

Desert locust swarm invasions and control: Determinants, duration, food security and effectiveness of control measures

Abstract

Migratory desert locusts are partly to blame for chronic food insecurity in semi-arid areas. However, insufficient risk information is available on locust determinants, duration, survival rates and impacts on food security, but also on effectiveness of reactive control measures. The data analysed included household survey (2020), MODIS Soil-Adjusted-Vegetation-Index (SAVI) and Climate-Hazards-Group-Infrared-Precipitation with Station-data (CHIRPS) of 2018-2020. Findings showed that the roaring swarms were determined by vegetation health, strong winds and soil type ($P \leq 0.05$). The invasions lasted for 3 to 4 weeks, however, 90% of locusts survived beyond one week. The ecosystems that favoured them included woodlands, wetlands, thickets/shrubs, grasslands and farmlands. The greenness of vegetation is an important parameter in the attraction of locusts. They fed on the green tree structure (leaves, nodes, shoots). Most swarm invasions occurred during the rainy season. Overall, the invasions reduced crop and livestock yields. After the attacks, most households depended on food purchases for at least four months. The most effective control measures implemented were ground and aerial pesticide spraying of locusts that killed them along their life-cycle. It is therefore, important to strengthen locust surveillance and use of chemicals in the management of locusts, but also strengthen disaster legal and institutional systems.

Keywords: Desert locusts; survival; locust control; food security; Uganda

1. Introduction

Globally, migratory desert locusts (*Schistocerca gregaria*) are a threat to vegetation and agricultural ecosystems. The locusts have been considered a major pest since ancient times (Sánchez-Zapata et al., 2007; Githae, 2021). They can change from a harmless solitary stage, during recession periods, to swarms of gregarious individuals that disperse long distances (Meynard et al., 2020). The locust outbreaks are dictated by environmental conditions such as the health of vegetation, winds, soil type and precipitation (Xu et al., 2021). These conditions favour their reproduction, movements and feeding patterns. In contact with the above ecosystems, the ever-grazing pests feast on the leaves and stems of trees, crop leaves/shoots and also eat grass (Mamo & Bedane, 2021). The damages caused by hopper bands and adult swarms are a threat to food security (Cressman, 2013). Studies show that a swarm of desert locusts can consume food grains that can feed up to 35,000 people (Chatterjee, 2022). It is worth noting that the outbreaks are highly unpredictable, but also cause uncertain devastating damages and losses. Occurrences of locust outbreaks are therefore an immense threat to the attainment of Sustainable Development Goals, especially from goals 1 to 3. Investigating human and environmental interaction of locusts is important in eradicating poverty, but also enhances food security, sustainable agriculture and conservation of biodiversity (Murali-Sankar & Shreedeevasena, 2020).

Over the past decades, the management of locust upsurges is still inadequate to reduce the risks associated with the invasions primarily due to limited surveillance systems, absence of coordination structures, inadequate manpower and equipment (Showler et al., 2022). Further, the supply of reliable, affordable pesticides and spraying equipment has been insufficient (Sultana et al., 2021). Under these conditions, the initiatives deployed such as spraying of insecticides are effective (Sánchez-Zapata et al., 2007) but inadequate to counteract the reproduction cycles of locusts because of inadequate measures to estimate the spatial extent of the risk (Lecoq, 2005; Showier, 2019). As a result, desert locust swarms have destroyed crops and pastures in over sixty countries from Africa to western Asia and thus causing food insecurity for about 10% of the world's population (Renier et al., 2015). Locust swarms are therefore highly devastating, especially for any country where agriculture represents 20% of gross domestic product (Sultana et al., 2021). Though it is important to note that there are two types of structures in desert control and these are at the national and regional levels in charge of coordination and control of locusts (Toleubayev et al., 2007). In this study regional support was sought for light aircraft to conduct aerial chemical spraying of locusts.

Geographical Information Systems (GIS) and Remote Sensing (RS) tools offer possibilities for the researcher to assess the impacts of locusts over a large landscape (Ahmad et al., 2022). Moderate and high-resolution images can be used to detect locust damage caused to vegetation and crop. The tools can further demonstrate the areas that are highly susceptible to locusts and thus important in locust control and surveillance. Spatial technologies play an important role in detecting changes in desert locust habitats (Cressman, 2013). The spatial platforms can provide accurate information

about locust occurrence, damages and spatial extents but also there are vital for early warning (Yao et al., 2021). Satellite-based time series data such as vegetation and rainfall have been increasingly applied to estimate the location of the desert locust, breeding and recession areas (Wang et al., 2021). They are also increasingly used to monitor and forecast locust species (Latchininsky, 2013). However, studies that use these technologies to examine the influence of rainfall, land use and vegetation in triggering locust outbreaks are rare.

Our literature search reveals that many studies have been conducted related to locusts, however, their scope differs from one region to another. The notable studies include assessing the economic costs of locusts on agricultural production (Chatterjee, 2022); impacts of locusts on crops and vegetation (Sultana et al., 2021), desert locust outbreak on food security and food supply chain (Xu et al., 2021), effective mitigation measures in desert locust management (Samejo et al., 2021); the influence of climate on the distribution of locusts (Bag & Bhoi, 2020), use of remote sensing and geographical information system to assess the factors that contributed to desert locust upsurge (Wang et al., 2021), prediction of breeding grounds for locusts (Kimathi et al., 2020), locusts as an alternative protein source (Peng et al., 2020) and how vegetation influences gregarisation (Despland et al., 2000). As per reviewed articles, the gaps this study identified are related to insufficient information about the determinants of locust invasions, duration, survival rates and seasonality of outbreaks, but also the impacts of locusts on food security and effectiveness of control measures. This study further explores the influence of rainfall and land use/cover types in influencing locust upsurges using vegetation health indicators.

In 2020, the regions of East Africa, Asia and the Middle East experienced unprecedented attacks of desert locusts (Kassegn & Endris, 2021). This study was conducted in East Africa because it can serve as a policy example for semi-arid regions that routinely experience locust outbreaks, but will also strengthen regional locust monitoring and surveillance systems. In particular, this research focused on understanding the desert locust invasions (duration, determinants, survival and seasonality) on food security and the effectiveness of control measures implemented. The specific objectives of this research were to 1) ascertain the locust vulnerable hotspots, duration and seasonality; 2) assess the determinants, survival rates and hazard function of locust outbreaks; 3) examine the impacts of locust swarm outbreaks on household food security and; 4) evaluate the perceived effectiveness of implemented control measures in response to the upsurges.

2. Methodology

2.1 Description of the Study Area

This study was conducted in northeastern (613447.1 N, 462970.2 E) Uganda, Eastern Africa (Fig. 1). It is bordered by Kenya in the east and South Sudan in the north. Administratively, the study area is subdivided into eleven districts. The region is characterised by dryland conditions because it receives a unimodal rainfall pattern (Gartrell, 2019), but also it is highly prone to invasion of migratory locusts. The study area was invaded with locusts in 2020 between March and May. Months that experience high rainfalls are March and June. Rainfall amounts range between 1,000 and 1,500 mm per annum (Egeru et al., 2019) while the dry months are from August to February. Soils of the landscape are dominated by sandy-clay loams that have limited support for agricultural production (Nakalembe et al., 2017). Vegetation is made of patches characterised by savanna grasslands, shrubs/ thickets and woodlands.

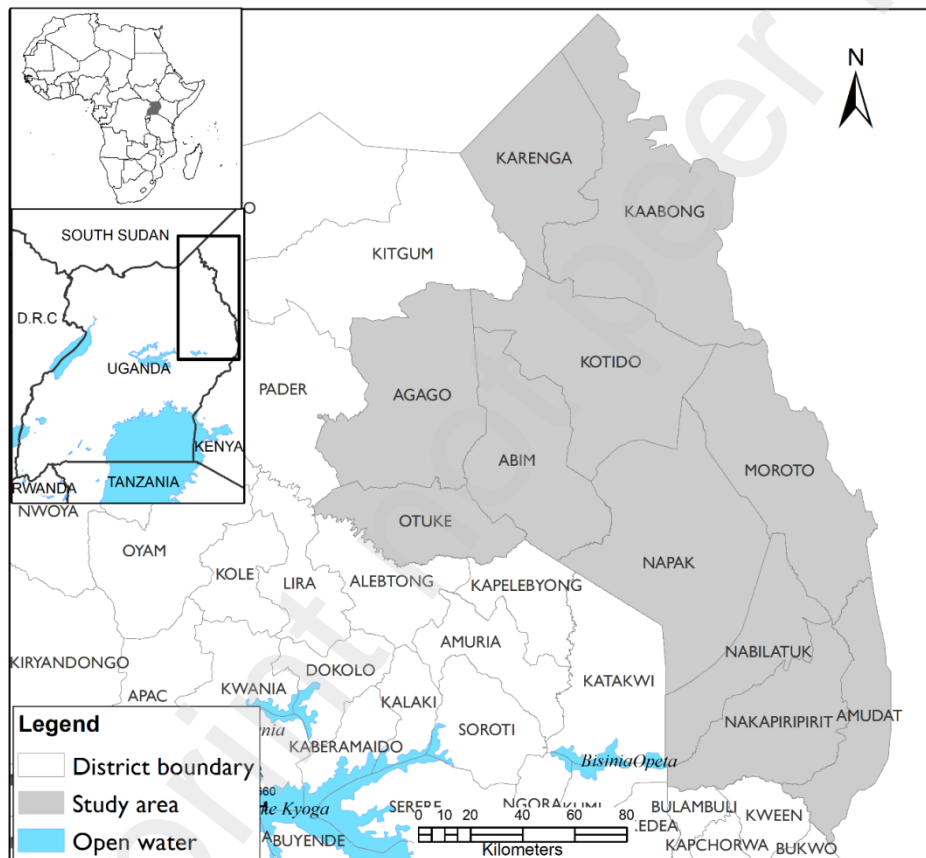


Fig. 1. Location of the study area

2.2 Socio-economic data collection

This study achieved collecting socio-economic data which was analysed to evaluate locust control measures, survival rates and impacts on food security. By this, the data was collected from households (smallholder farmers) and key informants. Before this study, permission was sought from the district administration leaders to access the communities to be sampled. Informed consent was obtained on the respondents sampled before interviews. The research tools that were developed, pretested and used included semi-structured questionnaires, key informant and focus group discussion guides.

A multi-stage sampling procedure was adopted where sampling was carried out from district, sub-county, parish and village levels. Our sample size of households selected was determined using Schonlau et al. (2010) procedures. A total of 183 smallholder farmers were selected and interviewed. While the considerations made in the sampling were the size of the population and settlement pattern. After determination of sample size, research assistants familiar with the local language were recruited and trained to administer the tools. The assistants in collaboration with the village leaders developed household membership lists which were used to select or sample the respondents. Respondents were selected using the snowball sampling technique (Leighton et al., 2021). The selected households were orally interviewed face to face and responses recorded on the hard copy questionnaires. Questions that were asked included but were not limited to duration, seasonality, survival and control of locusts. Still in the field, two focus group discussions (FGDs) sessions were conducted (Moroto, Napak, Amudat and Otuke districts) to gather qualitative data using an interview guide. These were conducted at the nearest local government administration office. Group members were randomly selected comprising of youths, elders, opinion leaders and farmers. The opinions of members were recorded on charts and later transcribed.

Additionally, twelve key informant interviews were held among the purposively selected expatriates thought to have sufficient understanding of the locust invasions, environment and agricultural production. With the use of key informant guides, the selected members were interviewed in their areas of jurisdiction in the districts. The collected household survey data were coded in SPSS software (version 23) and subjected to both qualitative and quantitative analysis. The indicator for effectiveness of locust control measures implemented was if the methods used were able to terminate locusts throughout their life cycle.

Descriptively, frequencies were used while inferentially a Cox Proportional Hazards Model and a Chi-square test were developed in Statgraphics software to assess the determinants (rainfall, temperature, wind, soil moisture, soil type and vegetation) of locust invasion, their survival times and hazard function. This model can analyse the survival and time it takes for events to occur (Bender et al., 2005). The hazard function at a selected combination of the input factors x is a multiple of the baseline hazard function $h(t|0)$, as shown below:

$$h(t|x) = h(t|0) * \exp(\text{Rainfall} * \text{Temperature} * \text{Winds} * \text{Soil moisture} * \text{Sandy soils} * \text{Vegetation type})$$

2.3 Influence of land use/cover types and rainfall on locust outbreaks

We hypothesised that the existing patchy land use/cover types and rainfall had an impact on the outbreak of locusts in the studied area. As such, remotely sensed data were acquired and used. Vegetation greenness was used as an indicator to assess the influence of locust outbreaks. Soil Advanced Vegetation Index (SAVI) values were used to determine vegetation greenness, which is a major indicator of risks attributable to desert locust invasion since it forms locusts' main food (Vallebona et al., 2008). Higher SAVI values indicate vegetation abundance while low values indicate stress.

The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images (250 m) were acquired for the years 2018, 2019, and 2020 were analysed on an annual basis. The datasets were obtained from the Earth Explorer portal (<https://earthexplorer.usgs.gov/>). MODIS data is widely used in the analysis and monitoring of the state of the environment (in vegetation and crop systems) using various indices thus capable of revealing the conditions before, during and after the locust invasion (Van Leeuwen et al., 2006). Its high temporal resolution provides an opportunity to capture vegetation changes over short periods of locust invasions.

The MODIS-enhanced vegetation indices can be correlated with rainfall and used to detect vegetation changes (Lu et al., 2015) as locust-feeding and /or breeding grounds (Hmimina et al., 2013). SAVI is preferred because it is more suitable for use in arid and semiarid zones (Vani & Mandla, 2017) since it eliminates the soil background drawbacks where the sparse vegetation is dominated in the land cover (Anderson et al., 2011). Both rainfall variability estimation and SAVI analyses were carried out to identify the influence of the monthly precipitation on vegetation greenness. For rainfall, Climate-Hazards-Group Infrared Precipitation with Station data (CHIRPS) rainfall data for the studied period was also acquired (<https://data.chc.ucsb.edu/products/CHIRPS-2.0/>) and used. It was preferred due to its reliability in assessing rainfall relationship with vegetation greenness (Ayanlade et al., 2021). Rainfall estimates can also give an insight into areas where locusts are anticipated (Lawton et al., 2022).

To understand how land use/cover types influenced locust outbreaks, a national land use/cover spatial dataset of 2019 was obtained from National Forestry Authority (NFA) and the area of study extracted, collated with field data and where gaps existed, these were updated. The classes of land use/cover types included shrubs and thickets, farmland, woodland, wetland and grassland. The authority is mandated to periodically develop and update national land use/cover maps for the country. To examine how land use/cover types and rainfall influenced locust upsurges, 1,500 randomly created points were used to exact values (Fig. 2). Areas that were affected by locusts were visited and mapped for validation purposes. Locust studies rely on ground-gathered data to improve the accuracy of utilised remote sensing data.

2.4 Hotspots of locust outbreaks

Using vegetation greenness as an indicator of invasions. Random points (1500) were developed to monitor vegetation health, rainfall and land use/cover types (Fig. 2). The value ranges were classified as woodlands (0.4-0.6), shrubs/thickets (0.37-0.39), grasslands (0.03-0.36) and bare land/water -0.015-0.2. Vulnerability value ranges were reclassified as very low (-0.015 - 0.2), low (0.21 - 0.34), moderate (0.35 - 0.38), high (0.39 - 0.42) and very high (0.43 - 0.6) as proposed by Yeganeh et al. (2014).

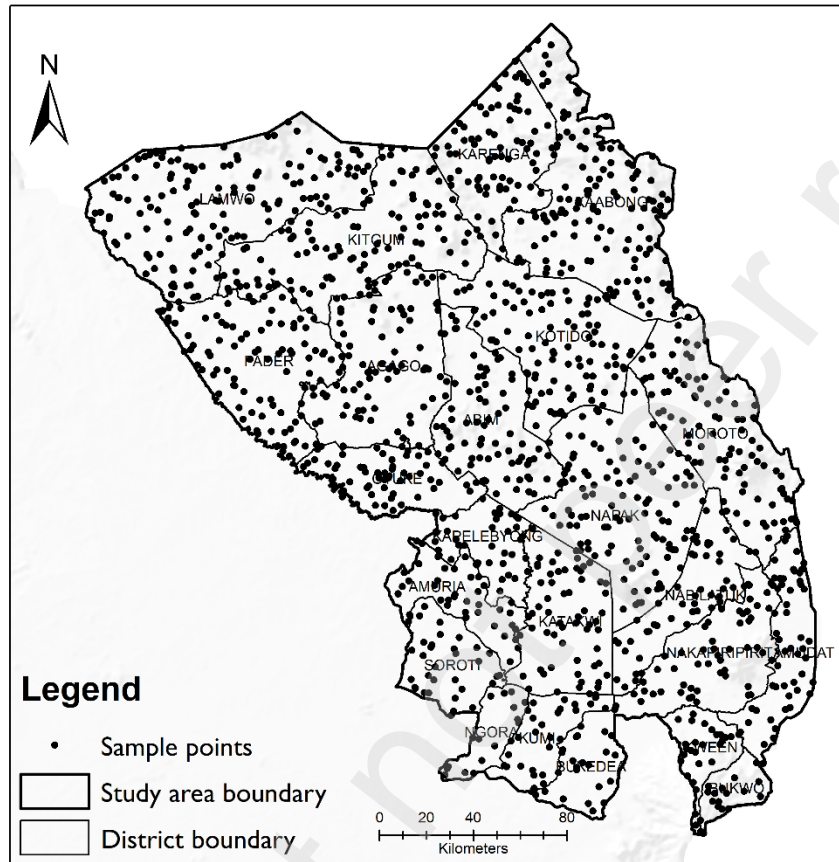


Fig. 2: Sampled random points

3. Results

3.1 Locust vulnerable hotspots, duration and seasonality

In this section, we illustrate how MODIS SAVI data can be used to predict areas that are likely to be affected by locust invasions, but also examined their duration and seasonality as perceived by the interviewed households. This study shows that the MODIS SAVI imagery can be used to demonstrate areas that are prone to devastating locust outbreaks (Fig. 3). The greenness of vegetation is an important parameter in the attraction of migratory locusts. Places with rich vegetation greenness were highly susceptible to gregarious locusts compared to those with less cover. The highly prone areas are composed of savanna woodlands followed by those occupied by shrubs, crops and grasslands. While the safer areas were made of bare lands, rocks and water bodies. This vulnerability was further confirmed by interviewed key informants and the mapping exercise conducted to validate the areas prone to the attacks. The migratory locusts entered Uganda from Kenya through Amudat District to all the districts in the studied area (Fig. 3). However, as per the interviewed key informants, the most vulnerable areas to locusts were low to moderately hilly areas (640-2,300m) compared to the highlands and mountainous areas (2,400-4,200m).

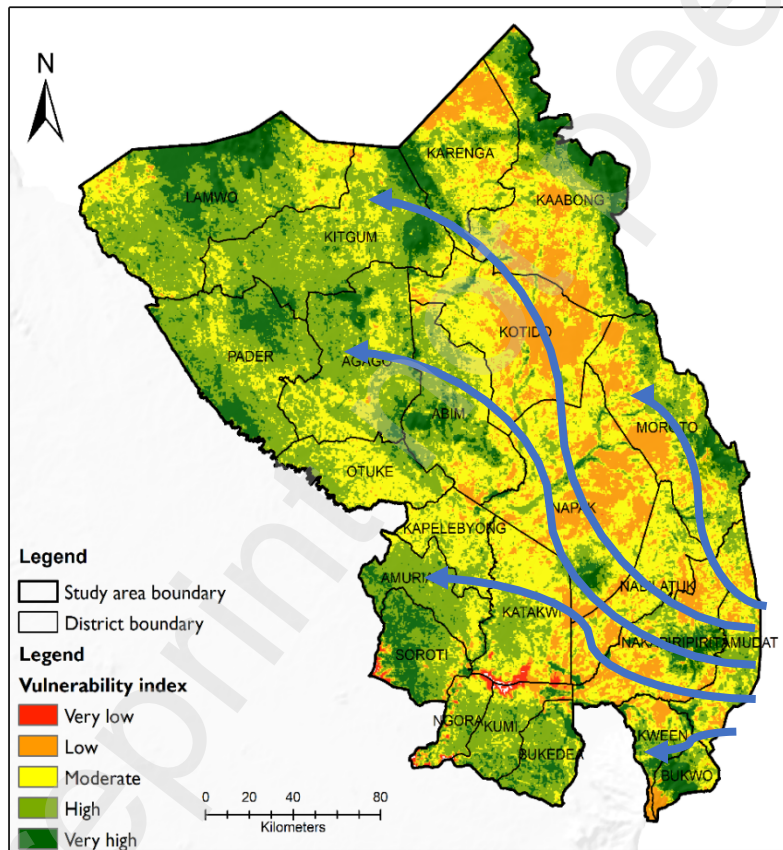


Fig. 3: Vulnerability of the study area to locust invasion and points of entry

The findings on the duration and seasonality of locusts in the year of invasion were collected through interviews of smallholder farmers as demonstrated in Fig. 4. This result shows that most swarm invasions lasted for a period of 3-4 weeks (70%) followed by 1-2 weeks (20%). However, despite the size and nature of swarm invasions, the maximum duration of locusts in an area was 4 months and above. At the district level, most durations of locusts were reported to occur in Moroto, Abim and Nakapiripirit districts. In a nutshell, on average the invasions lasted between one and four months. Seasonality in this study was defined by the annual cropping calendar. The most grown crops include maize, beans, sorghum, and millet. This study reveals that most of the invasions occurred before and after the crops were planted. Generally, most swarm invasions occurred during the rainy season characterised by crop growing. The districts that experienced locusts throughout the planting cycle were Moroto and Abim.

Members of the focus group discussions reported that “*within a garden, the locusts would take a day. On vegetation, they would take between four to five days. In the district, they took about two weeks. They kept migrating within the district*”. In addition, the FGD members revealed that they experienced two waves of locusts. The first wave was in March after they had planted and the crops had sprouted. This was the season of rain. The second wave was after three weeks to one month after the first one. It was in April. The second wave was after the mature first wave locusts had laid eggs and these hatched and formed the second wave that affected the seasonal cropping calendar. About the calendar, the respondents revealed that activities of land preparation and planting are undertaken between March and May, weeding starts in April to June and harvesting takes place between August and October of each year.

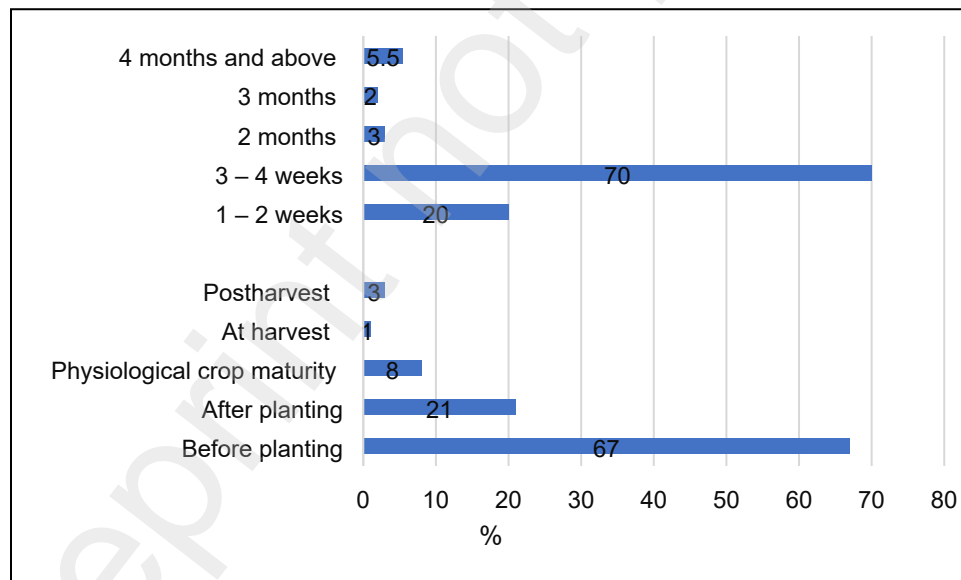


Fig. 4. Duration of locust invasion and seasonality

3.2 Determinants, survival probability and hazard function of locust swarms

The determinant factors were categorized into four classes as defined on a Likert scale (least favourable, moderate, favourable, and most favourable). As per the interviewed respondents, the major determinants of locust invasions reported were vegetation health, strong winds and soil type ($P \leq 0.05$). Other factors that also triggered the swarm invasions were rainfall, surface temperatures (30-36°C) and soil moisture (Table 1). This study also further examined the survival rates and hazard function of locusts in the areas invaded using a Cox Proportional hazard analysis depending on their duration. The result is dependent on risk factors sought to cause the survival of locust swarms. These include the amount of rainfall received, surface temperatures, soil moisture, vegetation health, strong winds and the presence of sandy soils (Table 2). However, for the survival of locusts, the most important factors were vegetation health and strong winds ($P \leq 0.05$). Members of the focus group discussion also explained that *“the locusts were found when the vegetation was green and fresh after some weeks of the first rains. They also followed the wind. People had also planted crops like beans and maize, which had sprouted fresh and soft leaves and these were eaten. The locusts would use their abdomens to dig holes in the sandy gardens to lay eggs”*.

Table 2: Determinants of locust outbreaks

	Least favourable		Moderately		Favourable		Most Favourable		Chi-Square	df	Asymp. Sig.
	Obs. N	Residual	Obs. N	Residual	Obs. N	Residual	Obs. N	Residual			
Rainfall	118	72.3	21	-24.8	43	-2.8	1	-44.8	171.426 ^a	3	.000
Surface temperature	64	18.3	64	18.3	54	8.3	1	-44.8	59.820 ^a	3	.000
Blowing Winds	39	-6.8	43	-2.8	94	48.3	7	-38.8	84.869 ^a	3	.000
Soil moisture	95	49.3	27	-18.8	59	13.3	2	-43.8	106.377 ^a	3	.000
Soil type (Sandy)	84	38.3	33	-12.8	63	17.3	3	-42.8	81.984 ^a	3	.000
Vegetation health	33	-12.8	34	-11.8	107	61.3	9	-36.8	118.093 ^a	3	.000

Table 2. Likelihood ratio tests

Factors	Chi-Square	Df	P-Value
Rainfall amount received	4.40915	3	0.2205
High surface temperatures	2.49203	3	0.4767
Strong blowing winds	9.58133	3	0.0225
High presence of soil moisture	1.10034	3	0.7770
Presence of sandy soils	0.617241	3	0.8925
Vegetation health	10.9	3	0.0123

In this study, patchy land use/cover types and rainfall were further hypothesised to cause locust swarm outbreaks in the studied area in the year 2020. By the annual SAVI values were extracted from different land use/cover types as of 2020 (woodlands, wetlands, thickets and shrubs, grassland, farmland and bare land). The ecosystems that attracted and sustained the lives of locusts

were woodlands, wetlands, and thickets and shrub (Fig. 5). The invasions were recorded in March and April. These were assumed to provide protection, food and water needed for the survival and reproduction of locusts. The SAVI values of 2020 were higher compared to 2018 and 2019 which is an indication of good habitat suitability.

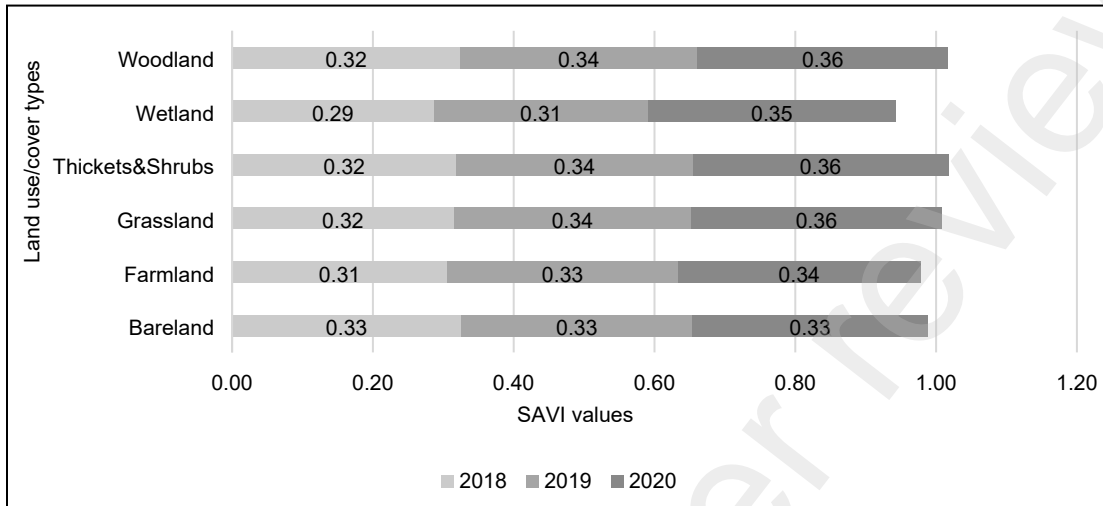


Fig. 5. Influence of land use/cover types on vegetation greenness

As for rainfall, the CHIRPS weather station data also shows a positive relationship with the health of vegetation (Fig. 6). For the studied period, this result also shows that March and April 2020 provided suitable conditions for the multiplication of locusts. The months were characterised by prolonged rains, strong winds and high soil moisture. These conditions were perceived by the interviewed key informants to favour the movement of locusts, feeding patterns and breeding conditions. It is worth noting that as significant amounts of monthly rainfall were received throughout 2020, the rainy conditions in March and April were more characterised by favourable conditions that led to locust outbreaks than those received in the subsequent months (August–November).

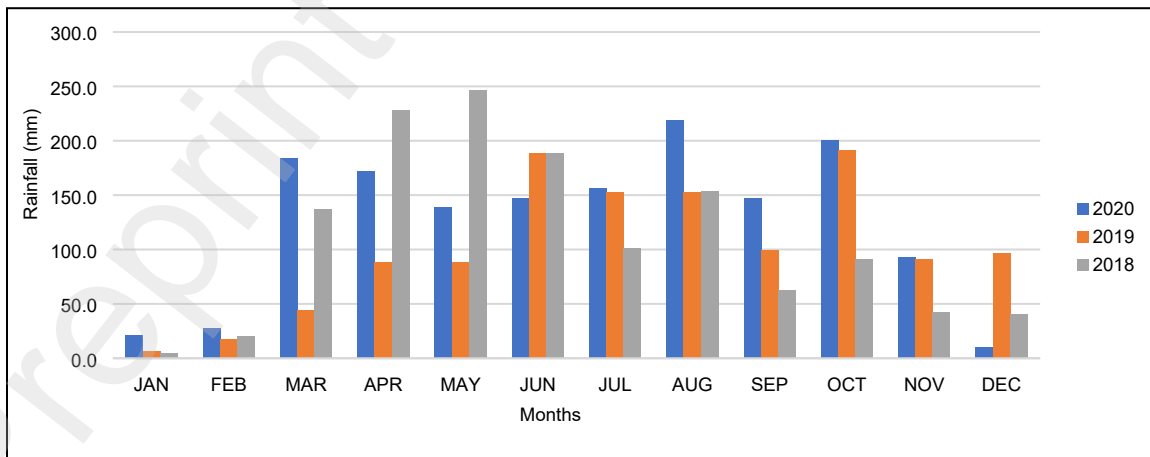


Fig. 6. Influence of rainfall on locust outbreaks

The findings on survival probability illustrate that about 90% of locusts had the probability to survive beyond one week (Fig. 7). However, only 40% were able to survive beyond one month. This means that the survival of locusts reduced with increase in time. While the hazard function graph reveals that the chances of locust death increased with the age of locusts.

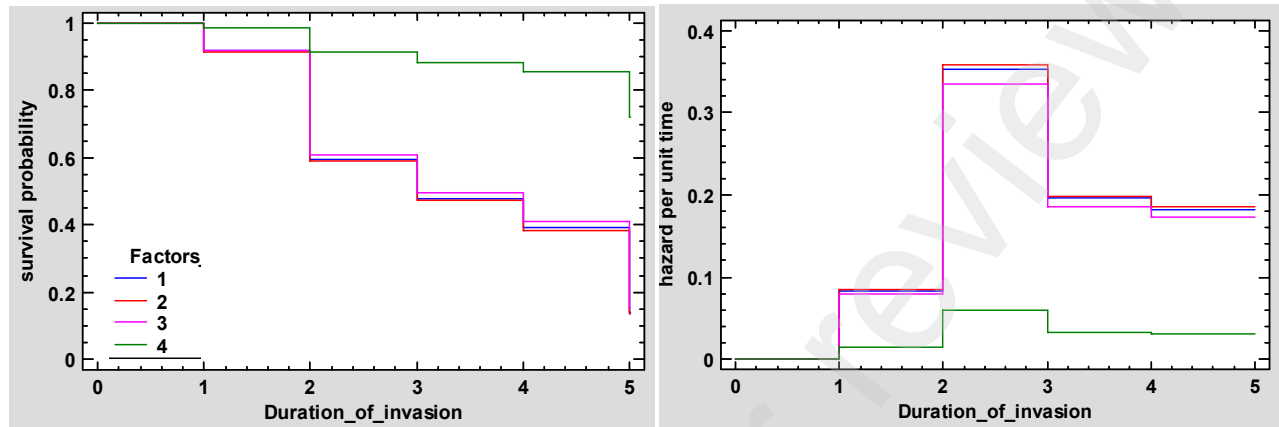


Fig. 7. Survival probability and hazard per unit time

3.3 Effects of locust swarm invasions on household food security

The interviewed smallholder farmers also reported that the locusts caused severe impacts on the structures of vegetation, crop and livestock production systems (Fig. 8). In crop production, it was reported that the locusts increased the costs of replanting lost crops (28%), interfered with crop sprouting (26%) and flowering processes (24%). The farmers also had to shift their cropping calendar to avoid further damages and losses. While in the rearing of livestock, the major effects recorded included a reduction in the coverage of areas under pasture (38%), trekking of farmers to longer distances in search of pasture (31%) and increased occurrences of livestock-related diseases (16%), especially in the cattle, goats and sheep. This study also shows that in contact with the vegetation, the locusts consumed more of the tree cover (leaves, shoots, branches and stems) leaving the trees bare and deformed. This was followed by grasslands. The young locusts ate grass because they were attached to them, while others were moving on the ground.

The members also further explained that “*where animals used to graze, there was no longer grass. Grass for cattle was finished in days. They also kept camels that feed on plant leaves, but they failed to get what to eat because the grasshoppers had eaten all the leaves. The grasshoppers ate the biggest part of the plant leaves and left a small hard part to drop off the tree and that is what the goats were left with to eat, but it was not enough. Animals failed to access pasture. They destroyed leaves of crops instead.*” They also reported that “*since the locusts invaded in 2020, they have been suffering from hunger and poverty. Some people migrated to the south to graze their animals after the locusts ate all the grass*”.

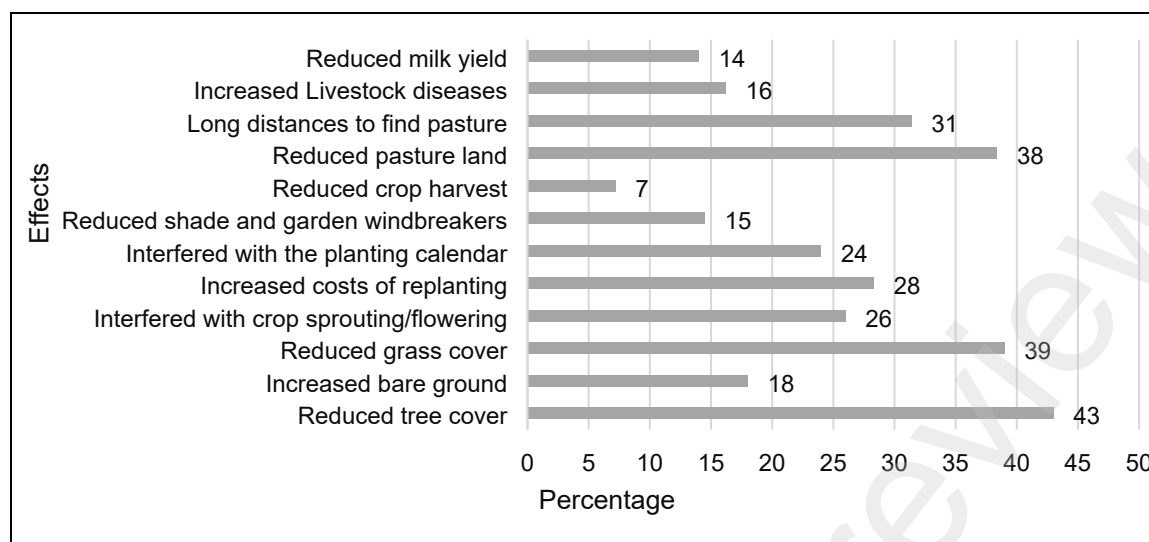


Fig. 8. Effects of locust invasion on vegetation, crops and livestock production

The findings of this study demonstrate that locusts caused food insecurity in households. This analysis is based on the number of days in the two months when the locust invasions were severe. The comparison was made before and during the invasions as per the number of days the households consumed the reported food items (Table 3). Crops that were predominantly planted during the invasions included maize, beans, sorghum and millet, ground nuts, green-gram, sunflower and peas as per the interviewed households. Our results show that before the invasion, the most consumed items were cereals, maize, beans, root tubers and vegetables, however during the locust outbreaks their consumption reduced. However, after the invasion, the farmers depended on food purchases for more than four months. A significant amount of what was harvested was sold/exchanged or used to repay loans as presented by key informants. They also further reported that food insecurity was caused by poor food preservation measures such as storing food on the ground and using tarpaulins or iron sheets and concrete floors. Damages were also as a result of moulds, pests/insects and rodents.

Table 3. Consumption of food items during and after invasions by mean days

Food items	Before Mean no. of days	During Mean no of days
Maize, maize porridge	15	7
Cereal (rice, sorghum, millet, bread, pasta etc.)	18	9
Roots and tubers (cassava, Irish potatoes, sweet)	13	5
Sugar or sugar products	4	7
Beans and peas	15	6
Groundnuts or cashew nuts	4	4
Vegetables	10	3
Fruits	2	1

Beef, goat or other red meat and pork	3	1
Poultry and eggs	3	2
Milk/yoghurt/other dairies	6	2

Since the landscape is characterised by agro-pastoralists and pastoralists, most of the households are highly dependent on their livestock for survival, prestige and wealth. The most predominant livestock reared include cattle, goats, sheep and poultry. However, the invasion of locusts destabilised the livestock production status of smallholder farmers (Table 4). The outbreaks resulted in the reduction of livestock numbers and increased the consumption, sale and purchase of more livestock which ultimately affected the household food security status of households. In response to curb food insecurity caused by migratory locusts, the interviewed key informants showed that the households diversified their sources of livelihood. Besides crop and livestock production, the households were engaged in the provision of casual labour, receipt of gifts/begging, reliance on remittances, pension/social grants, formal employment, indulgence in petty businesses and local brewing.

Table 4. *Livestock production during locust invasion*

Description	Animals owned	Animals bought	Animals consumed	Animals sold/exchange
Minimum	3	1	1	1
Maximum	200	15	20	22
Range	197	14	19	21
Median	11	3	4	4
Mean	25	4	5	6
Std. Deviation	45.1	3.4	3.2	5.4
Variance	2032	11.3	11.1	28.8
Skewness	3.54	2.1	2.6	1.5
Kurtosis	13.3	5.4	10.9	2.1

3.4 Perceived effectiveness of locust control measures implemented

This part of the study presents the modes of measures implemented to control locust outbreaks, their effectiveness and why so. The respondents confirmed that the most effective locust control measures applied were the use of pesticides on the ground (68%) and aerial spraying (29%). Other effective measures considered include use of fire and biological control (Table 5). The least effective measures applied to control locusts were digging trenches to limit ground movements, trampling on hoppers by households, bush burning, digging up egg pods and use of biological control measures. This result shows that the implementation of preparedness measures such as locust surveillance and the use of chemicals (pesticides) in response are important tools to consider in the management of locusts. The key informants interviewed revealed that this effect was a result of the appropriate selection of areas of interventions, the efficiency of pesticides used, methods used to spray locusts, training of community members in locust management and safety measures

implemented on humans and livestock. The initiatives were either community or government driven. Furthermore, despite monitoring the invasions and implementation of control measures, results from the focus group discussions revealed that the most effective means of communication were the use of radio/TVs, extension workers, newspapers, use of mobile phones, oral communication by neighbours and Non-Governmental Organisations.

Table 5. *Effectiveness of locust control measures*

Measures	Not effective		Somehow		Effective		Very effective	
	N	%	N	%	N	%	N	%
Aerial pesticide spraying	14	8	19	10	97	53	53	29
Ground pesticide spraying	4	2	29	16	26	14	124	68
Lighting bush fires	32	18	118	65	30	16	3	2
Digging trenches	43	24	128	70	9	5	3	2
Making loud noise	17	9	140	77	20	11	6	3
Trampling on hoppers	40	22	125	68	16	9	2	1
Biological control	20	11	122	67	34	19	7	4
Chasing of locusts	13	7	88	48	38	21	44	24
Digging up egg pods	21	12	135	74	24	13	3	2
Roosting/burning straw	17	9	140	77	20	11	6	3

4. Discussion

The use of remote sensing in locust studies is related to the developments registered in advancing knowledge of the use of the techniques and tools the technology offers as well, as advancements in the technology itself, especially in the last two decades (Klein et al., 2021). These studies have made use of AVHRR, Satellite Pour l'Observation de la Terre Vegetation (SPOT-VGT), MODIS as well as Landsat data focusing mainly on vegetation monitoring or land cover mapping as conditions for locusts feeding, breeding, and gregarization (Klein et al., 2021). SAVI results in the current study reveal that the 2020 desert locust invasion of north-eastern Uganda had a moderate impact on the natural cover and land use contrary to the hyped fears of massive impact. This signifies that the migratory locust swarms that reached north-eastern Uganda from western Kenya were induced by environmental variables but also interventions (spraying with chemicals) that never allowed the swarms enough residence time to breed and gregarize before migrating (FAO, 2020). Mature locusts of high density inflict the greatest damage to vegetation and crops during invasion. The fact that this was not the case in the current study area implies that the swarms that reached Uganda were either of low density or of weak, having been disintegrated by chemical spraying in Western Kenya or having been disrupted from feeding along their course thus travelling long distances without settling to feed on host vegetation. Wang et al. (2021) also argued

that locust invasion scenarios in the Arabian Peninsula, West Asia, and Northeast Africa were influenced by heavy rainfall and fresh vegetation that provided favourable conditions for locust breeding, multiplication, and gregarization and consequently causing enormous damage on vegetation cover.

The 2020 desert locust invasion in north-eastern Uganda was favoured by climate (rainfall) and vegetation conditions. The locust invasion was ensured shortly after crop planting and sprouting, which corresponded to the onset of the single rainfall season in the Karamoja region. The invasions lasted for more than two weeks. The first rains in Karamoja dramatically transform the landscape as it drives other environmental conditions, favourable for the desert locust breeding, maturation, gregarization concentration, and migration (Peng et al., 2020; Wang et al., 2021). The locusts were attracted to tall trees and savannah grasslands. The invasions occurred at the onset of the first rainy season, which is characterized by strong blowing winds and high surface temperatures (30-36°C) just like it is reported elsewhere (Sharma, 2015; Klein et al., 2022). Rainfall and soil moisture were reported by the key informants to favour the movement and breeding of locusts in the current study areas. The rainfall season in this way increases soil/sand moisture, and vegetation freshness, favourable for desert locust reproduction whereas the winds associated with the season favour migration of the mature swarms. Rainfall and land cover characteristics have provided desert locust outbreak prediction scenarios with high certainty elsewhere but also within the East African region (Kimathi et al., 2020; Klein et al., 2021). These predictions however depend on inverse conditions in the initial epicentres. Intense precipitation events in the Arabian Peninsula during 2018 provided suitable soil moisture and lush vegetation, which favoured desert locusts' invasion of the Arabian Peninsula and when the conditions shifted to West Asia and Northeast Africa the following year, the desert locusts too migrated to these regions (Wang et al., 2021). In Africa, Asia, and Europe, temperature and leaf area index play important roles in shaping the spatial distribution of desert locusts (Chen et al., 2020).

The locusts that invaded East Africa had their origin to the Arabian Desert (Wang et al., 2021) thus, the conditions that force these pests to migrate from their original breeding areas are usually in synch with the conditions for inhabitation and breeding in the migration destinations. Thus, there are intermittent periods of invasion recession in relation to variations in these environmental conditions (Van Huis et al., 2007). Desert locust monitoring and surveying efforts should put this into consideration while designing management strategies to predict and plan for the implementation of preventive strategies before invasions. This study shows that locust invasion durations were determined by environmental factors, stage of locust growth and distance from the Kenyan border (epicentre). In addition, the duration of locusts played a key role in the vegetation consumption rates, risks and reproduction that ultimately affected the health of natural ecosystems and food production systems (Zhang et al., 2019).

Our study revealed that the 2020 locust swarms in north-eastern Uganda had an indirect impact on smallholder farmers' food security. More damage was inflicted on natural vegetation cover

(grasslands and trees) as compared to crop production. It should be noted that communities in Karamoja are largely pastoralists who depend on grasslands for livestock production. Reduced grass and tree cover means limited access to sufficient livestock feeds to support increased meat and milk yield after the locust invasion. Besides, reduced vegetation cover forces pastoralists to move long distances in search of pasture for their livestock, which is often associated with territorial conflicts and movement away from livestock production infrastructures like valley dams and veterinary services centres (Loupa, 2019). Our study further reveals that whereas there were warnings during the 2020 locust invasion that swarms would continue to migrate into East Africa from Arabia and that these would continue to breed and spread further especially in farming areas at the start of the planting season thus causing crop destruction (FAO, 2020), this was not the case in Karamoja Region of Uganda. This is however expected from a region where crop production forms a very small percentage of the agricultural engagement and instead the communities rely on pastoralism (Nakalembe et al., 2017).

The locusts thus caused damage mainly to the natural vegetation forms that were abundantly available at the time of the invasion just as was reported by Kimathi et al. (2020). This affected the smallholder farmers' food security by reducing on livestock production upon which they mostly rely for income, labour supply, milk and meat. By any means locust outbreaks cause disruptions in food supply chain as well as food security (Xu et al., 2021). As a response, affected communities in Karamoja region attempted to diversify their livelihood sources like engaging in casual labour, reliance of remittances and petty businesses, which demonstrated some level of community resilience although the sustainability of the alternatives sought was questionable. There is need to diversify livelihood sources to build community resilience to desert locust upsurges in the East African region.

Knowledge of desert locust control and management has evolved for the earth's spaces that are occasionally invaded by these migratory pests (Sharma, 2015). For the Karamoja region in Uganda, invasion cases have been sporadic and unpredictable thus most of the measures implemented were reactive. Consequently, the most widely used control measures during the 2020-locust invasion included the traditional methods involving the use of chemicals and pesticides applied through aerial and ground spraying. For effective control, using chemicals and spraying hoppers in their early stages of development proved to be more effective (Prior & Streett, 1997; Cressman and Fresco, 2001; Showler et al., 2021). Whereas the results from the study show that these were very effective, the measures are associated with adverse negative environmental effects (Zhang et al., 2019). There is a need for jurisdictions in the region to develop capacity for the near future and future forecasting of desert invasions and plan for preventive management to minimize the use of spraying with chemicals that becomes the only reliable measure if invasions are detected only after occurrence (as a reactive control measure) (Prior & Streett, 1997).

Showler et al. (2021) argue that whereas chemical spraying may be effective in averting further development of locust swarm status and plantations, the associated costs and disruptions downplay the benefits. However, Mamo & Bedane (2021) reveal that chemical spraying of locusts can devastate crops and lead to severe human health and environmental risks. Besides, a lot more is spent on surveillance where interventions wait until the locust swarms reach the region. One of the major issues of discontent in the handling of the 2020 desert locust invasion in Uganda was related to the huge financial implications where up to a tune of \$ 4 million were borrowed for that purpose. Whereas biological control measures are suggested as being effective in pest control, (Githae, 2021), there was no evidence of constitution of the same in the current study area during the recent upsurges. This could be attributed to relatively low levels of investment in research towards such measures as well technical personnel requirements that East African region stress over. Moreover, the measure would complicate the locust management costs further. However, much as this study was conducted in north-eastern Uganda, the findings are of global importance to refer to, especially exploring the determinants, locust survival and evaluation of control measures.

5. Conclusion

This paper demonstrates the environmental and land use conditions that favoured the 2020 locust invasions in Uganda, risks to smallholder farmers' household food security as well as the effectiveness of the control measures instituted against the invasions. The northern parts of the Uganda are highly vulnerable to desert locust invasions beyond the points of entry on the border with Kenya. Reactive rather than proactive locust control measures were enacted and proved effective in managing the desert locust upsurge in Uganda. The findings will be instrumental in locust disaster preparedness and building resilience of communities in the locust affected regions of East Africa to copy up with future invasions. Planning for locust swarm management should focus on strengthening the community resilience to safeguard livelihood sources and food security. The regional locust control units in East Africa should be strengthened to acquire ability to conduct ground surveys as well as geospatial data, and timely reporting of invasions.

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Disclosure statement

The authors declare that there are no competing interests to declare regarding the publication of this manuscript.

Data availability statement

The field survey data used to support the findings of this study are available from the corresponding author upon request.

Authorship

Barasa Bernard: Conceptualization, Methodology and Analysis **Gudoyi Makoba Paul:** Data curation, Writing- Original draft preparation **Lutaaya Noah:** Data collection and supervision **Watsusi Walyalula Cosmas:** Spatial analysis and Validation.: **Akello Gertrude:** Writing- Reviewing and Editing

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