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Cropping System Dynamics, Climate Variability, and Seed Losses among East African Smallholder Farmers: A Retrospective Survey

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ABSTRACT

Climate variability directly affects traditional low input and rain-fed farming systems, but few studies have paid attention retrospectively to the cropping system's ability to mitigate climate risk. This study analyzes the impacts of rainfall variability on farmers' seed variety losses over time, considering changes in smallholder farming systems. The cropping system dynamics, in favoring maize at the expense of sorghum and pearl millet, have induced an increasing risk of seed loss during drought. Combining ecological anthropology and climatology, a retrospective survey asking farmers about the period 1961–2006 was carried out at three altitudinal levels (750, 950, and 1100 m) on the eastern slope of Mount Kenya. Over that period, based on 3204 seed loss events reported orally and independently by 208 farmers, the probability to lose sorghum seed (0.056–0.065) was significantly lower than the probability to lose maize seed (0.071–0.087). All crops were more impacted by droughts than by very wet years. Seed loss probability increased for rainy seasons shorter than 50 days, with less than 28 rain days, and with a precipitation amount under 400 mm. Losses are almost linearly related to the frequency of rain days. Logistic regression confirmed that a change in cropping systems, favoring maize at the expense of sorghum and pearl millet, increased the risk of seed losses due to drought over the 46-yr period.

1. Introduction

Mitigating the impacts of climate variability on smallholder rain-fed agriculture remains a challenge to ensure food security and to reduce poverty, notably in Africa, where it is the source of livelihood for the majority of the rural population. Historically, rainfall variability, including droughts, has been a major cause of famines (Glantz 1987), affecting smallholder rain-fed agriculture.

According to [FAO \(2008\)](#), climate events such as extreme droughts have played an important role in crop diversity changes. Comparing 15 major farming systems around the world, [Hyman et al. \(2008\)](#) and [Waddington et al. \(2010\)](#) noted that high drought risk areas coincide with those of high levels of poverty.

[Lobell et al. \(2008\)](#) used crop models and climate projections for 2030, analyzing climate risks for crops in 12 food-insecure regions. Negative impacts of climate change on yield are expected to be more important for maize than for sorghum in southern Africa, and for cowpea than for sorghum in East Africa. Similar analyses have been carried out on maize in Africa and Latin America ([Jones and Thornton 2003](#)), on maize and

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beans in East Africa (Thornton et al. 2009), and on sorghum and millet in West Africa (Sultan et al. 2013). However, these projections neglected the cropping system dynamics, and often simulated one crop at a time, whereas smallholder rain-fed agriculture favors multi-cropping systems.

Smallholder rain-fed agriculture systems are today increasingly dynamic, notably under the impulsion of agricultural policies encouraging adoption of maize in place of sorghum and pearl millet in arid and semiarid areas. Despite the fact that maize is known to be more susceptible to drought than traditional crops such as sorghum and pearl millet, this crop was widely accepted by farmers; Ouma et al. (2002) observed increasing rates of maize adoption from 1965 in Kenya. Maize became a dominant food crop through the 1990s in Kenya, Zimbabwe, Zambia, and Malawi (Smale and Jayne 2003). The partial conversion from sorghum and pearl millet to maize has never been considered as a factor potentially increasing the impact of climate variability on smallholder rain-fed multicropping systems. Models simulating crop response to future climates not only considered one crop at a time but also assumed the same use of current varieties with unchanged cultural practices (Jones and Thornton 2003; Thornton et al. 2009).

Combining ecological anthropology and climatology, our study analyzes impacts of past rainfall variability on East African smallholders agriculture systems, considering also their dynamics. While usual approaches consider present-day characteristics of agricultural systems to assess their adaptability to hypothetical rainfall variability (projection into the future), our study used a retrospective survey to look into the past. Thus, past rainfall variability is already known, not hypothetical, while farmers' knowledge allows recognizing the evolution of their past agricultural systems. Indeed, considering the year they adopted (or abandoned) each crop/variety, the dynamics of their cropping systems can be monitored over time. Do these dynamics affect the cropping system adaptability to climate variability? While this question is usually treated using yield parameter, it is documented here through seed losses, which is consistent with a multicrop system approach.

Assessing the vulnerability of rain-fed agriculture systems to extreme rainfall events is particularly relevant in Kenya. In smallholder farming systems, varieties mostly do not originate from the formal seed system but correspond to distinct morphotypes (landraces) that are selected, named, and managed by farmers from season to season. Here designated as "farmers' varieties," they remain a key component of agriculture systems in semiarid areas. Indeed, a large proportion of the seed is self-reproduced by farmers in a traditional way, as

in many other countries (see Leclerc and Coppens d'Eeckenbrugge 2012 for a synthesis). Such a farming system is based on a continuous link between harvesting and planting, which can be interrupted by crop failures and seed losses due to extreme rainfall events.

Farmers in Kenya manage two cropping seasons per year, corresponding to the short rains from October to December and to the long rains from March to May. The analysis of seed losses due to rainfall variability is limited here to the long rains for agronomic and climatic reasons. Crop variety life cycles can be short (i.e., the cycle is completed within a single growing season, from October to February or from March to June) or long (from October to July, spanning two growing seasons). In the latter case, "ratoon" varieties are used. Farmers start farming in October by sowing both single-season and ratoon varieties. In February, farmers harvest the single-season varieties and cut the ratoon varieties. The root system of ratoon varieties allows waiting for the next rainy season to complete their growth. When the rains come back in March, farmers sow again the single-season varieties, which are harvested in June, while the ratoon varieties resume their growth and are harvested in July. As both single-season and ratoon varieties are sown in October at the beginning of the short rains, seed availability is thus crucial at this time. The seed is selected from harvests at the end of the long rains (June and July). Crop failures during the long rains can thus interrupt the continuum in seed availability.

The interannual variations in seasonal rainfall during the long rains are poorly predictable, and result from a combination of many features, partly independent from each other, which include variations in onset, number of rain days, rainfall intensity, and cessation date (Camberlin et al. 2009). Mwongera et al. (2014) showed that the risk of crop failure 15 days after germination is 6.7 times higher for the long rains than for the short rains, because of the difficulty in predicting the onset, the irregularity of rain days, and the length of dry spells during the crop emergence phase. In sum, farmers face a difficult challenge during the long rains: this season is crucial to perpetuate their varieties over time, but with a high risk of seed losses.

On Mount Kenya, strong vertical gradients in both temperature and precipitation along the slope of the mountain result in a marked agroecological zonation (Jaetzold et al. 2007). Recently, Camberlin et al. (2014) documented the vertical (altitudinal) and horizontal variability of precipitation, including the intraseasonal distribution of the long rains. The seasonal amount of precipitation steadily increases uphill as well as the duration of the season, which increases at a rate of 3.6 days $(100\text{ m})^{-1}$. Thus, to assess the impacts of the long rains'

seasonal variability on seed losses, our retrospective survey was carried out at three altitudinal levels (750, 950, and 1100 m), for the period from 1961 to 2006. We asked farmers about the years they adopted (or abandoned) each crop, and for each variety the years they lost the seed consecutively to crop failure. Here “seed loss” refers to the fact that the seed selected by a farmer to perpetuate a given variety was lost, whether or not he/she later recovered this variety from another farmer’s seed lot.

From 1961 to 2006, we can fear that the farming system had lost part of its capacity to mitigate the risk of seed loss, as maize is known to be less resistant to drought than sorghum and pearl millet. Indeed, in Kenya, as in other countries, some farmers adopted maize only a few years ago, and are still cultivating traditional sorghum and pearl millet varieties, while others abandoned these varieties earlier in favor of maize. Farming systems were thus intrinsically dynamic with different crop assemblages over time, implying that in retrospect their capacity to mitigate the risks of seed losses due to extreme rainfall events was never constant. In such a context, ecological and social components cannot be analytically isolated but have to be considered as parts of a socioecological system. Is the probability to lose the seed the same for different crops when faced with extreme rainfall events? How do the different components of the rainy seasons contribute to seed losses?

2. Materials and methods

a. Rainfall data

The Kenya Meteorological Department provided rainfall data from three stations in the neighborhood of surveyed farmers. The three stations—namely, Ishiara (0.45°S, 37.78°E, altitude 872 m), Mitunguu (0.10°S, 37.78°E, altitude 1189 m), and Embu (0.50°S, 37.45°E, altitude 1433 m)—are located at three different altitudinal levels (low, mid-, and high levels, respectively). Their monthly and daily rainfall records, encompassing the period 1961–2006, were extracted from the recent analysis of [Camberlin et al. \(2014\)](#). The onset date of the rainy season was defined following criteria similar to those used by [Sivakumar \(1988\)](#), [Dodd and Jolliffe \(2001\)](#), and [Marteau et al. \(2009\)](#) as the first wet day of the first 2-day period recording at least 20 mm, not followed by a 10-day dry sequence, receiving less than 5 mm, in the next 20 days. To enable comparisons between the onset and the cessation of the rains, a symmetrical definition was adopted by [Camberlin et al. \(2014\)](#) for the cessation date of the rainy season (i.e., the last wet day of the last 2-day period recording at least

20 mm, not preceded by a 10-day dry sequence, receiving less than 5 mm, in the previous 20 days). The onset and cessation dates of the long rains were determined by considering the February–June subperiods. The duration of the rainy seasons (Dur) was computed as the length in days between the onset and the cessation dates, as well as the number of rain days over 1 mm (Nrd) and the seasonal amount (Ptot). The frequency of rain days during the rainy season (Frd) was computed as the number of rain days divided by the duration of the rainy season. Finally, the daily mean intensity (Int) of the rains was computed as the seasonal rainfall amount divided by the number of rain days. The interannual variability of temperature was not considered, since it is low (standard deviations of 0.56° and 0.74°C for March–May at high and low elevations, respectively ([Camberlin et al. 2014](#)), with a negligible impact of the interannual variations on the crop water demand.

b. Retrospective survey

A total of 208 farms were surveyed at three altitudinal levels across three Meru communities: 45 at 750 m, 93 at 950 m, and 70 at 1100 m ([Fig. 1](#)). The survey focused mainly on female farmers (126 females in contrast to 82 males), as farming activities are mainly their domain. The mean age declared by the respondents was 66 years old (minimum 26, maximum 99). Old farmers allowed a retrospective analysis of the dynamics of their cropping systems during the past decades. Farm distribution does not perfectly match that of the location of the three rainfall stations. However, a comparison with other stations located within the same altitudinal belts on the eastern slopes of Mount Kenya, but having shorter records, revealed strong correlations between the interannual rainfall variability at all these stations. This spatial coherence makes us feel confident about both the quality of the rainfall data and the farm sampling strategy. Thus, the lowest rainfall station was associated with low-altitudinal on-farm surveys, and so forth for mid- and high levels.

The retrospective survey was carried out in October 2009 by using the independent interview technique, whereby each farmer was interviewed individually and not in a group setting. Thus, the responses given by an individual farmer were not influenced by those given by a different farmer. The survey was done in the local language, which was the native language of the surveyor. Seed loss recall data were collected without referring to climate or to rainfall variation in the questions. For each variety, the year of its first acquisition, years of seed loss events, and, for each event, reasons given by farmers to explain it, were recorded. Farmers’ variety names were used to track seed loss events over time, as they

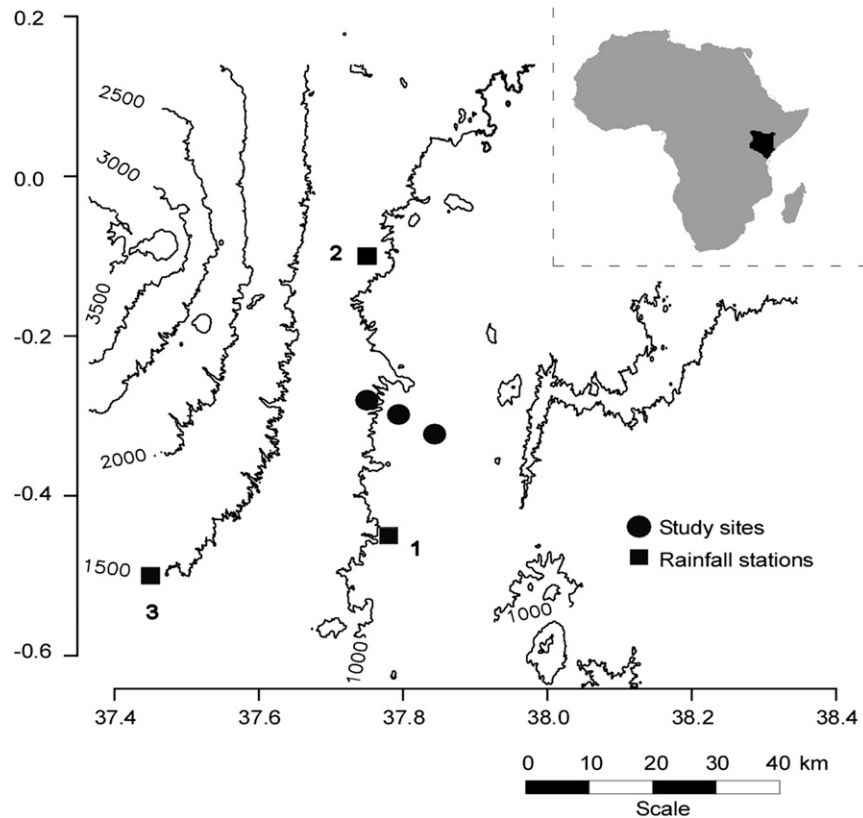


FIG. 1. Study site: the eastern slope of Mount Kenya. Farmers surveyed (solid circles) and rainfall stations (solid squares); 1—Ishiara (872 m), 2—Mitunguu (1189 m), and 3—Embu (1433 m). Contours show the altitudes in meters above sea level.

represent a distinct genetic (Soler et al. 2013) and morphological unit (Teshome et al. 1997; Louette et al. 1997).

In relation to their age distribution, farmer sample size decreased as time goes back. In 1961, 70 farmers were cultivating at least one crop variety; this size corresponds to the oldest 2009 respondents. On average each year 169 farmers were considered in the analysis. The number of farmer crop variety is for each crop the total number of different farmer variety pairs.

Our retrospective survey implied that the number of farmers considered was not constant, as old farmers started cultivating earlier than young farmers. Once a new crop was adopted by an individual farmer, this crop was usually still cultivated the year after, but, depending on new adoptions or abandons, the number of crops and the number of varieties cultivated per crop were never the same over time. Binomial error and logistic analyzes allowed controlling these variations by focusing on the proportion of lost seed. Each year was thus individually considered to determine the number of cultivated varieties, the number of farmers, and the

number of seed loss events in order to compute the proportion of lost seed.

c. Data analysis

We first considered seed losses during the entire 1961–2006 period, before analyzing the proportion of lost seed on a yearly basis, controlling for altitude and rainfall variables (Dur, Nrd, Ptot, Frd, and Int). To understand the effect of the different components of the rainy season on seed losses, analysis was carried out crop by crop, and on the whole farming system.

Crop responses to climate variability were analyzed by using logistic and smoothing models, the proportion of lost seed being the response variable. In both models, fitted values equal the logarithm of the odds. They can be transformed to probability using model parameters ($\alpha + \beta x$) and exponential function (Agresti 2007): $P(x) = \frac{\exp^{\alpha + \beta x}}{1 + \exp^{\alpha + \beta x}}$.

1) CROPPING SYSTEM DYNAMICS

The cropping system dynamics were assessed considering the variation in the crop assemblages on each farm

from 1961 to 2006. The area planted to a given crop was estimated using the number of varieties belonging to this crop, following the correlation between variety richness and crop popularity (Jarvis et al. 2008). Cropping system dynamics were thus shown as the interannual variations of the average number of varieties per crop and per farmer. This statistic was computed by considering the number of active farmers for each year of the period, thus avoiding the potential bias due to the interannual variation in farmer sample size. Considering the chronological evolution of the numbers of varieties per crop and per farmer, Pearson's correlation test was implemented to know which crops were substituted by which others. A positive correlation between two crops implied that both became synchronically more (or less) popular from 1961 to 2006, whereas a negative correlation implied increasing popularity for one and decreasing popularity for the other.

2) CROP AND ALTITUDINAL EFFECTS ON SEED LOSSES

The proportion of lost seed was analyzed at each altitudinal level during the period 1961–2006, first without considering rainfall. This proportion was thus considered per crop and computed as the total number of seed loss events divided by the total number of varieties cultivated by all farmers during the period. A backward elimination procedure (Agresti 2007; Crawley 2007) was used to select the minimal adequate model (model 1) to assess the marginal effect of crop, and of altitudes, on the proportion of lost seed (response variable). Goodness of fit, D^2 , which is similar to R^2 in linear regression, corresponds to the percentage of explained deviance. It was estimated in each model by comparing null deviance to residual deviance of the minimal adequate model, $D^2 = 1 - (\text{model deviance}/\text{null deviance})$. Model 1 was formalized as follows: $\log(p/1 - p) = \alpha + \beta_1 \text{crop}_i + \beta_2 \text{alt}_j + \epsilon$, where p is the proportion of lost seed, $i = 1-8$ crops, $j = 1-3$ levels (low, mid-, and high levels, respectively). Weighted regression was carried out, using logit link function to ensure linearity, which was confirmed graphically. Sample sizes were the total numbers of varieties, grouped by crop and by altitude.

3) IMPACTS OF RAINFALL VARIATIONS ON SEED LOSSES

(i) Crop response to extreme rainfall events

Rainfall characteristics, notably the maximum and minimum seasonal amounts (Ptot), depend on altitude. To control this interaction, (i) the seasonal amount was transformed into ranked deciles and (ii) this transformation was done separately for each altitudinal level,

allowing testing of the variety response to extreme dry conditions (i.e., the first deciles). The cells' Pearson residuals were used as descriptive statistics of the crops (lines) by rainfall deciles (columns) contingency table. The chi-square statistic, from Monte Carlo simulation and 999 replicates, was computed separately for each crop (conditional independence) in order to know if the number of seed loss events was randomly distributed among rainfall deciles. Under extreme dry conditions, the probability of seed loss for a given crop was computed with a 95% confidence interval (CI).

(ii) Seed losses and rainfall threshold values

A smoothing model (Chambers and Hastie 1992; Venables and Ripley 2002), also called generalized additive model (GAM), which is usual in social sciences by allowing a nonlinear relationship between response and explanatory variables (Keele 2008), was used to estimate the threshold values of rainfall triggering seed losses. This analysis was implemented for the 9 years that were most impacted by seed losses. Model 2 was formalized as follows: $\log(p/1 - p) = \alpha + s(\text{rain}_i) + \epsilon$, where s is the smoothing function applied successively to different rainfall variables and $i = \text{Dur, Nrd, Ptot, Frd, or Int}$.

A specific analysis was implemented with the frequency of rain days to compare crop responses to climate variability. Model 3 was formalized as follows: $\log(p/q) = \alpha + \beta \text{Frd}_i + \epsilon$. A backward elimination procedure from the saturated to the minimal adequate model (Agresti 2007; Crawley 2007) was implemented to confirm that altitude is not a significant factor per se. Quasi-binomial error was used to consider overdispersion. This model was computed separately for each crop to estimate the probability of seed loss along the slope.

4) VULNERABILITY OF FARMING SYSTEMS FROM 1961 TO 2006

Seed loss probability was analyzed in relation to interannual rainfall variability of the long rains. The proportion of lost seed was thus considered on a yearly basis, in order to evaluate the effects of year and that of cropping systems. Each year was thus individually considered to take into account the number of cultivated varieties and the number of seed loss events, in computing the proportion of lost seed.

The effects of year and that of cropping systems were assessed using the methods proposed in sociology by Fox (1987, 2003), after Hastie (1992), for computing marginal effects. Model 4 was formalized as follows: $\log(p/1 - p) = \alpha + \beta_1 \text{crop}_i + \beta_2 \text{rain}_j + \beta_3 \text{year}_k + \epsilon$, where $i = 1-8$ crops, $j = 1-5$ rainfall variables (Dur, Nrd, Ptot, Frd, or Int), and $k = 1-46$ years (1961–2006).

TABLE 1. Statistical summary. Mean and standard deviation of rainfall variables for the long rains from 1961 to 2006 (46 years) at three altitudinal levels (low, mid and high).

Variables	Low mean	Std dev	Mid mean	Std dev	High mean	Std dev
Duration of the season (days)	51.8	23.1	64.4	20.6	91.2	26.9
Number of rain days (days)	19.6	8.7	27.8	10.3	42.1	12.1
Seasonal amount (mm)	338.8	154.5	590.1	249.1	616.7	215.5
Frequency of rain days	0.39	0.13	0.43	0.1	0.47	0.1
Daily mean intensity (mm day ⁻¹)	17.2	4.9	21.5	5.4	14.6	3.3

The year effect, controlling rainfall and crop, was considered in order to show how the probability to lose the seed varied during the period 1961–2006. If the farming system sensitivity to drought was constant over the period, then the year effects should have also been constant; if not, the varying effect would imply that the farming systems’ response to climate variability was not constant. The regression of year fitted values on time was plotted and the linear trend tested for all five rainfall variables.

To consider the cropping system as a whole, marginal effects of each crop, controlling rainfall and year, were weighted based on their yearly popularity, the sum of weights equaling 1. For instance, if sorghum represented 30% of crop diversity cultivated by farmers, and maize 20% at a given year, then the sorghum effect was weighted by multiplying it by 0.3, that of maize by 0.2, and so forth for other crops. The cropping system was thus considered as an assemblage of crops, and its effect was computed in each year as the sum of weighted crop effects. Analyses were done using R software (R Team 2010).

3. Results

a. Seasonal rainfall variation from 1961 to 2006

A statistical summary of rainfall variables from 1961 to 2006 is presented in Table 1. The seasonal duration and the number of rain days increase markedly from lower to higher altitudinal levels. The same applies to rainfall intensity, but the latter is not linearly related to altitude (Camberlin et al. 2014). The seasonal amount is not significantly different between mid- and high altitudes, and the frequency of rain days increases slowly with altitude. The interannual variations of seasonal rainfall are correlated among altitudes ($r = 0.83$ between low and midlevels, 0.89 between low and high levels, and 0.85 between mid- and high levels), so that our sampling on three altitudes emphasizes spatial variability in climatic patterns.

The interannual variation of seasonal rainfall from 1961 to 2006 for the three levels is presented in Fig. 2. All the stations display negative trends; however, these are not significant according to both the Pearson and Spearman statistics. Most other variables display no

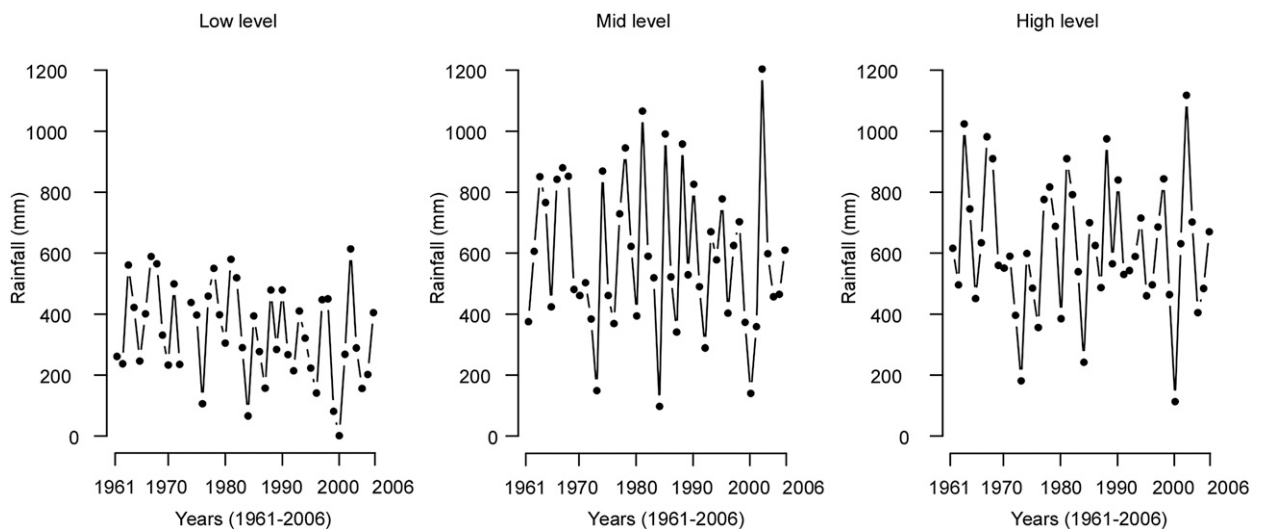


FIG. 2. Interannual variation of seasonal rainfall from 1961 to 2006 for the three levels. All the stations display negative trends; however, these are not significant according to both the Pearson and Spearman statistics.

significant trends, except for the frequency of rain days at high (95% CI) and low altitudes (90% CI).

b. Cropping systems' dynamics

In retrospect, eight main crops—namely, beans—*Phaseolus sp.*, cowpea—*Vigna unguiculata* (L.) Walp, finger millet—*Eleusine coracana* (L.) Gaertn, green gram—*Vigna radiata* (L.) R. Wilcz, maize—*Zea mays* (L.), pearl millet—*Pennisetum glaucum* (L.) R. Br, pigeon pea—*Cajanus cajan* (L.) Millsp, and sorghum—*Sorghum bicolor* (L.) Moench—have been identified as components of Mount Kenya rain-fed farming systems.

From 1961 to 2006, farmers cultivated a mean of 1.72 ($\sigma = 1.13$) varieties per crop at the low level, 1.17 ($\sigma = 0.44$) at the midlevel, and 1.15 ($\sigma = 0.39$) at the high level. However, intraspecific diversity managed by farmers varied considerably during the period. The evolution of the variety richness per crop reveals when maize became more popular than sorghum and pearl millet.

At the low level, maize popularity increased from 1960 to 1985, but sorghum and pearl millet remained the dominant crops over the period. However, the decreasing popularity of sorghum (from 3.0 to 2.0 varieties per farmer) was negatively correlated to the increasing popularity of maize (from 1 to 1.2 varieties per farmer; $r = -0.57$; $p = 0.001$). At the midlevel too, the increase of maize popularity was significantly ($p = 0.001$) correlated to the decreasing popularity of sorghum ($r = -0.81$) and pearl millet ($r = -0.55$). Maize popularity exceeded that of pearl millet by 1980, and that of sorghum by 2000.

At the high level (Fig. 3), while the popularity of maize increased continually from 1970, that of sorghum ($r = -0.81$; $p = 0.001$) and pearl millet ($r = -0.39$; $p = 0.006$), well known for their drought resistance, decreased from 1980. In 1970, pearl millet and sorghum were about 3 and 4 times more popular than maize, respectively. By 1990, maize adoption was stabilized and by 2000 maize had become the dominant food crop in place of sorghum and pearl millet.

c. Crop and altitudinal effects on seed losses

Farmers have reported orally 3204 events of seed losses from 1961 to 2006, over a total of 45 025 farmers crop varieties cultivated over the period. The mean number of seed loss events decreased with altitude with a mean of 4.6 per farmer at low altitude ($\sigma = 3.6$), 3.1 at midaltitude ($\sigma = 1.9$), and 2.0 at high altitude ($\sigma = 1.4$). This altitude effect was observed for all crops but with a different magnitude (Fig. 4, right panel). The estimated parameters for seed losses as a function of crops and altitudes are shown in Table 2.

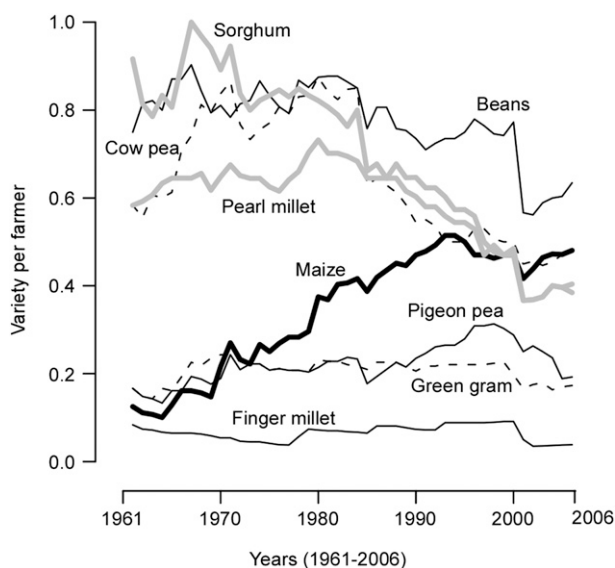


FIG. 3. Cropping system dynamics at high altitude (1961–2006). The number of varieties per farmer decreases for sorghum and pearl millet during the period, while it increases for maize.

Seed loss probability, given crop and altitude, are presented in Fig. 4. Seed loss probability was about twice larger at the low-altitudinal level (0.1 ± 0.007 , at $\alpha = 0.05$) than at the high level (0.057 ± 0.005 , at $\alpha = 0.05$, Fig. 4, left panel). The seed loss risk was thus higher at the low level than at the high level. Controlling altitude, the probability to lose maize seed was significantly higher than the probability to lose sorghum seed (Fig. 4, right panel). Considering the 95% confidence interval, seed loss probability was estimated from 0.086 to 0.101 for beans, and from 0.071 to 0.087 for maize, which is significantly higher than the probability for sorghum (from 0.056 to 0.065). Seed loss probability was thus contrasted between crops, being significantly higher for bean as compared to all other crops, and for maize as compared to sorghum.

d. Impacts of rainfall variation on seed losses

According to farmers, out of 3204 events of seed losses from 1961 to 2006 (Table 3), 81% were due to rainfall variation. “Drought” was mentioned 73% of times, whereas 8% of losses were associated with very wet years. The percentages of lost seed as a function of rainfall deciles, considering the three altitudinal levels, are shown in Table 3. They confirm the climatic factors identified by farmers to explain seed losses. Indeed, a high seed loss probability (0.24, considering all crops together) was associated with the first decile of seasonal amount ($p = 0.001$ from Monte Carlo simulations). Under very critical water conditions (first decile), Fig. 5

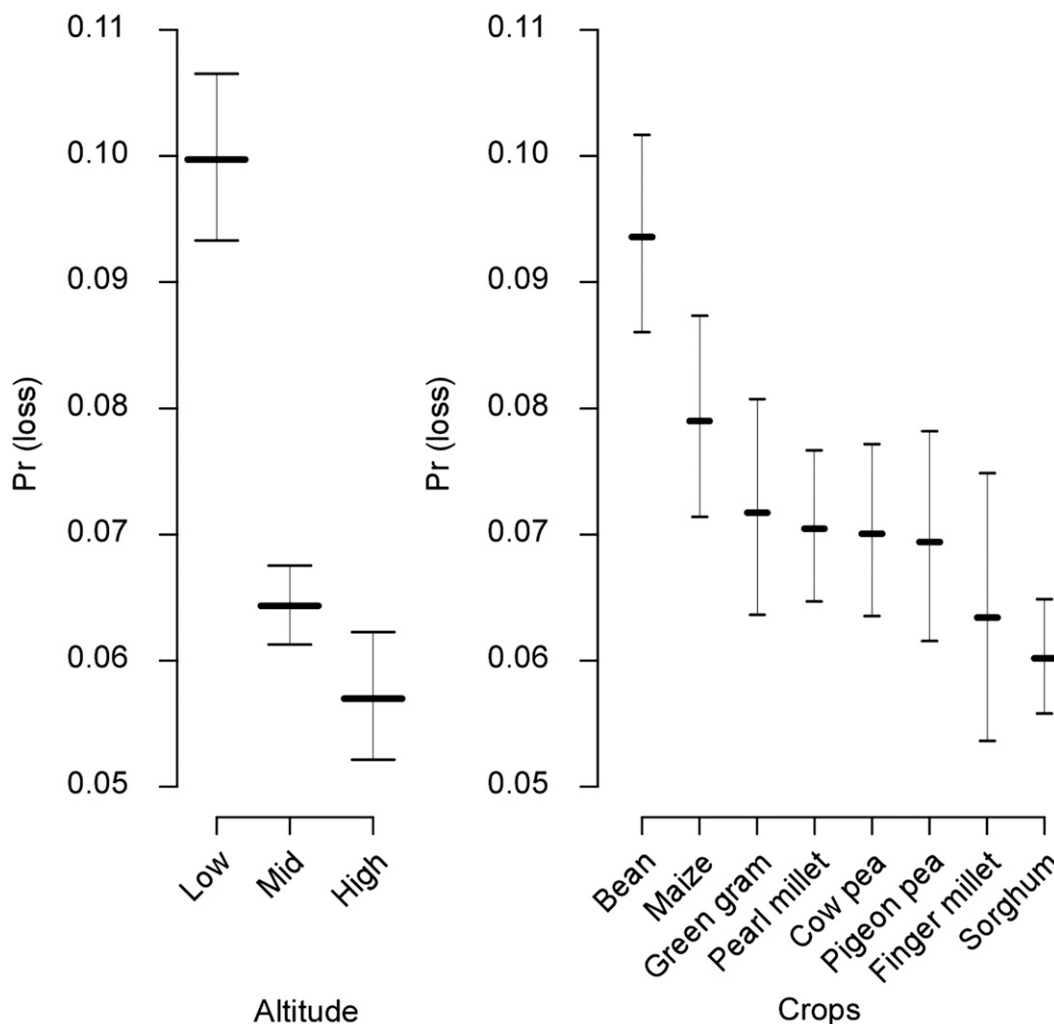


FIG. 4. Component and residuals from logistic regression computed without considering rainfall (model 1). (left) Altitude components (low, mid, high). Seed loss probability at low-altitudinal level was about twice larger than the probability to lose at higher level. (right) Crop components (beans, maize, green gram, pearl millet, cow pea, pigeon pea, finger millet, sorghum). The y axis expressed in the scale of probability. The probability to lose the maize seed was significantly higher than the probability to lose the sorghum seed.

shows that the probability of losing seed was significantly higher for maize (from 0.26 to 0.33), as compared to pearl millet (from 0.19 to 0.25) and to sorghum (from 0.18 to 0.23). Beans (from 0.24 to 0.30) and maize, which were the most popular crops over the period, were the most sensitive to drought.

Analyzing the distribution of Pearson’s residuals across rainfall deciles, Fig. 6 confirms that maize seed was highly impacted (positive residuals) at the first rainfall decile, as compared to sorghum and pearl millet, with negative residuals. The situation was reversed during the “normal” years (fourth–sixth deciles), seed loss probability being slightly higher for sorghum and pearl millet as compared to bean and maize. This

suggests that in favoring maize at the expense of sorghum and pearl millet, farmers have paid more attention to normal rainfall conditions than to drought conditions. However, at the seventh decile, bean remains much more impacted than pearl millet and sorghum.

Seed losses, as independently reported by farmers, mainly concerned 9 years (Fig. 7, left panel). These 9 years represented 83% of recorded seed losses, and all of them, except for 1962, were above the mean of the period that was 0.4 seed loss event per farmer and per year. The maximum was reached in 1984 with a mean of 3.8 seed loss events per farmer, followed by 2000 with a mean of 2.7. The bias associated with time telescoping that can be observed with recall data (Sudman and

TABLE 2. Estimated parameters from logistic regression model. Seed losses as function of altitudes and crops. Deviance of 90.4% explained.

	Estimate	Std error	z value	Pr(>z)
Intercept	-2.52	0.06	-42.57	$<2 \times 10^{-16a}$
Low altitude	0.61	0.06	10.20	$<2 \times 10^{-16a}$
Midaltitude	0.13	0.05	2.44	0.014498 ^b
Cowpea	-0.32	0.07	-4.54	5.672×10^{-6a}
Finger millet	-0.42	0.10	-4.18	2.972×10^{-5a}
Green gram	-0.29	0.08	-3.68	0.000234 ^a
Maize	-0.19	0.07	-2.64	0.008359 ^c
Pearl millet	-0.31	0.07	-4.66	3.212×10^{-6a}
Pigeon pea	-0.32	0.08	-4.12	3.842×10^{-5a}
Sorghum	-0.48	0.06	-7.56	4.072×10^{-14a}

^a <0.001.

^b 0.05.

^c 0.01.

Bradburn 1973) was not confirmed here, as the proportion of lost seed did not decrease as time goes back. The two most cited years correspond to droughts (– one standard deviation and lower) inventoried for Kenya (Nyamwange 1995; Ogallo et al. 2005), the 1984 drought being considered as the worst in the last century. Seed loss events also occurred during very wet seasons (plus one standard deviation and over) but also during normal seasons (Fig. 7, right panel).

The weak relationship between seasonal rainfall amounts and seed loss events, except in major drought

years, may reflect the fact that other rainfall variables, especially those depicting the temporal distribution of the rains, have a greater effect. Figure 8 shows that all rainfall variables had an increasing effect (although not linear) on seed losses as their values decreased, except seasonal duration. The analysis was carried out by combining all altitudes, in order to detect if absolute rainfall thresholds were impacting seed losses whatever the base climate. Term D^2 ranged from 0.39 to 0.82, suggesting that the variance of the data was reasonably explained by the predictors. Seed loss probability increased for seasons for which Dur was less than 50 days, Nrd was less than 28, Ptot was less than 400 mm, and Frd was less than 0.6. Among the five rainfall variables, Frd best explained seed losses in retrospect from 1961 to 2006 ($D^2 = 82\%$). Figure 8 also shows that seed loss probability increased slightly when rainfall variables reached their highest values. Indeed, there is a secondary increase of risk toward the right side of the plots (i.e., for higher values of the climate variables), at least for Dur, Nrd, and Ptot. In the latter case, seed loss probability increases below 400 mm and above 700 mm, but it remains constantly low between these values. The increasing probability of losses below 400 mm seasonal amount corresponds to both drought conditions at mid- and high altitudes (first and second deciles, reported in Table 3 as upper bounds) and to normal seasonal amounts at low altitude, which are usually below 400 mm (sixth decile and less, Table 3). The increasing

TABLE 3. Seed loss frequency as a function of crop (rows) and as a function of deciles of seasonal rainfall amount (columns). The upper bound of rainfall (mm) in each decile was indicated per altitude. The 3204 events of seed losses were orally reported by farmers from 1961 to 2006, over a total of 45 025 farmers crop varieties cultivated during the 46-yr period.

Upper bounds	Deciles									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Low altitude (mm)	141	214	246	277	321	398	422	479	550	614
Midaltitude (mm)	341	384	457	490	529	610	703	842	880	1204
High altitude (mm)	385	464	496	551	590	634	700	792	910	1118
All crops	Deciles									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Number of loss events	5221	4543	4068	4602	4017	4998	3961	5149	3928	4538
Frequency of loss	0.24	0.02	0.07	0.04	0.05	0.05	0.09	0.04	0.07	0.01
Breakdown by crop	Deciles									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Maize	0.30	0.03	0.08	0.01	0.02	0.03	0.10	0.05	0.08	0.01
Beans	0.27	0.03	0.07	0.02	0.04	0.04	0.20	0.03	0.09	0.01
Pigeon pea	0.25	0.03	0.08	0.04	0.03	0.03	0.07	0.03	0.08	0.01
Green gram	0.25	0.02	0.06	0.04	0.04	0.04	0.08	0.03	0.09	0.02
Cowpea	0.25	0.03	0.06	0.03	0.03	0.03	0.08	0.04	0.08	0.01
Pearl millet	0.22	0.02	0.08	0.07	0.06	0.07	0.07	0.05	0.06	0.01
Finger millet	0.22	0.01	0.11	0.03	0.04	0.04	0.05	0.02	0.08	0.01
Sorghum	0.21	0.02	0.05	0.07	0.07	0.06	0.05	0.05	0.05	0.01

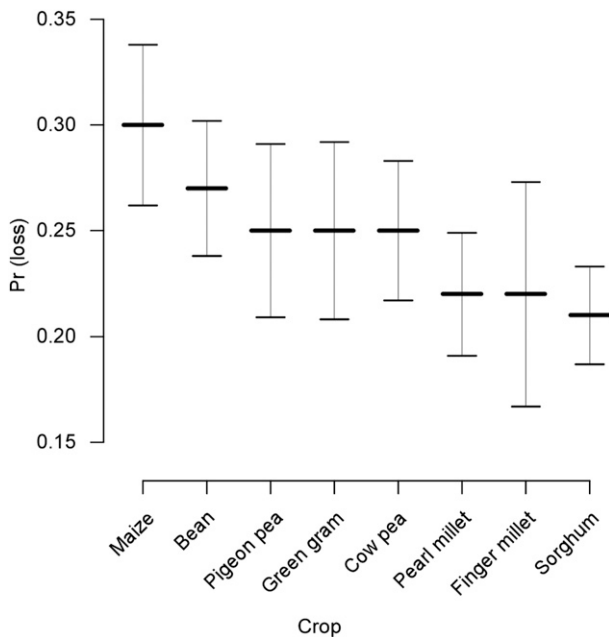


FIG. 5. Seed loss probability for each crop, under extreme drought conditions, i.e., the first decile of seasonal amount estimated at each altitude. Bars display 95% CIs. Seed loss probability was significantly higher for maize, as compared to pearl millet and sorghum.

rate of seed loss due to very wet seasons mainly concerns the ninth decile (Table 3), which corresponds to seasonal amounts ranging between 700 and 900 mm in Fig. 8c.

Figure 9 shows how the seed loss probability increased for each crop, as the frequency of rain days decreased. Term D^2 ranged from 0.49 to 0.79, suggesting that the variance of data was reasonably explained by predictors. For all crops, the magnitude of parameter β in the equation determines how fast the seed loss probability increased as the frequency of rain days decreased. It allows estimating the percentage of seed lost for a given rainfall value. If there were an average of only one rainy day per week during the season, then about 70% of the seed would be lost. The β parameters were not significantly different among crops, as all crops inevitably failed under very drastic water conditions. However, the relationship between the frequency of rain days and seed loss probability was steeper for maize ($\beta = 8.87$) as compared to pearl millet ($\beta = 6.17$) and sorghum ($\beta = 4.97$).

e. Vulnerability of farming systems from 1961 to 2006

Seed loss probabilities were analyzed over time in light of the interannual rainfall variability of the long rains. The deviance of 93.7% was explained with quasi-binomial

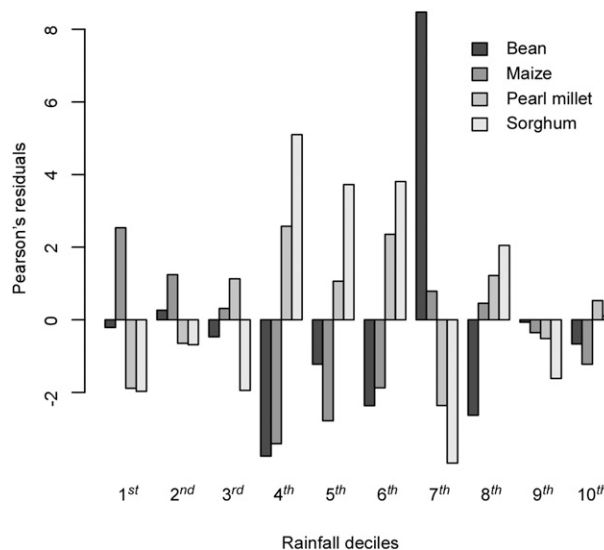


FIG. 6. The distribution of Pearson's residuals across rainfall deciles for maize, bean, pearl millet, and sorghum. The y axis: Pearson's residuals; the x axis: ranked decile from the first to tenth. Maize seed was highly impacted (positive residuals) at the first rainfall decile as compared to sorghum and pearl millet, whose residuals were negative. The situation was reversed during the normal years.

error. The analysis concerned both year and crop effects over the period. Farming system sensitivity to drought was not constant from 1961 to 2006 (Fig. 10a). A linear regression was computed on normal years (dots with dashed line), and the effect of years, controlling for effects of crop and rainfall, increased significantly from 1961 to 2006 ($p < 0.05$) for all five rainfall variables. In the right panel (Fig. 10b), the analysis focuses on the 1970–2000 period, which corresponds to the substitution of sorghum and pearl millet by maize (see section 3b). In this case, the effects of cropping systems were estimated yearly by considering the relative popularity of crops assembled in cropping systems. Although it was not significant, seed loss probability increases regularly from 1970 to 1990, stabilizing then after.

4. Discussion

Assuming the Meru farmers' ability to recall past seed loss events, we used a retrospective survey to document the impact of rainfall variability on their rain-fed agriculture systems, considering their dynamics. The dynamics of farming systems have generally not been considered by models that simulate future crop responses to climate change. Indeed, these models usually follow a Ricardian approach that assumes in the future a continued use of current varieties and unchanged cultural practices. Our results illustrate how the farming

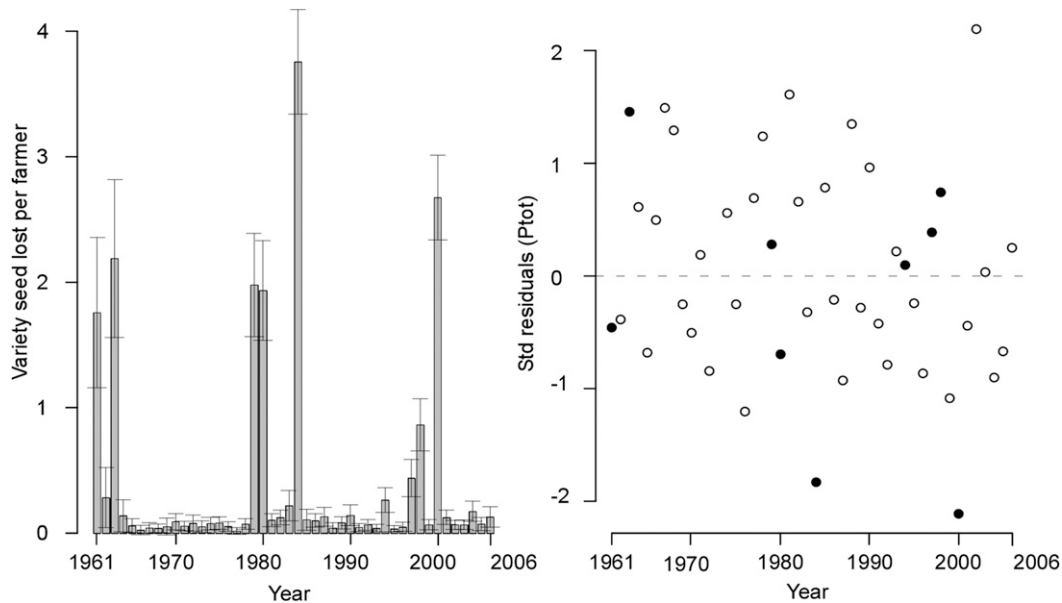


FIG. 7. (left) Number of seed losses per farmer from 1961 to 2006 (all altitudes). Nine years were more impacted than others (over the mean of the period). (right) Rainfall standardized residuals based on the mean seasonal amount. Filled circles represent the most impacted years. Seed losses occurred during the years of extreme climatic events as well as during normal years.

systems were highly dynamic from 1961 to 2006, maize being gradually favored by farmers in place of sorghum and pearl millet.

In this respect, our results reveal a paradox. The popularity of crops less resistant to drought (maize and beans) increased or remained constant from 1961 to 2006, whereas the popularity of crops more resistant to drought (pearl millet and sorghum) decreased. The consequence is that the cropping system dynamics itself induced an increasing risk of seed losses over the period.

Seed loss probability was influenced by altitude, crops, and rainfall variation. It was higher at the low altitude than at the high altitude. It was contrasted between crops, being significantly higher for beans and maize as compared to sorghum and pearl millet. Thus, the relative risk of seed loss was about 30% more for maize than for sorghum.

The effects of the low altitude and bean were similar in magnitude (about 9%), as well as the effects of sorghum and the high altitude (about 6%, see Fig. 4). We can deduce that seed loss probability highly increases for farmers cultivating beans and maize at low altitude. Indeed, under very critical water conditions (first decile of rainfall, Fig. 5), it was significantly higher for maize, as compared to pearl millet and sorghum.

The five rainfall variables analyzed did not equally explain seed losses (Fig. 8). Frequency of rain days, seasonal precipitation amount, and number of rain days during the season better explained seed losses than

seasonal duration and rainfall intensity. Frequency of rain days is almost linearly related to losses. Intra-seasonal variations, notably the length of the dry spells occurring after seed germination, can cause sowing failures (Mwongera et al. 2014). It is reasonable to think that the number of prolonged dry spells within the season increases as the frequency of rain days decreases, therefore increasing the risk of seed losses, whereas a high frequency of rain days limits this risk. It may worsen the cropping system vulnerability if encountering a drying trend, as indicated by the recent decline of long rains (Lyon and DeWitt 2012).

Indeed, the increasing seed loss probability from 1970 to 2000 can be related to crop assemblage changes, but a climatic shift could also play a role. Lyon and DeWitt (2012) have shown that the long rains' seasonal amount has decreased regularly since the 1990s. Climatic data from the three stations of our study also displayed negative trends for seasonal rainfall, but they were not significant. Thus, the dynamics of the farming systems remain a key factor in the increased vulnerability of smallholder farmers faced with drought, although rainfall trends may marginally contribute as well.

Considering rainfall variability (section 3a), our results indicate that changes in farming systems (section 3b) substituting drought resistant crops with less resistant crops (sections 3c and 3d) increased seed loss risk over the period, even during the normal seasons

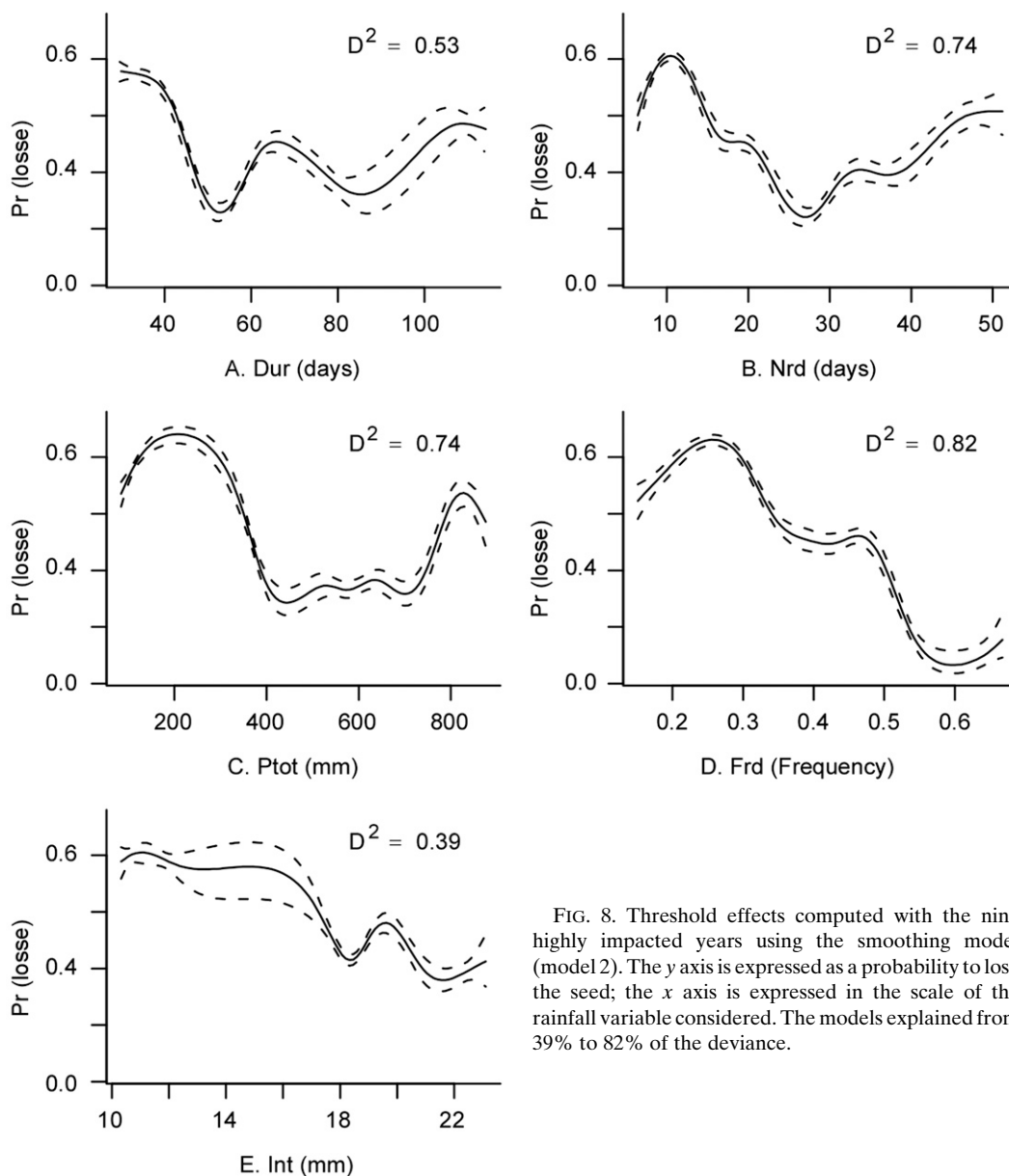


FIG. 8. Threshold effects computed with the nine highly impacted years using the smoothing model (model 2). The y axis is expressed as a probability to lose the seed; the x axis is expressed in the scale of the rainfall variable considered. The models explained from 39% to 82% of the deviance.

(section 3e). As many farmers turned to maize cultivation in place of sorghum and pearl millet, notably under the impulsion of agricultural policies, the farming systems' capacity to mitigate seed loss risks due to rainfall variations has been declining.

This conclusion needs to be considered together with our comparative field setting, and the variation of the rainfall parameters along the slope. The decile values (reported in Table 3 as upper bounds) at the mid- and high altitudes globally coincide, but at the low altitude they are by far lower than at higher altitudes. The fifth–tenth deciles at the low altitude range from 321 to 614 mm, which correspond to the first–sixth deciles

range at the mid altitude. When varieties less tolerant to drought are faced with an extreme event of 400 mm at high altitude (first or second deciles), this situation corresponds to a normal year at low altitude, that is, around the sixth deciles. Cultivating at low altitude crops that are adapted to highlands is likely to increase the vulnerability of the low-altitude farming systems during normal seasons.

Crops that are less tolerant to very wet years at low altitude may be impacted by high amounts of rainfall at midaltitude too (above the sixth decile in Table 3). Indeed, at this altitude, the sixth decile (610 mm) is equivalent to the maximum seasonal amount experienced

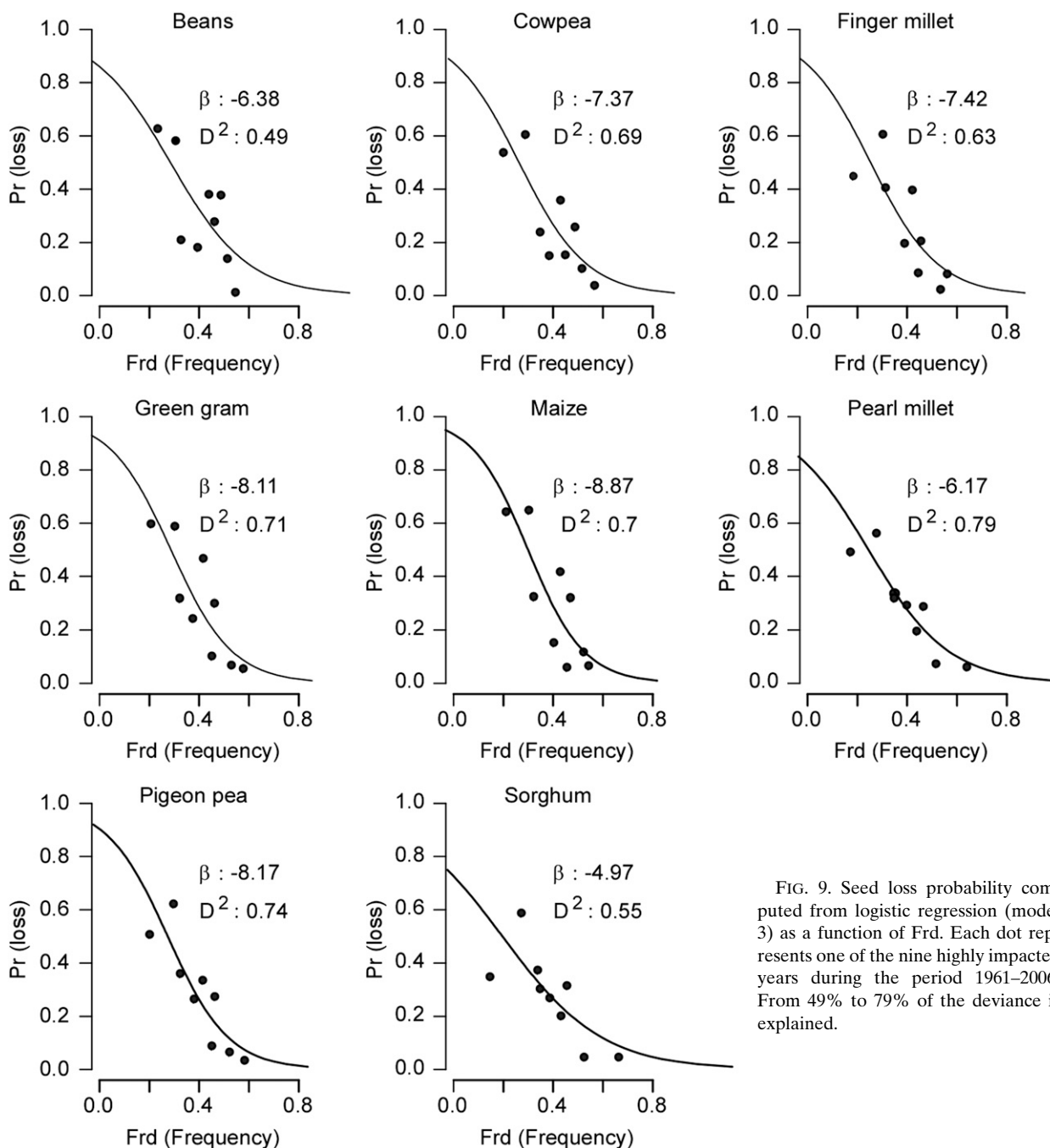


FIG. 9. Seed loss probability computed from logistic regression (model 3) as a function of Frd. Each dot represents one of the nine highly impacted years during the period 1961–2006. From 49% to 79% of the deviance is explained.

by crops at the low altitude (614 mm, tenth decile in Table 3). In addition, crops adapted to the low altitude are likely to be less impacted by drought at higher altitude. Mwongera et al. (2014) show that crops originating from high altitude (1100 m) are more sensitive to long dry spells in midaltitude (950 m) than the crops originating from low latitude (750 m).

The East African cropping system dynamics are partly related to agricultural policies that positively valued

maize, whereas sorghum and pearl millet were devalued, being perceived as “the crop of the poor people” (personal observation). Aside from being more resistant to pests and diseases, according to Hassan and Karanja (1997), maize grew in popularity because it was easier to store and process than traditional food crops. Maize currently covers 25 M ha in sub-Saharan Africa, largely in smallholder farming systems (Smale et al. 2011; Byerlee and Eicher 1997; Smale and Jayne 2003). The adoption of

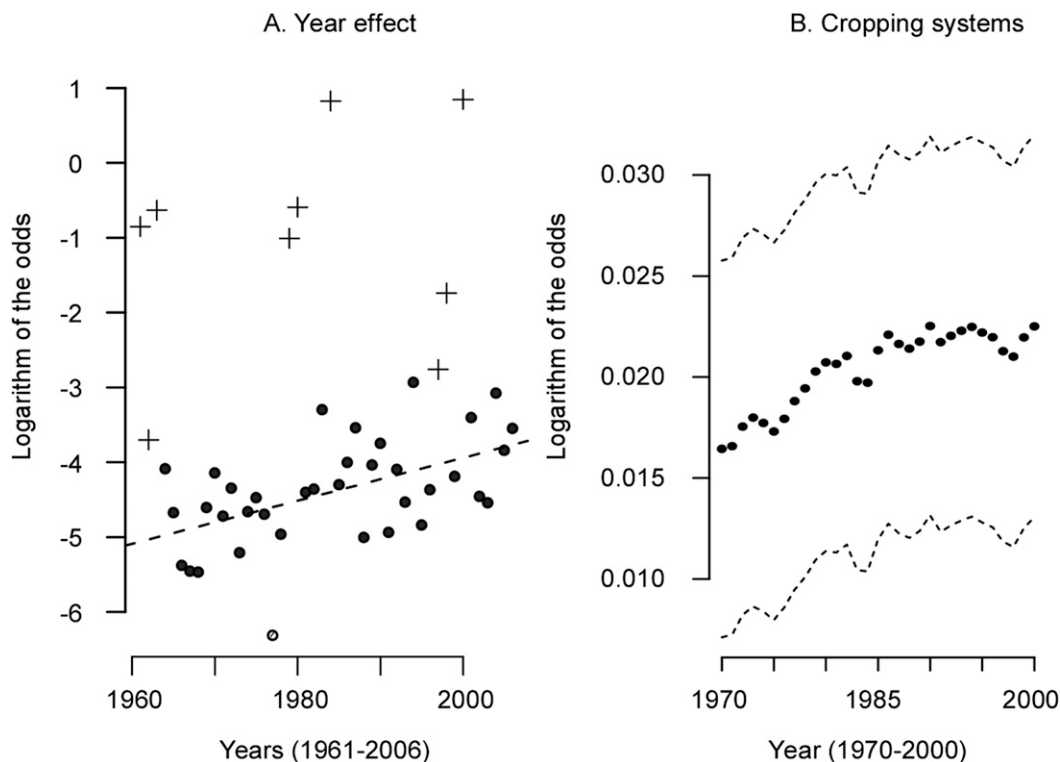


FIG. 10. Increasing risk of seed loss estimated by logistic regression (model 4). (left) Year effect on seed losses, controlling frequency of rain days and crop from 1961 to 2006; crosses represent the nine most impacted years and dots the normal years. Regression line was computed on the normal years. The risk of seed loss significantly increased during the period. (right) Cropping systems' effect weighted on crop yearly popularity, controlling the frequency of rain days and year from 1970 to 2000. Dash lines represent the standard error. The cropping systems' effect increased regularly during the period.

maize was stabilized from 1990 (Fig. 3), as in other East African countries. Maize adoption may indicate that this crop was valuable for farmers in terms of incomes under normal rainfall conditions. However, we have no data to test this hypothesis.

The potential impact of agricultural policies on cropping system dynamics, and adaptation to climate variability, must be considered in addition to other factors, notably farmers' food preferences and market value of crops. Bernard (1972) already noted by 1970 the remarkably rapid diffusion of maize as a consequence of new roads and markets, even in areas where the crop cannot be successfully grown. The increasing popularity of maize occurred even earlier, that is, beginning of 1950, among Kikuyu communities located on the southern slope of Mount Kenya (Middleton 1953). As maize was culturally favored with a positive valuation as compared to sorghum and pearl millet, the current dynamics of agricultural systems imply many dimensions, not only economical, political, and agronomical, but also cultural.

As far as we know, recall survey has never been used in studying cropping system dynamics. Asking retrospective

questions on periods of several decades is cheaper and quicker than longitudinal studies, which involve repeated observations of the same farmers over a long duration. But several types of reporting error and biases can affect the quality of recall data (Beckett et al. 2001). Many studies have criticized such a method by underlying the time telescoping and omission effects (Sudman and Bradburn 1973), or the fact that magnitude of the recall error increases over time. Our results do not suggest time telescoping bias, and the error has not increased over time (see 95% CI error bars in Fig. 6, left panel).

More recent studies showed that not all memories decay with time, and that the rate of decline in recall ability over time varies with the type of event considered, and can be limited by processes of active and repeated construction (Friedman 1993). Events that are highly salient, or that are closely related to lifestyle or self-identity of the respondent, are better recalled. Thus, cultural and social factors favor the ability of recalling ancient events.

Farmers' varieties are usually inherited from parents among Meru farmers, and can be considered as both

biological and social objects. In addition, a social process helps farmers remember the time of past events. Among Meru farmers, indeed, generations are subdivided into many classes, each individual being a member of a given class (Peatrik 1999, 2000). Usual in East African societies, this age set system combines individual life cycle with the successive generation classes, allowing individuals to know their own temporal position as compared to other generation classes. Leclerc et al. (2013) showed how such a system helps in recalling past extreme climatic events, as drought and very wet years, and how accurate this social knowledge is, by comparing it to rainfall data. The age–class system is also closely related to the Meru farmer social identity, and as a social process it is reasonable to think that it helps farmers dating past events.

Farmers' knowledge is both common and diverse but largely underconsidered in agro-climatic studies (see Orlove 2005; Orlove et al. 2000; Phillips et al. 2002; Roncoli 2006; Roncoli et al. 2001; Thomas et al. 2007). In the present case study, the way the logistic regressions fitted the proportion of lost seed as a function of rainfall data suggests a high suitability of the recall data provided by Meru farmers.

5. Conclusions

The purpose of this paper was to document the impact of rainfall variability on rain-fed agriculture systems managed by East African smallholders, considering their dynamics. The retrospective survey and the farmers' memory-based approach allowed diachronic analyses. We were able to show how, faced with drought, the cropping system dynamics itself induced an increasing risk of crop failures, and as a direct consequence an increasing risk to lose the seed that farmers used to perpetuate their varieties. From year to year, the increasing popularity of maize cultivated in place of drought-resistant sorghum and pearl millet has modified crop assemblages, and reduced the capacity of the farming system to mitigate the risk of crop failure.

The possibility for the cropping system to return, after a seed loss, to its previous level of diversity directly relates to its resilience (Holling 1973, 1986, 2001). In a resilient socioecological system as defined by Folke (2006), a disturbance has the potential to create opportunity for innovation and development, by emphasizing nonlinear dynamics rather than linear ones. Indeed, the capacity for traditional farming systems to get back lost seed has not been considered here. It imposes to study the role of the informal seed supply systems, which are based on social relations that also work outside of the agricultural domain (Leclerc and Coppens d'Eeckenbrugge 2012).

Bellon et al. (2011) assessed the vulnerability of traditional maize seed systems to climate change in Mexico. The structure and spatial scope of seed systems of 20 communities in four transects across an altitudinal gradient from 10 to 2980 m above sea level in five states of eastern Mexico were studied. Results indicate that 90% of all the seed lots are obtained within 10 km of the community and 87% within a ± 50 -m altitudinal range. Other studies have shown how crucial the role of social relations is for seed supply (Badstue et al. 2006; Mcguire 2008), but all analyses were based on a synchronic perspective, not a diachronic one.

The functioning of such a system remains unknown when we consider it over time, and when it is linked to rainfall variability. Does the seed supply system work differently if droughts are severe? If seed losses mainly concern farmers living at lower altitudinal levels, do farmers replace seed from upper levels? Do they obtain it from other farmers or local markets?

If crop genetic diversity that is managed by smallholder farmers is a means to mitigate the negative impacts of rainfall variability, then combining ecological anthropology, climatology, and agronomy should help preserve these systems against seed losses and genetic erosion.

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