014). What do we learn from the weather? The new climate-economy literature. *Journal of Economic Literature*, 52(3), 740–798. <https://doi.org/10.1257/jel.52.3.740>
- Dijksterhuis, A., & Bargh, J. A. (2001). The perception-behavior expressway: Automatic effects of social perception on social behavior. In *Advances in experimental social psychology* (Vol. 33, pp. 1-40). Academic Press.
- Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., & Ceccato, P. (2018). Validation of the CHIRPS satellite precipitation estimates over eastern Africa. *Quarterly Journal of the Royal Meteorological Society*, 144(January), 292–312. <https://doi.org/10.1002/qj.3244>
- Doss, C., Kovarik, C., Peterman, A., Quisumbing, A., & Van Den Bold, M. (2015). Gender inequalities in ownership and control of land in Africa: myth and reality. *Agricultural Economics*, 46(3), 403-434. <https://doi.org/10.1111/agec.12171>
- FAO. (2002). Land tenure and rural development. *FAO Land Tenure Studies*, ISBN 92-5-(Rome).
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific Data*, 2, 150066. <https://doi.org/10.1038/sdata.2015.66>
- Ghebru, H., & Girmachew, F. (2019). *Perceived Tenure (In)Security in the Era of Rural Transformation Gender-Disaggregated Analysis from Mozambique*, Feed the Future Innovation Lab for Food Security Policy Research Papers 303017, Michigan State University, Department of Agricultural, Food, and Resource Economics, Feed the Future Innovation Lab for Food Security (FSP).
- Ghebru, H., & Lambrecht, I. (2017). Drivers of perceived land tenure (in)security: Empirical evidence from Ghana. *Land Use Policy*, 66, 293–303. <https://doi.org/10.1016/J.LANDUSEPOL.2017.04.042>
- Graef, F., Sieber, S., Mutabazi, K., Asch, F., Biesalski, H. K., Bitegeko, J., Bokelmann, W., Bruentrup, M., Dietrich, O., Elly, N., Fasse, A., Germer, J. U., Grote, U., Herrmann, L., Herrmann, R., Hoffmann, H., Kahimba, F. C., Kaufmann, B., Kersebaum, K.-C., ... Uckert, G. (2014). Framework for participatory food security research in rural food value chains. *Global Food Security*, 3(1), 8–15. <https://doi.org/10.1016/j.gfs.2014.01.001>
- Greco, E. (2015). Landlords in the making: class dynamics of the land grab in Mbarali, Tanzania. *Review of African Political Economy*, 42(144), 225–244. <https://doi.org/10.1080/03056244.2014.992403>
- Higgins, D., Balint, T., Liversage, H., & Winters, P. (2018). Investigating the impacts of increased rural land tenure security: A systematic review of the evidence. *Journal of Rural Studies*, 61, 34-62. <https://doi.org/10.1016/j.jrurstud.2018.05.001>
- Holden, S. T., Deininger, K., & Ghebru, H. (2011). Tenure Insecurity, Gender, Low-cost Land Certification and Land Rental Market Participation in Ethiopia. *The Journal of Development Studies*, 47(1), 31–47. <https://doi.org/10.1080/00220381003706460>
- Holden, S. T., & Ghebru, H. (2016). Land tenure reforms, tenure security and food security in poor agrarian economies: Causal linkages and research gaps. *Global Food Security*, 10, 21–28. <https://doi.org/10.1016/j.gfs.2016.07.002>

- Hsiang, S. M., & Burke, M. (2014). Climate, conflict, and social stability: What does the evidence say? *Climatic Change*, *123*(1), 39–55. <https://doi.org/10.1007/s10584-013-0868-3>
- Hsiang, S. M., Burke, M., & Miguel, E. (2013). Quantifying the influence of climate on human conflict. *Science*, *341*(6151). <https://doi.org/10.1126/science.1235367>
- Huntington, H., & Shenoy, A. (2021). Does insecure land tenure deter investment? Evidence from a randomized controlled trial. *Journal of Development Economics*, *150*, 102632. <https://doi.org/10.1016/j.jdeveco.2021.102632>
- Jacoby, H. G., Li, G., & Rozelle, S. (2002). Hazards of expropriation: Tenure insecurity and investment in Rural China. *American Economic Review*, *92*(5), 1420–1447. <https://doi.org/10.1257/000282802762024575>
- Jenkins, A. C., Karashchuk, P., Zhu, L., & Hsu, M. (2018). Predicting human behavior toward members of different social groups. *Proceedings of the National Academy of Sciences*, *115*(39), 9696–9701. <https://doi.org/10.1073/pnas.1719452115>
- Kalkuhl, M., Schwerhoff, G., & Waha, K. (2020). Land tenure, climate and risk management. *Ecological Economics*, *171*, 106573. <https://doi.org/10.1016/j.ecolecon.2019.106573>
- Kendon, E. J., Stratton, R. A., Tucker, S., Marsham, J. H., Berthou, S., Rowell, D. P., & Senior, C. A. (2019). Enhanced future changes in wet and dry extremes over Africa at convection-permitting scale. *Nature Communications*, *10*(1). <https://doi.org/10.1038/s41467-019-09776-9>
- Koubi, V. (2019). Climate change and conflict. *Annual Review of Political Science*, *22*, 343–360. <https://doi.org/10.1146/annurev-polisci-050317-070830>
- Kotz, M., Levermann, A. & Wenz, L. (2022). The effect of precipitation changes on economic production. *Nature*, *601*, 223–227. <https://doi.org/10.1038/s41586-021-04283-8>
- Kubitza, C., Krishna, V. V, Urban, K., Alamsyah, Z., & Qaim, M. (2018). Land Property Rights, Agricultural Intensification, and Deforestation in Indonesia. *Ecological Economics*, *147*, 312–321. <https://doi.org/10.1016/j.ecolecon.2018.01.021>
- Laudien, R., Schauburger, B., Makowski, D., & Gornott, C. (2020). Robustly forecasting maize yields in Tanzania based on climatic predictors. *Scientific Reports*, *10*(1), 1–12. <https://doi.org/10.1038/s41598-020-76315-8>
- Lawry, S., Samii, C., Hall, R., Leopold, A., Hornby, D., & Mtero, F. (2017). The impact of land property rights interventions on investment and agricultural productivity in developing countries: a systematic review. *Journal of Development Effectiveness*, *9*(1), 61–81. <https://doi.org/10.1080/19439342.2016.1160947>
- Linkow, B. (2016). Causes and consequences of perceived land tenure insecurity: Survey evidence from Burkina Faso. *Land Economics*, *92*(2), 308–327. <https://doi.org/10.3368/le.92.2.308>
- Massay, G. (2013). Adjudication of land cases in Tanzania: A bird eye overview of the District Land and Housing Tribunal. *Open University Law Journal*, *4*(2), 167–182
- McGuirk, E. F., & Nunn, N. (2020). *Transhumant pastoralism, climate change, and conflict in Africa* (No. w28243). National Bureau of Economic Research.
- Notess, L., Veit, P., Monterroso, I., Andiko, Sulle, E., Larson, A. M., Gindroz, A.-S., Quaedvlieg, J., & Williams, A. (2021). Community land formalization and company land

- acquisition procedures: A review of 33 procedures in 15 countries. *Land Use Policy*, 110, 104461. <https://doi.org/10.1016/j.landusepol.2020.104461>
- Odgaard, R. (2003). Scrambling for Land in Tanzania: Process of Formalisation and Legitimation of Land Rights. In C. Benjaminsen, T.A., & Lund (Ed.), *Securing Land Rights in Africa (1st ed.)*. Routledge. <https://doi.org/10.4324/978020304588>
- Odgaard, R. (2005). *The struggle for land rights in the context of multiple normative orders in Tanzania*, in Evers, S., M. Spierenburg and H. Wels (eds.) 'Competing Jurisdictions: Settling Land Claims in Africa', Brill Publishers, Leiden, The Netherlands
- Pedersen, R. H. (2015). A Less Gendered Access to Land? The Impact of Tanzania's New Wave of Land Reform. *Development Policy Review*, 33(4), 415–432. <https://doi.org/10.1111/dpr.12121>
- Place, F., & Migot-Adholla, S. E. (1998). The economic effects of land registration on smallholder farms in Kenya: Evidence from Nyeni and Kakamega districts. *Land Economics*, 74(3), 360–373. <https://doi.org/10.2307/3147118>
- Platteau, J.-P. (1996). The Evolutionary Theory of Land Rights as Applied to Sub-Saharan Africa: A Critical Assessment. *Development and Change*, 27(1), 29–86. <https://doi.org/10.1111/j.1467-7660.1996.tb00578.x>
- Platteau, J. P. (2000). Allocating and enforcing property rights in land: informal versus formal mechanisms in Subsaharan Africa. *Nordic Journal of Political Economy*, 26(1), 55-81.
- Prindex. (2020). *Prindex Comparative Report - a global assessment of perceived tenure security from 140 countries*. Overseas Development Institute. Available at: <https://www.prindex.net/reports/prindex-comparative-report-july-2020/>
- Reerink, G., & van Gelder, J.-L. (2010). Land titling, perceived tenure security, and housing consolidation in the kampongs of Bandung, Indonesia. *Habitat International*, 34(1), 78–85. <https://doi.org/10.1016/j.habitatint.2009.07.002>
- Robinson, B.E., Diop, M. (2022). Who Defines Land Tenure Security? *De Jure and De Facto Institutions*. In: Holland, M.B., Masuda, Y.J., Robinson, B.E. (eds) *Land Tenure Security and Sustainable Development*. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-81881-4_3
- Robinson, B. E., Holland, M. B., & Naughton-Treves, L. (2014). Does secure land tenure save forests? A meta-analysis of the relationship between land tenure and tropical deforestation. *Global Environmental Change*, 29, 281–293. <https://doi.org/10.1016/j.gloenvcha.2013.05.012>
- Rubakula, G., Wang, Z., & Wei, C. (2019). Land conflict management through the implementation of the national land policy in Tanzania: Evidence from Kigoma region. *Sustainability (Switzerland)*, 11(22). <https://doi.org/10.3390/su11226315>
- Rwegasira, A. (2012). *Land as a human right - a history of land law and practice in Tanzania*. Mkuki na Nyota Publishers. <https://doi.org/10.2307/j.ctvk3gmx4>
- Sarsons, H. (2015). Precipitation and conflict: A cautionary tale. *Journal of Development Economics*, 115, 62–72. <https://doi.org/10.1016/j.jdeveco.2014.12.007>
- Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences*, 106(37), 15594 LP – 15598. <https://doi.org/10.1073/pnas.0906865106>

- Schreiber, L. (2017). *Registering Rural Rights: Village Land Titling in Tanzania, 2008-2017*. 2008–2017. Global Challenges Land: Tanzania. Available at: https://successfulsocieties.princeton.edu/sites/successfulsocieties/files/LS_Tanzania_Land_GC_CC_1.pdf
- Sipangule, K. (2017). Agribusinesses, Smallholder Tenure Security and Plot-level Investments: Evidence from Rural Tanzania. *African Development Review*, 29, 179–197. <https://doi.org/10.1111/1467-8268.12271>
- Sjaastad, E. and Bromley, D.W. (2000), The Prejudices of Property Rights: On Individualism, Specificity, and Security in Property Regimes. *Development Policy Review*, 18: 365–389. <https://doi.org/10.1111/1467-7679.00117>
- Sjaastad, E., & Cousins, B. (2009). Formalisation of land rights in the South: An overview. *Land Use Policy*, 26(1), 1–9. <https://doi.org/10.1016/j.landusepol.2008.05.004>
- Tseng, T. W. J., Robinson, B. E., Bellemare, M. F., BenYishay, A., Blackman, A., Boucher, T., Childress, M., Holland, M. B., Kroeger, T., Linkow, B., Diop, M., Naughton, L., Rudel, T., Sanjak, J., Shyamsundar, P., Veit, P., Sunderlin, W., Zhang, W., & Masuda, Y. J. (2021). Influence of land tenure interventions on human well-being and environmental outcomes. *Nature Sustainability*, 4(3), 242–251. <https://doi.org/10.1038/s41893-020-00648-5>
- Valsecchi, M. (2014). Land property rights and international migration: Evidence from Mexico. *Journal of Development Economics*, 110, 276–290. <https://doi.org/10.1016/j.jdeveco.2014.01.010>
- van Gelder, J.-L. (2010). What tenure security? The case for a tripartite view. *Land Use Policy*, 27(2), 449–456. <https://doi.org/10.1016/j.landusepol.2009.06.008>
- Walwa, W. J. (2020). Growing farmer-herder conflicts in Tanzania: the licenced exclusions of pastoral communities interests over access to resources. *Journal of Peasant Studies*, 47(2), 366–382. <https://doi.org/10.1080/03066150.2019.1602523>
- Wily, L.A., 2003. Community-based land tenure management – Questions and answers about Tanzania’s new Village Land Act, 1999. Issue paper no.120, International Institute for Environment and Development, London.
- Wooldridge, J.M. (2013). *Introductory econometrics: A modern approach* (5thed.) Cengage Learning Publishers.
- World Bank. (2018). *Land Tenure Improvement Project Information Document: Tanzania*. Available at: <https://documents1.worldbank.org/curated/en/934461589985643361/pdf/Project-Information-Document-Land-Tenure-Improvement-Project-P164906.pdf>
- Yi, Y., Köhlin, G., & Xu, J. (2014). Property rights, tenure security and forest investment incentives: Evidence from China’s Collective Forest Tenure Reform. *Environment and Development Economics*, 19(1), 48–73. <https://doi.org/10.1017/S1355770X13000272>

Tables

Table 1: Description of key variables.

Variable name	Variable description
Perceived tenure security	Household owns at least one plot that it perceives as ‘very tenure secure’
Land conflict	Household experienced a land conflict in the previous 12 months
New land certificate	Household acquired a new land certificate for a plot since the last panel wave, or newly acquired a plot with a land certificate
Dry spell	Number of times a dry spell of 15 consecutive dry days (CDD15) occurred in the previous growing season, with each day < 0.5 mm precipitation
Precipitation CV	Coefficient of variation of the daily precipitation sum in the previous growing season
Median temperature	Median of the daily mean temperature in the previous growing season
Agricultural production	Crop production in kg per ha in the previous season
Total net income	Net annual household income, adjusted for purchasing power parity (PPP) and converted to 2011 USD
Net wage income	Net annual wage income, adjusted for purchasing power parity (PPP) and converted to 2011 USD
Wage employment	At least one household member was employed as wage laborer in the year preceding the interview

Table 2: Summary statistics for key variables.

Variable type	Variable name	Mean	St. Dev.	Min	Max	N
Dependent variables						
	Perceived tenure security (wave 1)	0.36	0.48	0	1	763
	Perceived tenure security (wave 2)	0.53	0.50	0	1	760
	Perceived tenure security (wave 3)	0.86	0.35	0	1	777
	Land conflict (wave 1)	0.10	0.30	0	1	741
	Land conflict (wave 2)	0.09	0.29	0	1	763
	Land conflict (wave 3)	0.09	0.29	0	1	773
	Pastoral land conflict (wave 1)	0.03	0.16	0	1	741
	Pastoral land conflict (wave 2)	0.06	0.24	0	1	763
	Pastoral land conflict (wave 3)	0.07	0.26	0	1	773
	Other land conflict (wave 1)	0.07	0.26	0	1	741
	Other land conflict (wave 2)	0.04	0.18	0	1	763
	Other land conflict (wave 3)	0.02	0.15	0	1	773
	New land certificate (wave 2)	0.02	0.14	0	1	766
	New land certificate (wave 3)	0.14	0.35	0	1	766
Main explanatory variables						
	Dry spell (wave 1)	0.19	0.39	0	1	778
	Dry spell (wave 2)	0.41	0.49	0	1	778
	Dry spell (wave 3)	1.45	0.50	0	2	778
	Precipitation CV (wave 1)	2.02	0.17	1.67	2.31	778
	Precipitation CV (wave 2)	1.74	0.16	1.47	2.03	778
	Precipitation CV (wave 3)	1.54	0.12	1.35	1.86	778
Weather controls						
	Median temperature (wave 1)	24.95	0.69	22.69	25.65	778
	Median temperature (wave 2)	24.84	0.70	22.90	25.61	778
	Median temperature (wave 3)	23.66	0.74	22.02	24.46	778
Household and farm controls						
	Household size (wave 1)	4.91	2.26	1	18	778
	Household size (wave 2)	5.28	2.33	1	19	778
	Household size (wave 3)	5.37	2.32	1	15	778
	Household owns livestock (wave 1)	0.67	0.47	0	1	778
	Household owns livestock (wave 2)	0.82	0.39	0	1	778
	Household owns livestock (wave 3)	0.82	0.39	0	1	778
	Farm size (in ha) (wave 1)	1.60	1.03	0.00	6.07	770
	Farm size (in ha) (wave 2)	1.69	1.03	0.02	6.27	771
	Farm size (in ha) (wave 3)	1.51	0.92	0.002	6.18	777
	Number of plots (wave 1)	2.59	1.16	1	7	770
	Number of plots (wave 2)	2.45	1.05	1	7	766
	Number of plots (wave 3)	2.82	1.24	1	7	777
Main channels						
	Agricultural production (kg/ha) (wave 1)	1,643.55	2,155.63	0.00	14,645.78	739
	Agricultural production (kg/ha) (wave 2)	1,647.68	1,849.42	0.00	11,627.17	752
	Agricultural production (kg/ha) (wave 3)	3,079.35	4,323.61	204.99	33,286.53	773
	Total net income (wave 1)	1,499.74	1,766.98	-584.70	10,306.70	778
	Total net income (wave 2)	1,692.99	1,995.52	-235.69	11,821.62	778
	Total net income (wave 3)	2,137.04	2,188.23	-252.26	11,385.66	778
	Net wage income (wave 1)	276.14	1,086.49	0.00	17,060.92	778

Net wage income (wave 2)	138.00	386.48	0.00	7,056	778
Net wage income (wave 3)	224.10	627.45	0.00	10,277	778
Wage employment (wave 1)	0.35	0.48	0	1	778
Wage employment (wave 2)	0.42	0.49	0	1	778
Wage employment (wave 3)	0.39	0.49	0	1	777

Data sources: Trans-SEC household panel survey (waves 1-3), CHIRPS (precipitation) and ERA5 (temperature). The balanced sample comprises 778 households surveyed in all three waves. For some households, information is missing for some variables.

Table 3: Effects of weather on perceived tenure security (OLS).

Dependent variable:	Perceived tenure security			
	(1)	(2)	(3)	(4)
Dry spell	-0.05 *** (0.01)	-0.05 *** (0.01)		
Precipitation CV			-0.23 *** (0.05)	-0.23 *** (0.06)
Median temperature	-0.20 (0.13)	-0.20 (0.13)	-0.06 (0.08)	-0.06 (0.08)
Household controls	No	Yes	No	Yes
Household fixed effects	Yes	Yes	Yes	Yes
Enumerator fixed effects	Yes	Yes	Yes	Yes
Wave fixed effects	Yes	Yes	Yes	Yes
R ²	0.79	0.79	0.79	0.79
N	2,288	2,288	2,288	2,288

Note: Standard errors are clustered at the level of the precipitation data points with * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Data sources: Trans-SEC household panel survey (waves 1-3), CHIRPS (precipitation) and ERA5 (temperature).

Table 4: Effects of weather on land conflict (OLS).

Dependent variable:	Any land conflict				Conflicts with pastoralists		Other land conflicts	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dry spell	0.05 *** (0.01)	0.05 *** (0.01)			0.02 * (0.01)		0.03 *** (0.01)	
Precipitation CV			0.16 *** (0.02)	0.16 *** (0.03)		0.10 *** (0.02)		0.06 *** (0.02)
Median temperature	-0.13 *** (0.04)	-0.13 *** (0.04)	-0.25 *** (0.07)	-0.25 *** (0.08)	-0.11 ** (0.04)	-0.17 ** (0.07)	-0.02 (0.02)	-0.08 *** (0.02)
Household controls	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Household fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Enumerator fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wave fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R ²	0.52	0.52	0.52	0.52	0.55	0.56	0.46	0.45
N	2,266	2,266	2,266	2,266	2,266	2,266	2,266	2,266

Note: Standard errors are clustered at the level of the precipitation data points with * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Data sources: Trans-SEC household panel survey (waves 1-3), CHIRPS (precipitation) and ERA5 (temperature).

Table 5: Effects of weather on the acquisition of land certificates (OLS).

Dependent variable:	New land certificate					
	(1)	(2)	(3)	(4)	(5)	(6)
Dry spell (lag 1)	0.04 *** (0.01)	0.03 *** (0.01)	0.03 *** (0.01)			
Dry spell		-0.02 (0.02)	-0.01 (0.02)			
Precipitation CV (lag 1)				-0.06 * (0.03)	-0.21 *** (0.05)	-0.16 ** (0.06)
Precipitation CV					-0.27 *** (0.08)	-0.22 ** (0.09)
Median temperature	0.13 *** (0.04)	0.06 (0.10)	0.07 (0.08)	0.14 *** (0.04)	-0.02 (0.04)	0.01 (0.05)
Household controls	No	No	Yes	No	No	Yes
Household fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Enumerator fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Wave fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
R ²	0.66	0.66	0.68	0.66	0.67	0.68
N	1,521	1,521	1,516	1,521	1,521	1,516

Note: Standard errors are clustered at the level of the precipitation data points with * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Data sources: Trans-SEC household panel survey (waves 1-3), CHIRPS (precipitation) and ERA5 (temperature).

Table 6: Potential weather impact channel (OLS).

Dependent variable:	Agricultural production (kg/ha) (inverse hyperbolic sine)		Net household income (inverse hyperbolic sine)		Net wage income (inverse hyperbolic sine)		Wage employment	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dry spell (lag 1)	-0.11 ** (0.05)		0.12 (0.08)		0.22 (0.16)		0.03 (0.02)	
Dry spell	-0.45 *** (0.02)		-0.18 *** (0.06)		0.14 * (0.07)		0.02 ** (0.01)	
Precipitation CV (lag 1)		-0.25 (0.24)		0.43 (0.54)		0.84 ** (0.32)		0.14 (0.09)
Precipitation CV		-1.30 *** (0.08)		-0.94 *** (0.30)		0.88 *** (0.26)		0.13 *** (0.04)
Median temperature	-1.02 (0.84)	-0.08 (0.62)	-0.33 (0.38)	0.34 (0.31)	2.41 *** (0.65)	2.16 *** (0.53)	0.34 *** (0.09)	0.30 *** (0.07)
Household controls	No	No	No	No	No	No	No	No
Household fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Enumerator fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wave fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R ²	0.58	0.57	0.39	0.40	0.58	0.58	0.58	0.58
N	2,252	2,252	2,322	2,322	2,322	2,322	2,321	2,321

Note: Standard errors are clustered at the level of the precipitation data points with * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Data sources: Trans-SEC household panel survey (waves 1-3), CHIRPS (precipitation) and ERA5 (temperature).

Figure titles

Figure 1: Number of households experiencing different types of land conflict, by wave. Data source: Trans-SEC household panel survey (waves 1-3).

Footnotes

ⁱ The focus group discussions were conducted as part of a follow-up project jointly carried out by Ardhi University and PIK. Focus groups were held with farmers and village leaders, the primary discussion topic was the implementation of agroforestry systems in the villages. We are grateful to Luitfred Kissoly and Nelson Ochieng for implementing the focus group discussions.

ⁱⁱ Unconditional t-tests on differences in means indicate that dropped households do not differ significantly in their perceived tenure security and the reported incidence of land conflicts from households that remained in the panel (Table A1 in the Appendix). Next, we run a probit regression on the determinants of the probability of a household being interviewed in all three panel waves, using the same set of control variables as in the baseline model (Table A2 in the Appendix). Tenure security and the experience of land conflicts, the key variables of interest, are not significantly correlated with households being interviewed in all three waves. Few other explanatory variables are statistically significant and those that are have relatively small effect sizes. An added regressor test points into the same direction (Table A3 in the Appendix): When regressing the experience of land conflicts or households' perceived tenure security on the main set of control variables constructed from wave 1 data, a dummy variable for panel attrition, and interaction terms between the attrition dummy and all control variables, the attrition dummy is not statistically significant at conventional levels in either model. Note, however, that livestock ownership has heterogeneous effects: While for households that stayed in the panel, the ownership of livestock is significantly and negatively correlated with the experience of land conflicts, this relation is significant and positive for households that dropped out of the survey. The effect is no longer significant if we instead employ the number of livestock (Table A3, col. 2 and 3). For both outcomes, a likelihood ratio test on the null hypothesis that the interaction terms are jointly zero reveals that the model with interaction terms does not fit significantly better, with a p-value of 0.42 in the land conflicts regression and 0.65 in the tenure security regression.

ⁱⁱⁱ More precisely, data collection took place January-March 2014 (wave 1), November-December 2016 (wave 2), and November-December 2018 (wave 3). The reference period for questions on agricultural production is January-December 2013 (wave 1), September 2015-August 2016 (wave 2), and October 2017-September 2018 (wave 3).

^{iv} In the survey, plots were not assigned unique identifiers, as the survey implementers did not originally intend to match plots across waves. Rather, survey items were asked at plot-level to record agricultural productivity as precisely as possible. Thus, we matched plots for each household based on the following criteria: main use of the plot, size, and mode of acquisition. Specifically, we matched plots if at least two of the three criteria matched across waves. As the plot size was at times difficult to estimate for respondents, we allowed for a divergence of the precise number of up to 25%. If the main use of the plot was 'homestead' in one of the waves, we only considered it a match if this plot was labelled as 'homestead' in all three waves. However, for the homestead we tolerated larger divergence in plot size across waves, since the homestead plots are usually rather small. For the other possible land uses (e.g., 'annual crops' or 'permanent crops') we tolerated divergences if the other criterion matched. In some cases, households possessed only one plot in each wave, but only one of the above criteria matched. In these cases, we examined additional characteristics to facilitate plot matching. Such auxiliary information was derived from the plot's position in the plot roster used in the questionnaire and the tenure status.

^v Unconditional t-tests on the equality of means shows that matched and unmatched plots do not differ significantly in their perceived tenure security and reported incidence of land conflicts (Table A4 in the Appendix). However, they are significantly different in their size; plots that cannot be matched over time are larger on average. There is also a slight difference with regard to land certificates attached to plots, with matched plots being more likely to be certified. As for the household-level attrition analysis, we run a probit regression on the determinants of plots being matched over all three survey waves (Table A5 in the Appendix). Land certificates, livestock ownership, and the plot size are significantly correlated with plots being matched over time, albeit with rather small effect sizes. An added regressor test (Table A6 in the Appendix) reveals that the attrition dummy is statistically significant only in the tenure security model. The coefficient is positive and sizeable, potentially

explaining the smaller weather effect observed in the plot-level analysis compared to the household-level analysis (Table A14 in the Appendix).

^{vi} Unfortunately, no information was recorded on the intensity of the conflict. However, some households reported crop losses due to livestock intrusion onto their land.

^{vii} For 50 households, no GPS data are available. For these cases, we draw on information on the sub-village location and impute precipitation and temperature over the respective sub-village (out of a total of 48 sub-villages).

^{viii} Across the three waves, 68 enumerators conducted the survey interviews, with most enumerators only joining the team during one panel wave. Auxiliary regressions revealed that enumerators were systematically assigned to sample households in which the head exhibited similar demographic characteristics. When removing enumerator fixed effects, the effects of weather risk on land conflicts and the acquisition of a land certificate remain qualitatively similar to baseline estimations, while the effects of weather risk are no longer statistically significant for the tenure security outcome. This can potentially be explained by different levels of subjectivity and sensitivity inherent in those outcomes. During survey interviews, the role of enumerators may be more influential when asking respondents about their perceived tenure security compared to asking respondents about the possession of land certificates or the experience of land conflicts. F-tests comparing models with and without enumerator fixed effects support the inclusion of enumerator fixed effects.

^{ix} Clustering standard errors at the household or village level yields only minimally larger standard errors. All main effects remain significant at least at the 10% level, except for the effect of precipitation variability on the acquisition of a new land certificate.

^x In Tanzania, all land is vested in the president, which means it cannot formally be owned by farmers. As such, the president has considerable power over land and can for instance transfer land from one category to another (village land, reserve land, general land), which also influences the way the land is governed and the purposes it can be used for. The state can also obtain land for public purposes, e.g. infrastructure development. In theory, if the state wants to acquire land for public purposes, it needs to notify and consult the affected landowners and determine and pay a just and fair compensation based on the market value of the land. In the case of customary land tenure, a consultative process with the community needs to be held. However, in practice, the implementation of these regulations varies.

