Technical Paper: Desert Locust and Climate

A Weather and Bio-climatic Case Study of Desert Locust Conditions in Northern Kenya

Authors: • Bill McCabe • Sofía Barboza • Maitrayee Basu • Laura Hohmann • Emmah Mwangi • Mark Arango • Maurine Ambani • Halima Saado Abdillahi

Columbia University, Climate and Society Master's Programme

ICHA International Center for Humanitarian Affairs At the Kenya Red Cross Society
Inquire • Understand • Influence

Columbia University in the City of New York

Kenya Red Cross

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Abstract

Changes in the climate system caused by anthropogenic climate change make locust plagues more likely. The 2019/2020 desert locust plague in Eastern Africa, the worst of its kind in more than 70 years, was likely exacerbated by shifts in rainfall patterns and intensity, as well as high cyclone activity in late 2019. Due to higher than usual average temperatures, conditions for desert locusts have become more conducive to plague development in recent years. This climate and desert locust study examines the interconnections between climate and weather parameters, locust breeding, and spread over Kenya. The initial context was that shifts in temperature and the hydrological cycle, already being observed and linked to a changing climate, are believed to create a more conducive environment for desert locusts. The key question addresses the conditions that allowed desert locust to thrive in Kenya from the end of 2019 to mid-2020. The analysis is thus based on the dekadals that show the highest frequency of sightings within the relevant time period (December 2019 - May 2020). In light of different favorable growth and development conditions for each lifecycle stage (hoppers, adults, bands, swarms) and behavioral stage (solitarious vs. gregarious), the central finding of this analysis is that although many of the observed highest-frequency sightings are indeed within the favorable desert locust thresholds, there are noticeable deviations from literature that warrant further exploration. This study adds value to literature established by WMO and FAO by further exploring the relationship between soil moisture, cloud cover, NDVI, and locust sightings. Locusts were most observed in the counties of Turkana, Marsabit and Isiolo. Continued research of these counties could serve as an informative entry point for the development of an early warning system.

Keywords: Climate change, dekadals, desert locust, hydrological cycle, temperature

1. Introduction

The Desert Locust, scientifically known as *Schistocerca gregaria*, poses an agricultural based threat to livelihoods and food security. Millions of people are facing acute food insecurity in arid and semi-arid areas in Africa, the Middle East and Southwest Asia.[1] East Africa faces a significant level of vulnerability with shocks from climate crises such as poor rainfall and flooding, with locust threat to agriculture in countries such as Ethiopia, South Sudan, and Kenya becoming a serious concern since these countries are already facing high levels of food insecurity with almost 25 million people already facing severely acutely food insecure.[2]

One of the most notable desert locust events in Africa within the last few decades was the 2003–2005 upsurge that occurred primarily in Western Africa. During the period from July to September 2003, there were periods of widespread heavy rains in this region, which included the recession areas. This created ideal conditions for desert locust development and reproduction.[3] There was very little planning and warning provided by some of the main agencies responsible for desert locust preparedness at the time. Moreover, there were very few locust specialists in those regions at the time and funding for successful implementation of desert locust monitoring and control plans was tied-up and delayed. Due to some of these precluding factors, a total of over 8 million people were affected in the Sahel Region by the time the upsurge ended. In many cases, livestock owned by households were sacrificed as a way to help compensate for losses from crop destruction both from the drought episode and the desert locust upsurge. Other negative effects included overall increased poverty, young people vacating villages in search of work resulting in a reduction of the agricultural workforce and increase of food insecurity. After all of the case studies were concluded, the latter proved to be the biggest impact.[4]

The most recent desert locust upsurge and invasion in Africa started in 2018 and made its way into Kenya during the latter period of 2019 (Figure 1). It has proven to be the worst the country has seen in 70 years. A locust invasion is different from any other kind of pest infestation especially when the environmental conditions are suitable, their population increases and starts to swarm, and this is the most dangerous/destructive phase of their cycle. Swarms are tens of billions of solitarious locusts that become gregarious through evolution, and can fly up to 100 square miles or more.[5] They are migratory transboundary pests that ride downwind to areas of lush vegetation. In late 2019, favorable conditions in the Arabian Peninsula, which included ample precipitation from multiple cyclones in the eastern Indian Ocean, spawned a surge in desert locusts in that region. A prolonged period of north and northeasterly winds during this surge in Saudi Arabia, Yemen, Sudan, Eritrea, Ethiopia, and Somalia aided in directing the desert locusts south and southwestward towards Kenya.[6]

25 Million

People already facing severely acutely food insecure.

1 Food Security and Nutrition Working Group, 2020.
2 UNOCHA: East Africa Locust Infestation
3 Ceccato et al., 2007.
4 Brader et al., 2006.
5 Kennedy, 2020.
6 NOAA NCEP-NCAR CDAS-1 Dekadal Wind Reanalysis: See Appendix B & 3.

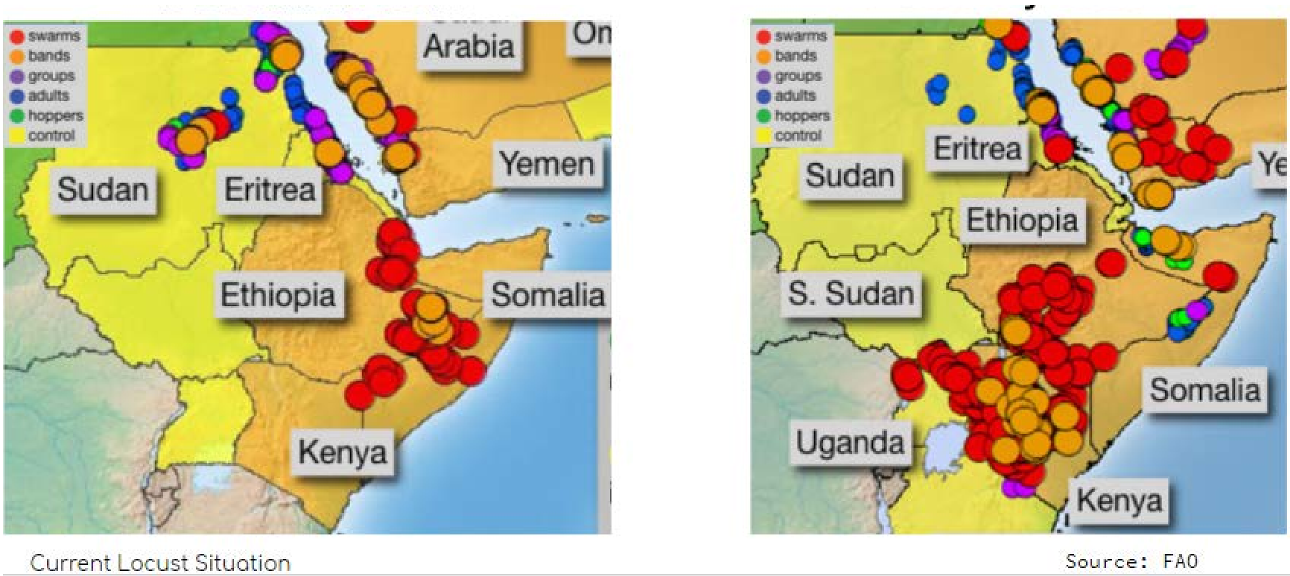

Figure 1: Desert Locust risk maps from The Food & Agriculture Organization (FAO) showing the existing location and movement of different desert locust stages from December 2019 to Feb 2020.

Areas known for being arid, and with unpredictable rainfall patterns or temperatures are strong factors to the evolution of desert locust and can ravage agriculture, eating healthy vegetation to the amount of their body weight. Assuming favorable conditions in Kenya in December 2019 and early 2020, it allowed for quick development of new bands and swarms. Populations of desert locusts began exploding during this time period, spreading throughout the country, particularly north and west of the Rift Valley.

There are many variables to consider when studying the development and propagation of desert locust. Some are more important than others, depending on which stage the desert locust is in. A recent study published in the Scientific Reports journal found that temperature had the most influence on desert locust development, followed in close by soil moisture.[7] This study is the beginning of a foundational examination needed for control operations and monitoring, posing various questions and weather variables that are important to development and migration of desert locusts.

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Areas known for being arid, and with unpredictable rainfall patterns or temperatures are strong factors to the evolution of desert locust...

7 Kimathi et al., 2020.

1.1 Study objective

The research objective was to analyze weather and climate conditions that created a conducive environment for the prevalence and growth of desert locusts in Northern and Eastern Kenya from December 2019 to May 2020. Symptoms of the impacts from desert locusts are primarily evidenced through vegetation damage and loss. It is essential to narrow down a better understanding of favorable locust conditions and at what stage in their life cycle these correlate so that the information can be used for proactive locust management. Kimathi et al 2020 focused on weather variables such as temperature, soil moisture, soil content and rainfall, weighted by importance of the variable that steered desert locust invasion.[8] However, our study employed a more holistic approach and examined all the possible variables, spanning all development stages of the desert locust.

These included surface temperature, soil moisture, soil temperature, boundary layer wind direction and speed, boundary layer relative humidity, dekadal and daily precipitation, total air column cloud cover, and dekadal Normalized Difference Vegetation Index (NDVI).

The derived objective of this research is to inform the future development of weather and climate services to proactively manage desert locust invasion in Kenya and its impacts on livelihoods and food security. The information provided in this report establishes a groundwork to inform the future design of climate services as well as for creating county-based case studies that can be used by local stakeholders to better manage future invasions. The main objective that drives this study is to reduce crop and pasture loss in order to reduce the vulnerability of rural livelihoods and prevent worsening food insecurity, as well as to be able to take preventative controls before damage occurs.

The deliverable is a case study analysis of ideal conditions favored by different stages of desert locust during the recent locust proliferation and to discuss how these are similar to, or different from, ideal weather and climate conditions found in the established literature.

8 Kimathi et al., 2020.

2. Literature review

2.1 Desert Locusts

The *Schistocerca gregaria* is just one species of locust, however, it is one of the most dangerous locust species due to its ability to fly great distances in a single day. A fascinating trait of the desert locust is that it has the ability to completely change its physiology and behavior based on the quantity of other locusts in its proximity. When locusts are present but at low densities, they are in the solitarious phase and move independently. However, when the locust population increases, they begin to congregate in groups and transform into a gregarious state as can be seen in Figure 2, below. During the transition phase, the locusts are referred to as transiens.[9] Until 1921, it was actually believed that desert locust had two different species due to the vast difference in appearance between the locust in its solitarious state versus gregarious state. In reality, solitary adults are brown while gregarious adults are either pink when they are immature or yellow once they have matured.[10]

Desert locusts usually do not pose serious threats to agriculture and food security because they tend to stay in semi-arid regions off of large cropping areas and have low population density.[11] In the "calm" state, referred to as the recession phase, most locusts are found as isolated individuals (solitarious behavior), overall population level is low, and bands and swarms are typically absent.[12] Solitarious locusts exist naturally and are in fact antisocial creatures that tend to seek isolation.[13] Figure 2 shows the recession area as delineated by the black line, which is where locusts reside during calm periods in between outbreaks. During this time, the locusts move with the winds and thus are seen in different areas depending on the season. However, when conditions are favorable and heavy rainfall occurs in the seasonal breeding areas, locusts will multiply quickly, gregarize, and can expand their reach as far as the invasion area shown by the dotted red line (Figure 2). This potentially affected invasion area covers about 30 million square kilometers and makes up 20% of the Earth's landmass.[14]

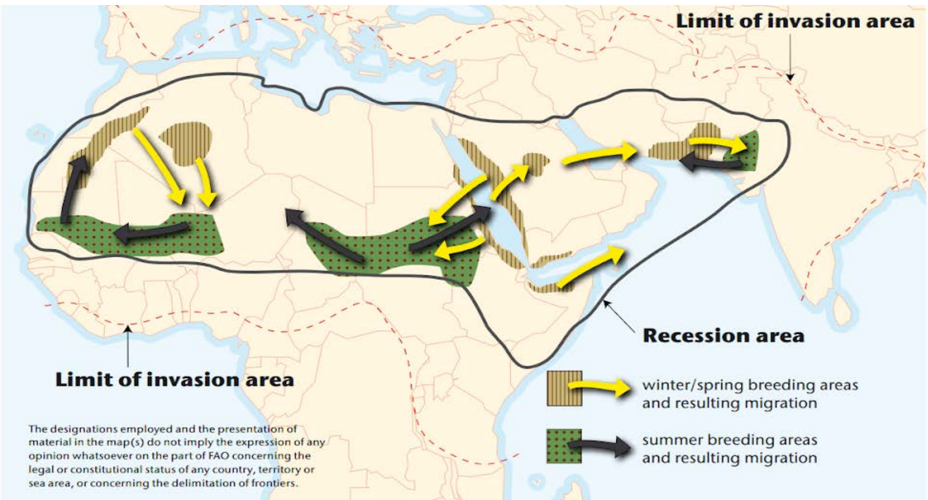

Figure 2: The desert locust recession area which covers16 million km2 spanning from West Africa to West India. This is the area during which locusts are normally seen, even during calm periods, with the red dotted line being the maximum distance locusts will travel.[15]

9 Symmons & Cressman, 2001.
10 FAO (FAQs), 2009.
11 Cressman, 2020; Brader et al., 2006.
12 Cressman, 2020; Brader et al., 2006.
13 Topaz et al., 2012.
14 Global Watch Locust FAO, 2004.
15 WMO & FAO, 2016.

The gregarious phase can be identified when locusts begin to move in the same direction and take on a "one-mind" mentality. At this point, they become ravenous and can consume their own body weight in vegetation in a single day which is about 2.5 grams. It is important to note that individual solitarious locusts are not a threat to humans nor to crops. They become dangerous to food security and the livelihood of humans once they gregarize, whether that occurs in the hopper stage or the adult stage as indicated in Figure 3. Gregarization at the hopper stage will lead to the formation of non-flying hopper bands and gregarization at the adult stage will lead to swarms that are able to easily fly up to 100 kilometers in a single day.[16]

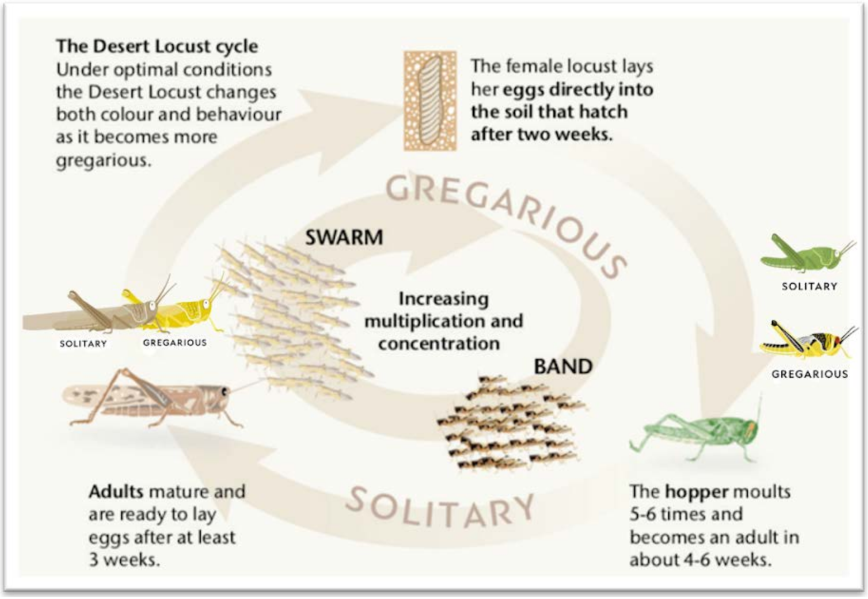

Figure 3: Desert locusts go through multiple stages before maturing. They can either gregarize as hoppers and form into bands or gregarize as solitary adults into swarms. At each stage, their outward appearance differs depending on whether they have become gregarious or not.[17]

As locust numbers increase, individuals form small groups. Grouping can be considered as an intermediate step in the change from solitary hoppers and adults to gregarious hopper bands and adult swarms. If sufficient numbers of locusts are present an outbreak can occur. An outbreak can be defined as an observed multiplication of locusts on the order of several months in relatively small, localized contexts. Two or more successive seasons of transient-to-gregarious breeding in the same or immediate location can lead to upsurges. Upsurges are typically initiated by a very significant increase in locust numbers following a recession period.[18] A plague can develop if an upsurge is not controlled and certain favorable weather conditions continue to be present. If, such outbreaks and upsurges grow more frequent and can turn into a sustained plague. A desert locust plague is the most severe and possibly most destructive category, marking a period of one or more years of widespread and significant infestations on a regional or continental scale, affecting up to 50 countries. Hopper bands and swarms are common during this time. If two or more regions are affected simultaneously on such a scale, it is considered a major plague.[19]

2.2 Climatic Drivers

Desert locust upsurges generally occur when the environmental conditions suddenly become suitable for the locusts to come out of the recession phase and reproduce rapidly. Past plagues and outbreaks have

16 WMO & FAO, 2016.
17 WMO & FAO, 2016.
18 van Huis et al., 2007.
19 van Huis et al., 2007; Joffe, 1995.

been linked to cyclones, as cyclone events produce the heavy rainfall needed for locust proliferation.[20] Due to climate change, more extreme weather events such as cyclones and extreme rainfall events are expected to occur in the region.

The Indian Ocean Dipole (IOD), nicknamed "ENSO's neighbor", is a recurring climate pattern across the Indian Ocean. Much like the El Niño-Southern Oscillation (ENSO), IOD also has negative, neutral, and positive phases that result in teleconnections in the region surrounding the Indian Ocean. During its positive phase, sea surface conditions in the western Indian Ocean become warmer than usual while sea surface conditions in the eastern Indian Ocean become cooler than usual.[21] This east-west contrast of ocean conditions impacts the wind, precipitation, and temperature patterns in each region. For example, along the coast of east Africa, a positive IOD phase leads to increased convection, increased chances of precipitation, and even flooding. In 2019, the Dipole Mode Index, which measures the strength of IOD events, indicated that 2019 was the most extreme positive event in the last 40 years.[22] Positive anomalous rainfalls create extremely favorable conditions for locust breeding and development.

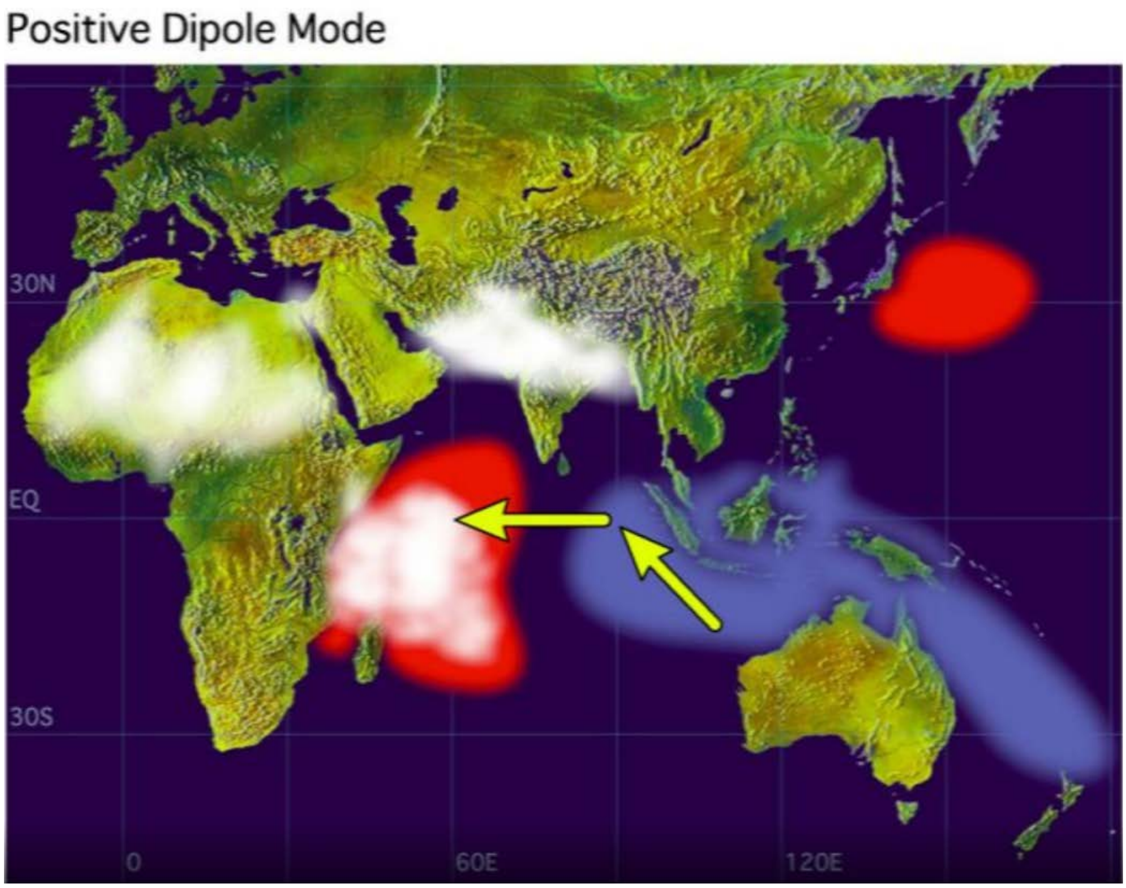

Figure 4: A positive Indian Ocean Dipole Event in which positive sea surface temperature anomalies occur in the western Indian Ocean basin. The red area indicates warmer pools of water and the blue area indicates cooler areas of water. The white areas indicate increased convective activity.[23]

In fact, in a world that is 1.5°C warmer, extreme positive IOD events are expected to occur twice as often.[24] This is compounded by the fact that temperatures are also predicted to continue to rise. Since desert locust egg and hopper development is linked to temperature, warmer temperatures will allow eggs to incubate and hoppers to develop into adult locusts more quickly. Locust generations will be able to reproduce more rapidly which can lead to outbreaks, upsurges, and even plagues at a faster rate.[25]

20 Bhalla, 2020.
21 Johnson, 2020.
22 Johnson, 2020.
23 Marchant et al., 2007.
24 Salih et al., 2020.
25 WMO & FAO, 2016.

Recently, cyclones off the coast of East Africa contributed to the conditions that allowed for the current locust plague (Figure 5). Guleid Artan, the Director of IGAD's Climate Predictions and Applications Center (ICPAC), highlighted the extreme weather conditions and climatic anomalies that the region faced in 2019 saying that it was the highest number of cyclones in one year since 1976 in the northern Indian Ocean.[26] Kenya received an unusually high amount of rainfall from October to December 2019 due to the positive IOD event, and was further impacted by Cyclonic Storm Pawan which also made landfall in December and continued to maintain favorable conditions for the locusts.

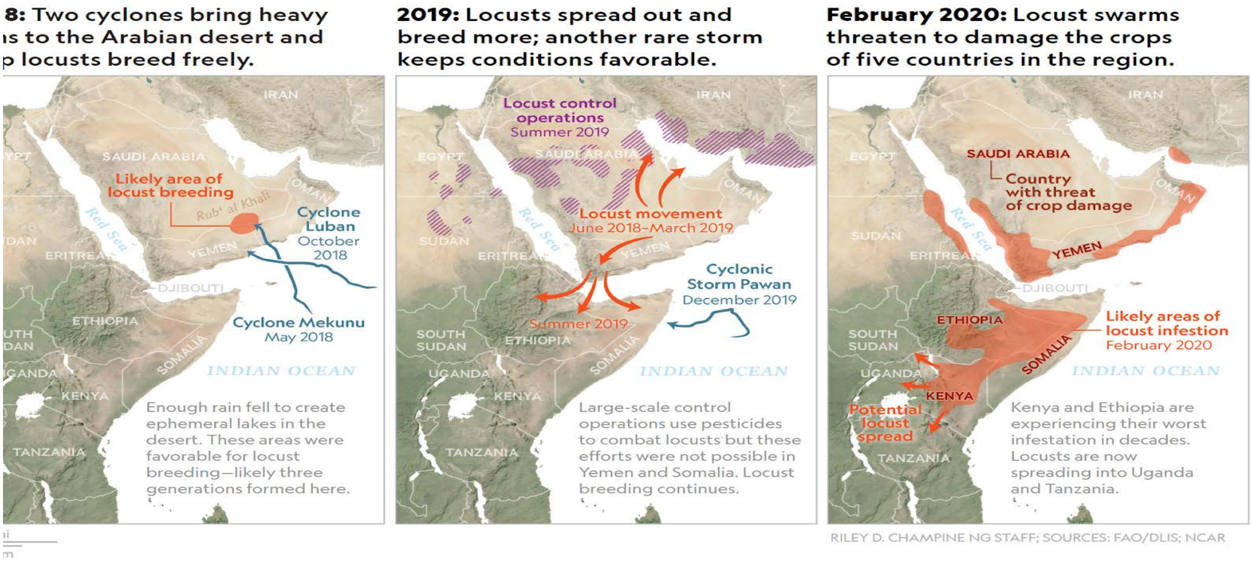

Figure 5: Rare cyclones and storms over the last two years (2018-2020) have produced anomalously wet conditions in the region, creating and maintaining favorable conditions for locusts to breed.[27]

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In fact, in a world that is 1.5°C warmer, extreme positive IOD events are expected to occur twice as often.

26 Food Security and Nutrition Working Group, 2020.
27 Stone, 2020.

2.3 Specific Weather and Bioclimatic Thresholds at each Desert Locust Stage

Figure 6 indicates how the rate of development at each stage of desert locust is impacted by a variety of factors including weather and environmental conditions. It showcases the general thresholds that desert locusts adhere to. As can be seen, not all variables are equally important at each stage of the desert locust's life. The full categorized literature thresholds can be seen in See Appendix A.

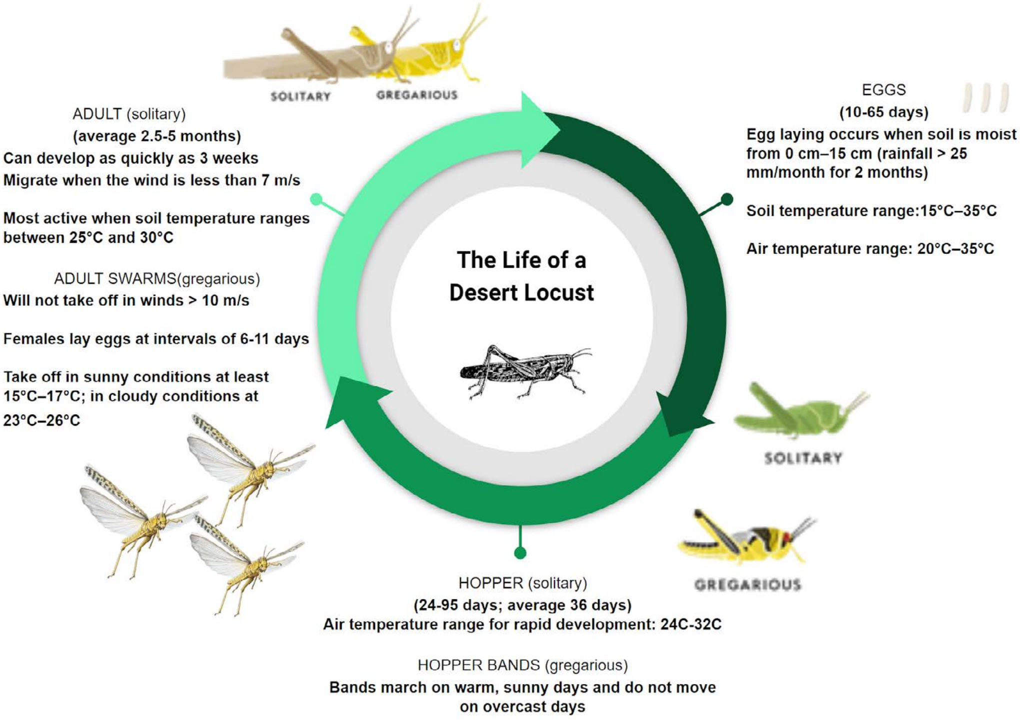

Figure 6: The rate of development at each stage of the desert locust life cycle as impacted by a variety of factors

The different stages of desert locust and the factors in which they thrive are highlighted below:

Eggs

Desert locust eggs are normally laid by females in areas of bare sandy soil when the soil is moist from a depth of 0 to 15 centimeters. Typically, moist soil at this depth indicates that there has been previous rainfall greater than 25 millimeters in two consecutive months; this is the amount assumed to be necessary for locusts to breed and develop.[28] In the case that eggs are laid in dry soil, they will dry out unless there is rainfall soon after they have been laid.[29] However, excess precipitation can be damaging, as the eggs can also be destroyed if extreme rainfall or flooding takes place after they have been laid.[30] Apart from requiring moist soil conditions, egg development is also a function of the temperature of the soil at the depth at which the eggs were laid. The suitable soil temperature range for egg viability is from 15°C – 35°C, with temperatures exceeding 35°C possibly leading to egg mortality.[31]

Hoppers

On average, hoppers develop in about 36 days, but can develop in as quickly as 24 days or as slowly as 95 days. Hoppers are locusts that are at the wingless, juvenile stage. The hopper will moult 5 or 6 times before eventually becoming an adult in about four to six weeks. The development from eggs

28 WMO & FAO, 2016.
29 WMO & FAO, 2016.
30 WMO & FAO, 2016.
31 WMO & FAO, 2016.

into hoppers is a function of temperature, with the hopper development period decreasing as daily air temperature increases from 24°C to 32°C. The warmer the air temperature is, the faster hoppers will develop into adults. It is important to note that the correlation between air temperature and hoppers is a bit less clear than the relationship between air temperature and eggs; this is attributed to the fact that hoppers are able to considerably control their body temperature by basking or by seeking shade when necessary. For example, at midday when temperatures are the warmest, hoppers take shelter inside of plants.[32] Hoppers indirectly need rainy conditions since they require edible vegetation to consume as they develop. Hoppers are more likely to be found when NDVI is between 0.12 and 0.60, according to a study done by Gómez et al. in 2019.[33] This vegetation index level indicates the presence of low vegetation such as shrubs and grassland. Figure 1 in Appendix A shows the range of NDVI values and their corresponding land cover characteristics. In terms of movement, hoppers are not able to fly, but when they march, they tend to move downwind.

Hopper Bands

If hoppers are in their optimal conditions, they can congregate to form bands which will then become adults and swarms. Hopper grouping normally occurs in less uniform, open terrains, where there are patches of dense vegetation interspersed with large areas of bare soil.[34]. As the hoppers continue to congregate, they become more gregarious until they eventually form a band. Bands will march downwind in search of vegetation to consume on warm, sunny days, but do not move on overcast days. During warm and sunny days, the bands will move in an alternating pattern of marching and roosting in vegetation throughout the day. If the vegetation is too dry, bands may continue marching throughout the night in search of green vegetation.[35]

Adults

Adults mature on average in about 2-4 months, but can mature as quickly as 3 weeks or up to 9 months. Adults start to mature and will mature more rapidly when they are in areas that have received "recent significant rains", and mature more slowly when they are in dry habitats or areas with low temperatures. As adults, they are able to fly and reproduce. When they first begin to fly, adults are sexually immature, but eventually they become sexually mature and are able to copulate and lay eggs.[36] Solitarious adults will fly and migrate at night when the wind speed is less than 7 meters per second and when the temperature is above 20–22°C. They are able to fly for up to 10 hours, but normally will only fly for a few hours at a time. They can fly at heights of up to 1800 meters but generally stay below 400 meters at speeds of 25-65 km/hr. If the temperature goes below 20°C, sustained flights will be rare. Solitarious locusts are most active when the soil temperature ranges between 25°C and 30°C.[37].

Swarms

In the absence of wind, locusts fly at about 3-4 meters per second. They fly downwind, although some swarms may fly upwind briefly if the wind is light. Swarms may fly up to 9 or 10 hours in one day and will begin to settle about one hour before sunset as convection slows down (WMO & FAO, 2016: 6). Swarms fly downwind during the day at heights up to 1700 meters with a ground speed of 1.5 to 16 km/hr and fly out to 5-200km. They generally take off 2-3 hours after sunrise in warm weather and 4-6 hours after sunrise in cool weather. In sunny conditions, they will take off if the temperature is at least 15°C–17°C and in cloudy conditions if the temperature is at least 23°C–26°C.[38]

32 WMO & FAO, 2016.
33 Gómez et al., 2019.
34 WMO & FAO, 2016.
35 WMO & FAO, 2016.
36 WMO & FAO, 2016.
37 WMO & FAO, 2016.
38 WMO & FAO, 2016.

3. Study Area

This study focused on the Northern part of Kenya which was adversely impacted by the desert locust invasion and has counties that are most vulnerable due to high poverty and food insecurity. As predicted by FAO's initial map on desert locusts in January 2020,[39] desert locusts flying in from Somalia would likely spread to the northern counties first and then migrate further inland. Figure 7 shows the counties that were already affected by early June 2020.

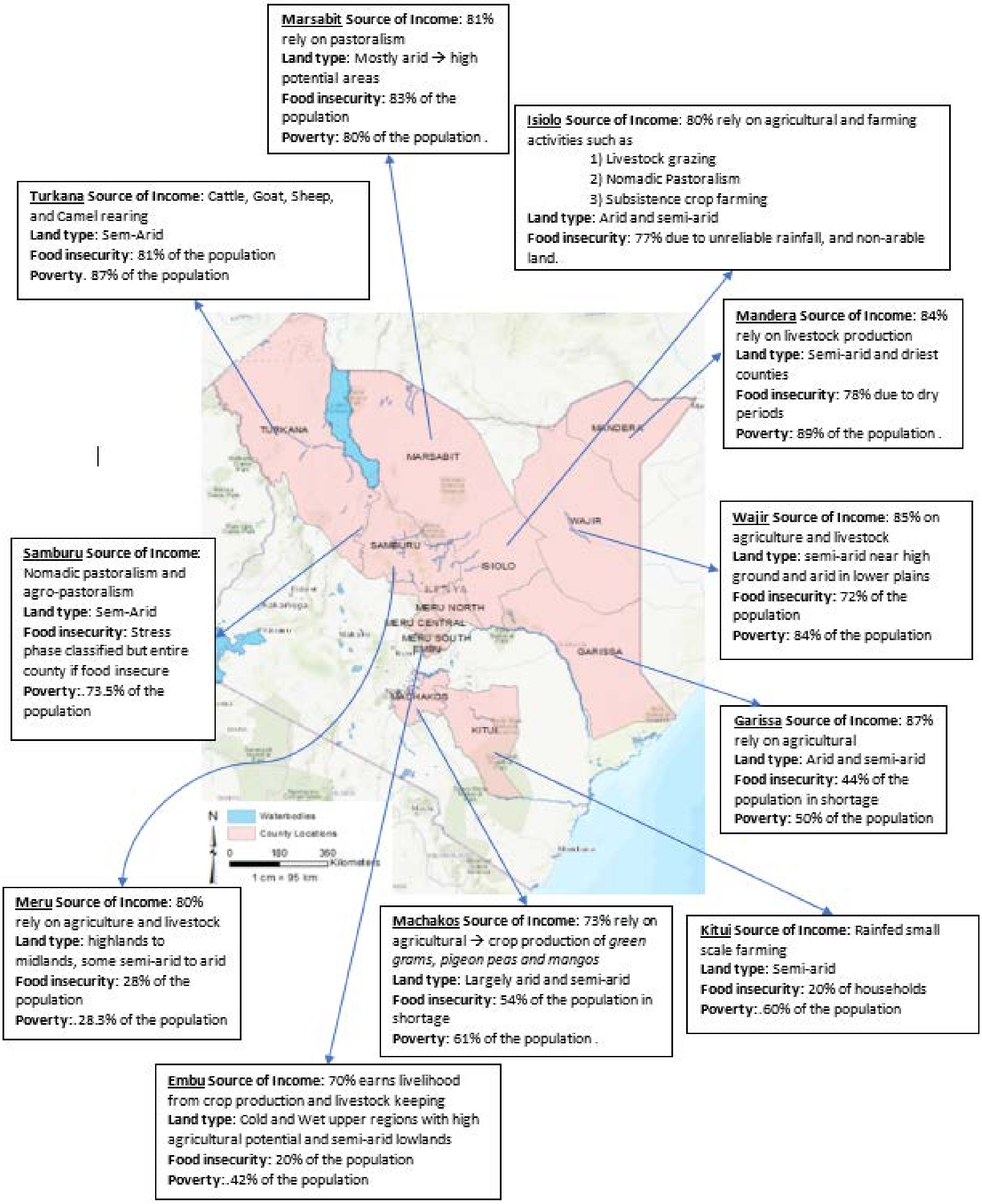

Figure 7: The study focused on the ten counties shaded in pink, in northern and Eastern Kenya. Land type, primary source of income, and levels of food insecurity and poverty of the county's population are summarized in each box.

39 FAO Locust Watch, 2020.

4. Data and Methodology

4.1 Data sources

Cyclones, October to December 2019 rains, and other environmental factors and weather conditions may all have led into the attraction and expansion of locusts in Northern and Eastern Kenya.[40] Based on literature review conducted at the beginning of the data collection period, a typology table was created in order to understand the ways in which the desert locust development stages are influenced by environmental, weather, and bioclimatic variables. The typology compiled from literature included specific preferred thresholds for each locust stage (egg, hopper, band, adult) for different variables.

Remote sensing and ground data of the relevant weather parameters were extracted from various sources, all of which are summarized below in Table 1. Social media data was collected to provide additional depth to the analysis and to fill in reporting gaps. Sightings of the different life cycle stages of locusts are the center of the desert locust and climate study and were extracted from the FAO Locust Hub which is updated weekly (Figure 8) combined with desert locust observations obtained from Kenya Red Cross Society.

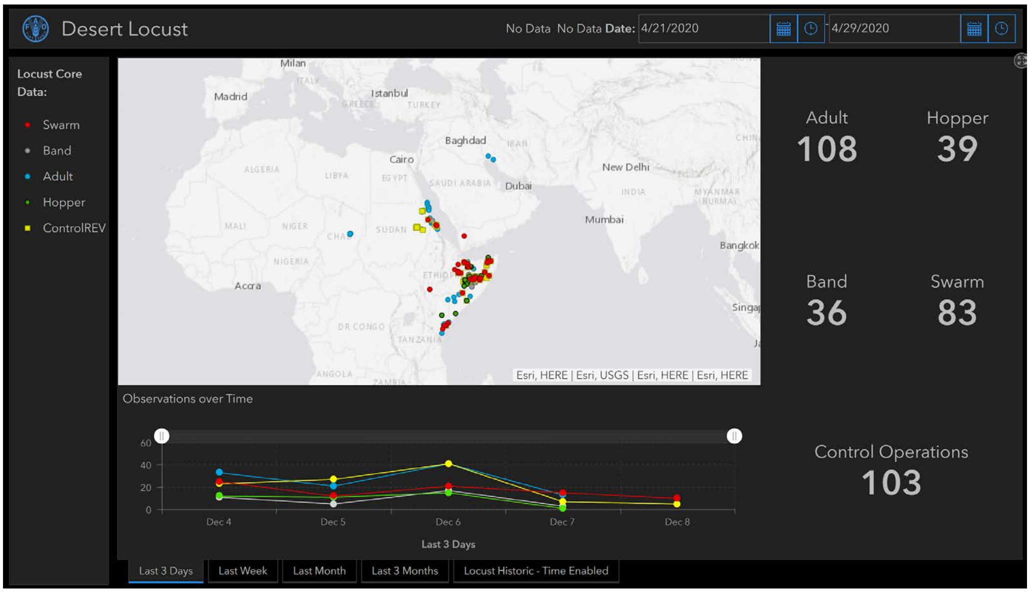

Figure 8: The FAO Desert Locust Hub shows observations over time categorized by desert locust life cycle stage.

Daily and dekadal precipitation, daily relative humidity, daily cloud cover, daily wind speed/direction, and monthly soil moisture were obtained from Columbia University's IRI Data Library, whereas daily soil temperature data was obtained from NASA NSIDC and daily global temperatures (max and min) are from NOAA Physical Sciences Laboratory.[41] The Copernicus Global Land Service provided us with the Normalized Difference Vegetation Index (NDVI), which was utilized to identify possible areas with appropriate/sufficient vegetation levels for locust growth and consumption. Kenya's soil type was gathered from ISRIC website, the KENSOTER 2.0 database that has compiled soil composition information from 1996 to 2004. Soil profile selection for KENSOTER, is not probabilistic but based on available data and expert knowledge.[42]

40 Salih et al., 2020; Cressman, 2020.
41 See Annex for detailed list of data sources with links.;;
42 Batjes & Gicheru, 2004.

A Twitter Scraper was coded in Jupyter Notebook to search for Tweets linked to the relevant counties and time periods of this study and had been used for selected keywords (social media web scraping).[43] No such license could be obtained for Facebook and Instagram which is why the focus remained on Twitter.

Table 1: Data sources used in this study

DATA SOURCES FOR LOCUSTS SIGHTINGS, WEATHER PARAMETERS, AND SOCIAL MEDIA DATA									
Sources **Weather Parameters**	**Resolution**	**FAO Locust Hub**	**IRI Data Library**	**Copernicus Global Land Service**	**NASA NSIDC**	**NOAA/OA/R/ESRL/PSL**	**KRCS**	**ISRIC**	**Twitter**
desert locust Sightings (daily)	NA	X					X		
Soil Temperature [in°C] (daily)	36km				X				
Soil Moisture &)	210km (IRI- monthly: 0-10cm) 36km (NASA- (daily: 0-5cm)		X		X				
Wind Speed [m/s] & Direction [deg] (daily)	275km		X						
NDVI (dekadal)	300m			X					
Precipitation [mm] (dekadal, daily)	11km		X						
Precipitation Anomaly [mm] (monthly)	275km		X						
Cloud cover [Total air column cloud coverage] (daily)	210km		X						
CPC Daily Global Temp, Min, Max Temp [in°C], *average derived	55km					X			
Soil Type (KENSOTER 2.0)	100km							X	
Social Media Data	NA								X

43 Keywords applied: *locust invasion, locusts, locust in Kenya, locusts in east Africa, hoppers,desert locusts,locust infestation, locusts spotted, locust Marbabit/Turkana/Wajir…,nzige*

4.2 Preprocessing, Data Selection and Assumptions

Due to challenges related to high data quantity, very limited computing capacity and relatively short timelines (on the order of two months), a decision was made to narrow the originally proposed time period (Dec 2019 - May 2020) down by identifying the dekadal periods with the single most sightings per category (hoppers, adults, bands and swarms respectively). This resulted in two dekads. Most swarm sightings fall into the Apr 21-29 dekad, whereas most sightings for adults, hoppers and bands were all sighted from May 21-31. A central criterion for the selection of these dekads is the assumption that the selected cases with highest observed sightings are a proxy for ideal conditions (meaning that highest locust counts reflect ideal conditions). Furthermore, this implies that the observations within these dekads provide meaningful information about exceptionally favorable climate conditions for different locust life cycle stages which allows for a comparison between thresholds in the literature and observed conditions.

Each weather parameter has a category with predefined ideal thresholds determined by existing desert locust literature. The high frequency sightings observations are compared to these ideal conditions and according to the literature thresholds, a computation is conducted to categorize whether the observed values fit into the ideal range, or fall below or above the ideal thresholds. Most of our weather variables, including temperature and cloud cover are reanalysis data of daily averages. We understand that daily average is a generalization of the day and that at certain times of the day, some weather conditions may have been more or less favorable for movement and or development. The variable average obtained at that point for that day, along with the 'ideal' thresholds found in previous literature and case studies were used to make a decision as to how we expected the desert locusts to move, behave, or develop on that particular day. These decision columns were added to our final data excel sheets.

Each weather parameter has a category with predefined ideal thresholds determined by existing desert locust literature.

Rainfall for corresponding and preceding dekads were considered, however, no correlations were made between the two variables. Doing so would give us an even better idea of whether or not a decrease in the NDVI value in a particular area over time was primarily a result of destruction from desert locust or lack of rainfall. Instead, monthly precipitation anomalies were referenced when determining whether rainfall was sufficient or not for vegetation growth in a particular area. At or above normal monthly precipitation anomalies were considered sufficient rainfall, while negative monthly precipitation anomalies were not.

Due to the lack of information in the surveys regarding desert locust phase at the time of observation, we worked under the assumption that all desert locusts in our 'adult' category were solitarious. Only some of the data points specified which phase the adults were spotted in. However, since there was a specific category for swarms, which we know are gregarious adults, we had to assume that the "adults" data were not gregarious (and therefore solitarious). This is important because there could be different results based on the exact behavioral stage of the desert locust, as compared to placing all of the hoppers or adults into one general behavioral category as was the case in this particular study. An example of this would be a more significant and noticeable decrease in NDVI values with gregarious adults moving through an area as compared to solitarious adults.

4.3 Social Media Data Mining

After requesting a license from Twitter to work with their data for the purpose of this research study, social media scraping was applied to extract tweets sent from the selected counties within the relevant time period (December 2019 to May 2020). The tweets linked to counties and keywords that connect to locust sightings and discussion of the perceived locust plague in Kenya. The generated data provided insight into how the Kenyan society perceives the damage and handling of the locust plague and may prove useful for creating a sensitive desert locust climate service that is truly effective at the community level.

While on the one hand, it became very clear that there is a significant proportion of Kenyans who are very religious and tend to link the recent plague to the ten plagues mentioned in the Bible; a noticeable portion of tweets also suggested that there is a mistrust in science (primarily regarding the science of climate change) and a lack of trust in official governmental agencies that are responsible for managing this humanitarian crisis. The tweets also contain information regarding external factors that are not well documented otherwise, but which provide insight as to how the plague worsened in light of disrupted supply chains caused by COVID-19. In one case, a twitter user linked the delayed delivery of pesticides in Eastern Africa to the drastic unfolding and spread of the plague. Given the complex differentiations between various lifecycle stages of locust and the nature of social media content, it did not prove very applicable to map social media sightings in GIS for the purposes of this study.

The average twitter user does not have expert knowledge regarding the different lifecycle stages of locusts (hoppers, adults, bands, swarms) that are pivotal for this study. Furthermore, open-source data can distinguish between counties but it was not possible to retrieve specific latitude and longitude data points due to privacy policies. Eventually, there was overwhelmingly low evidence that the average user of the social media platform Twitter (correctly) distinguishes between locusts categories or objectively reports a sighting rather than commenting on their overall feelings and emotions regarding the locust crisis that is ravaging over Kenya and neighboring countries. Due to such insufficient distinction between categories, it was not recommendable to match the social media sightings with adequately reported FAO or KRCS sightings because the possible errors could lead to a misrepresented picture of reality rather than adding to the correct reporting of sightings. Nonetheless, the information provided by such tweets greatly enhance the qualitative scope of this study and account for socioeconomic impact, while informing careful design of future climate service and adaptation products.

The tweets linked to counties and keywords that connect to locust sightings and discussions and discussion of the perceived locust plague in Kenya.

...possible errors could lead to a misrepresented picture of reality rather than adding to the correct reporting of sightings.

4.4 Tools and Methods used in data analysis

Since locusts were first sighted in Kenya in late December 2019, the relevant time period of this research project was defined as December 2019 to May 2020, although it needs to be acknowledged that the months following our research period, the locust plague intensified in East Africa. Key questions to be answered are, ***"What are the conditions that make locusts thrive in Kenya?" and "Are there notable differences from the conditions described in the literature?".***

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"What are the conditions that make locusts thrive in Kenya?" and "Are there notable differences from the conditions described in the literature?".

The tools employed for data analysis were ArcDesktop software and Excel. Most of our data were in the form of GIS compatible layers and rasters, with each desert locust data separated into different stages and using raster geoprocessing tools to extract bio-climatic data on the locations sighted. Soil type information from KENSOTER similarly was already symbolized into lithology, landform and dominant soils which was compared to FAO's major soil components categorization report. Data points from KRCS survey and FAO's Locust Hub that categorized desert locusts into separate categories were used. Each stage was then queried and represented as a point layer in GIS with an attribute table of the seven weather variables analyzed in our study. Maps of the desert locust stage layers and bio-climatic data rasters were overlaid in order to visualize the conditions in parts of Kenya during certain dekadal/ daily time periods within the case study time frame of December 2019 to May 2020. The data we had for weather variables ranged from daily to dekadals to monthly.

The GIS attribute tables belonging to each desert locust stage and time period of most sightings were then converted to excel sheets where calculations were done for comparison between ideal weather conditions and observed weather conditions. Averages were calculated for each weather variable to be assigned to the dekadal average maps from the data extracted at the sighted points of each stage. For this study, we also decided to utilize mode in order to identify the most commonly occurring values within our sample of dekadal data to be able to create a table of preferred conditions at each locust stage in the ten specified counties of Kenya. The mode was calculated for each weather/ bioclimatic parameter (air temperature, soil temperature, wind speed, cloud cover, NDVI, precipitation) at each desert locust stage (hoppers, bands, adults, swarms). Pie charts were made to visualize the percentage of data for each stage that matched the literature threshold range and the percentage that did not within the selected dekad for that specific desert locust life cycle stage. Additionally, scatter plots were made of the most relevant weather and bioclimatic variables at each stage, which helped in visualizing the distribution of the points around the mean as well as where the points aligned in relation to the thresholds obtained from literature. Understanding the extent of the range of our observed data also allowed us to visualize the probability distributions of each weather/bioclimatic variable and how much of the data was found within one standard deviation of the mean, outside one standard deviation, or outside the bounds of the literature thresholds. These graphs can be found in the Results section of this paper.

After analyzing all GIS maps, histograms, pie charts, and probability distribution/standard deviation graphs, a table of frequently observed characteristics and overall range of observed characteristics for each desert locust stage and weather/bioclimatic variable was created and is located in the Results and Discussion section of this paper (Table 2, 3). This table summarizes the findings of the case study analysis for the dekad with the highest sighting frequency for each stage of the desert locust life cycle that had no previous bioclimatic thresholds based on earlier desert locust studies. It has the potential to serve as a base for a future typology that covers the entire period from December 2019 to May 2020, or as long as locusts are still present in Kenya. Table 3 compares our case study thresholds with ideal conditions from literature so we can understand to what extent the conditions of desert locusts in Kenya differs from conditions elsewhere.

4.5 Limitations and Challenges

A significant assumption in our case study was that the most frequent observations of desert locusts were solely based on where different stages were congregated at a particular period in time. In other words, we were assuming it was not because surveying was being performed in a particular area, during a specific time, which created a spike in observation points in that area for that time period. This could have indeed been the case, but without the survey plan and background information, we could not confirm. Either way, the fact there were sighting points encompassing all stages, regardless of timing and location of surveys, desert locusts were present and propagating during this time and our team was still able to capture the conditions that were present in order to produce our FOCs chart based on this.

Surface air temperature utilized was the daily average temperature. This limited the scope of our study because we were not able to distinguish between night and day temperatures, which we know can fluctuate quite meaningfully. Furthermore, locust movement and roosting periods are often based on temperature, thus further precise study suggestions are listed in the recommendations.

Due to data storage capacity limitations and restricted access to certain material and non-material resources (mostly caused by the COVID-19 pandemic), the desert locust and climate study had to be subjected to certain adjustments and was adopted for a narrower focus in comparison to its initial proposal. The data extraction period was adjusted by 3.5 weeks to accommodate research for open source, high resolution data and unforeseen large data downloading delays this data due to GIS issues with extracting files compatible with software and incomplete latitude/longitude layers. remotely, from private devices. This resulted in storage issues which had to be dealt with from private devices as members worked remotely, handling large bytes of files, and added to time to the data extraction process.

Additionally, geoprocessing on individual laptops and high-programming software slowed analysis speed on simple tasks such as creating raster layers from one variable of weather data or converting months of locust sightings into one working analysis layer. Multiplying this by over ten weather variables is in itself enough to set a project back several weeks. A viable solution to these challenges was to limit the proposed time period (December 2019 - May 2020) from a broad approach to more selective time periods that identified the respective dekadals with the highest frequency sightings for each locust life cycle category. Increased computing capacity and storage in any future case studies similar to this one would be advised.

Increased computing capacity and storage in any future case studies similar to this one would be advised.

5. Results and Discussion

This section compares the weather and bioclimatic characteristics that were most often observed in this case study to the desert locust literature thresholds established by the WMO and FAO. Any figure that mentions ideal conditions is referring to the conditions established by literature.

The two dekads under analysis were April 21-29 and May 21-31, 2020. The most impacted counties in these time periods were Turkana, Marsabit and Isiolo. Swarms were mainly concentrated in Samburu and western Isiolo. Bands were seen in Turkana and western Marsabit. Adults were equally concentrated in Marsabit, Mandera, Wajir, and Turkana counties. Most sightings for hoppers were in Turkana and western Marsabit in proximity to Lake Turkana.

There are many bioclimatic variables to consider when studying the development and propagation of desert locust. Some are more important than others, depending on which stage the desert locust is in. A recent study published in the Scientific Reports journal found that temperature had the most influence on desert locust development, followed in a close second by soil moisture (Kimathi, et al). Although further analysis would be needed, this could potentially be one of the reasons why desert locusts were able to propagate so quickly after they made their way into Kenya back in December of 2019. In a more general sense, our study examined all the possible variables, spanning all development stages of the desert locust (Table 2 and 3). These included average surface temperature, soil moisture (0-10cm), soil temperature (0-5cm), wind direction and speed (1000mb), dekadal and daily precipitation, total air column cloud cover (% coverage), and dekadal Normalized Difference Vegetation Index (NDVI).

Table 2: Frequently Observed Characteristics & Internal Ranges

Table 2 shows the frequently observed characteristics for each relevant weather and bioclimatic variable, including the ranges with the highest frequency counts, based on the dekads used for the case study analysis. The percentage of total observations are shown for both the mode and highest frequency range.

Ideal Thresholds for Desert Locust Stages	Wind Velocity	Avg Temperature	Soil Temperature	Soil Moisture	Cloud Cover	NDVI
Eggs	N/A	Mode: 22.3°C	Mode: 26.7°C	0.27cm³/cm³	N/A	N/A
Hoppers (assumed S) - 363	Mode: 2.6 m/s (40/363=11.0%) Range for Highest: 2.55m/s - 2.76m/s (49/363 = 13.5%)	Mode: 28.3°C (24/363=6.6%) Range for Highest: 27.89°C - 28.68°C (96/363 = 26.5%)	Mode: 36°C (56/363=15.4%) Range for Highest: 34.47°C - 35.26°C (121/363 = approx. 33%)	Mode: 0.1 cm³/cm³ (297/363=81.8%) Range for Highest:0.09-0.11cm³/cm³ 297/363=81.8%	Mode: 30% (36/363=9.9%) Range for Highest:41.84% to 45.53% (79/363 = 22%)	Mode: 0.17 (21/363=5.8%) Range for Highest: 0.23 - 0.29 (81/363 = 22.3%)
Adults (assumed S) - 163 locust sightings	Mode: 3 m/s (23/163=14.1%) Range for Highest: 2.32-2.73 (30/163=18.4%)	Mode: 23.8°C (16/163=9.8%) Range for Highest:28.18-29.55 (46/163=28.2%)	Mode: 31°C (17/163=10.4%) Range for Highest: 33.18-34.55 (51/163=31.3%)	Mode: 0.1cm³/cm³ (147/163=90.2%) Range for Highest:0.10-0.12 cm³/cm³ (134/163=82.2%)	Mode: 50% (26/163=16.0%) Range for Highest: 55.91-62.73 (35/163=21.5%)	Mode: 0.42 (11/163=6.7%) Range for Highest: 0.18-0.25 (36/163=22.1%)
Hopper Bands (G) - 322	Mode: 4.1 m/s (54/322=16.8%) Range for Highest: 2.55-2.76 (49/322= 15.2%	Mode: 31.2°C (38/322=11.8%) Range for Highest: 27.89-28.68 (96/322=29.8%)	Mode: 36.2°C (85/322=26.4%) Range for Highest: 34.47-35.26 (121/322=37.6%)	Mode: 0.1cm³/cm³ (206/322=64.0%) Range for Highest: 0.09-0.11cm³/cm³ (297/322=92.2%)	Mode: 42% (54/322=16.8%) Range for Highest: 41.8-45.5(79/322=24.5%)	Mode: 0.16 (37/322=11.5%) Range for Highest: 0.23-0.29(81/322=25.2%)

Ideal Thresholds for Desert Locust Stages	Wind Velocity	Avg Temperature	Soil Temperature	Soil Moisture	Cloud Cover	NDVI
Swarms (G) - 116	Mode: 2.9m/s (21/116=18.1%) Range for Highest: 2.14-2.68 (29/116=25.2%)	Mode: 27.2°C (13/116=11.2%) Range for Highest: 21-22°C (46/116=39.6%)	Mode: 26.1 (39/116=33.6%) Range for Highest: 26-27°C (45/116=38.8%)	NA	Mode: 66% (26/116=22.4% Range for Highest: 61-65.5 (30/116=25.9%	Mode:0.93 (11/116=9.5%) Range for Highest: 0.27-0.36 (28/116=24.1%)

Table 3: Overall Range of Observed Characteristics

Table 3 shows the full range (minimum value observed to maximum value observed) of observed characteristics for each relevant weather and bioclimatic parameter based on the dekads used for the case study analysis. The content in bold are the observations from this case study, while the normal font below denoted with an asterisk refers to the literature.

Observed Ranges in Study Area	Wind Velocity	Avg Temperature	Soil Temperature measured at a depth of: 0-5cm	Soil Moisture measured at a depth of: 0-5cm 0-10cm (eggs)	Cloud Cover	NDVI
Eggs	N/A	**21.0°C - 23°C**	**25°C - 27°C**	**<0.3cm³/cm³** Laying of eggs occurs when soil is moist 0 cm–15 cm (rainfall > 25 mm/month for 2 months)*	**N/A**	**N/A**
Hoppers (assumed S) - 363	**1.73m/s - 5.21m/s, towards N/NW** Movement is usually downwind*	**22.8°C - 31.4°C** Development period decreases with increasing daily air temperature from 24°C to 32°C*	**26.8°C - 36.4°C**	**0.0cm³/cm³ - 0.3cm³/cm³** Development indirectly requires sufficient rainfall, since the hoppers require edible vegetation for survival*	**8%- 73%**	**-0.08/0.06 - 0.93** More likely to be found at an NDVI value of 0.12**

Observed Ranges in Study Area	Wind Velocity	Avg Temperature	Soil Temperature measured at a depth of: 0-5cm	Soil Moisture measured at a depth of: 0-5cm 0-10cm (eggs)	Cloud Cover	NDVI
Adults (assumed S) - 163	**1.5m/s - 5.6m/s, towards N/NW** Migrate when the wind is less than 7 m/s, usually downwind*	**23.6°C - 31.2°C** Migrate at night when the temperature is above 20–22°C and wind < 7 m/s*	**26.8°C - 36.4°C** Most active when soil temperature ranges between 25°C and 30°C*	**$0.1cm^3/cm^3$ - $0.3cm^3/cm^3$** Adults mature rapidly in areas receiving recent significant rain*	**16%- 66%**	**0.11 - 0.93**
Hopper Bands (G) - 322	**1.7m/s - 4.7m/s, towards N/NW** Movement is usually downwind*	**23.8°C - 31.4°C**	**30.9°C - 36.4°C**	**$0.0cm^3/cm^3$ - $0.3cm^3/cm^3$** Development indirectly requires sufficient rainfall, since hopper bands require edible vegetation for survival*	**15%- 65%** March on warm, sunny days; bands do not move on overcast days*	**0.09 - 0.93**

Observed Ranges in Study Area	Wind Velocity	Avg Temperature	Soil Temperature measured at a depth of: 0-5cm	Soil Moisture measured at a depth of: 0-5cm 0-10cm (eggs)	Cloud Cover	NDVI
Swarms (G) - 116	1.91m/s - 5.02m/s Will not take off in winds > 10 m/s. Movement is moving downwind during the day, although mature swarms may sometimes move a short distance upwind if the wind is light*	19.3°C - 29.06°C In general, sustained flight of swarms is rare if temperatures are below about 20°C; however in sunny conditions they will take off if 15°C–17°C or higher. If there are overcast conditions, then this lower limiting temperature is about 23°C-26°C or higher*	25.4°C - 34.38°C	N/A	27% - 66% Will take off in sunny conditions at least 15°C–17°C; in cloudy conditions at 23°C–26°C*	0.13 - 0.93

***WMO & FAO 2016**

****Gómez et al. 2019**

Case Study Frequently Observed Characteristics vs. Established Literature Thresholds

5.1 Hoppers

After synthesizing the entire dataset from December 2019 to May 2020, the dekad with the most hopper sightings was from May 21st to 31st (3rd Dekad of May). Figure 9 shows the spatial overlay of hoppers to the geography of Kenya and the weather variables within that dekad. Most of the sightings were observed in Turkana county, the western side of Marsabit county and in close proximity to Lake Turkana. Figure 9 shows seven weather variables of the 3rd dekad of May. These weather variables are overlaid with coinciding hoppers seen in the ten counties of Kenya. The case studies show the average for soil temperature at the hopper points is 34°C, average NDVI index of 0.28, average soil moisture index of 0.1 cm3/cm3 (10% saturation for that dekad), total precipitation of 0 mm, average air temperature of 28°C, average cloud cover between 37.5% and average wind speed of 3 m/s from a south to southeast direction.

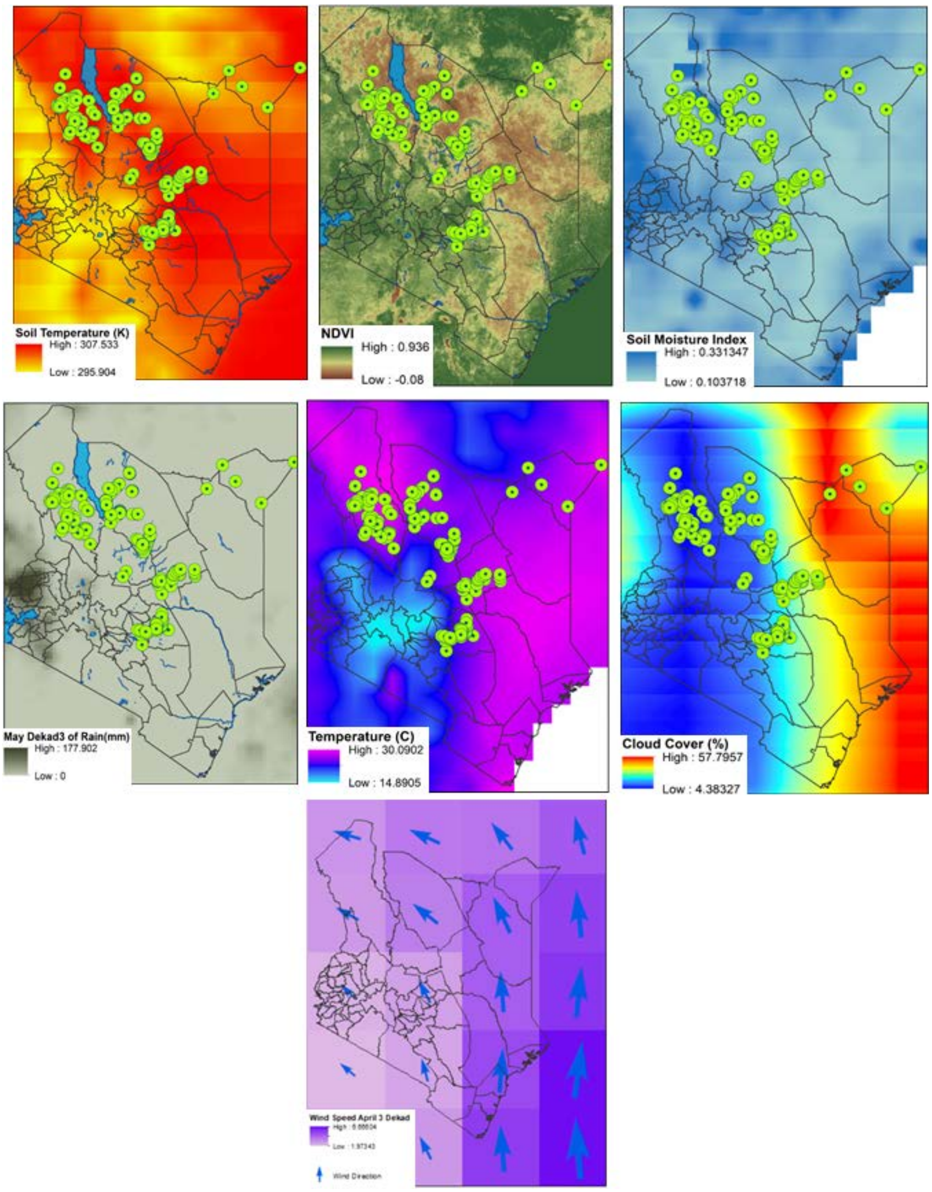
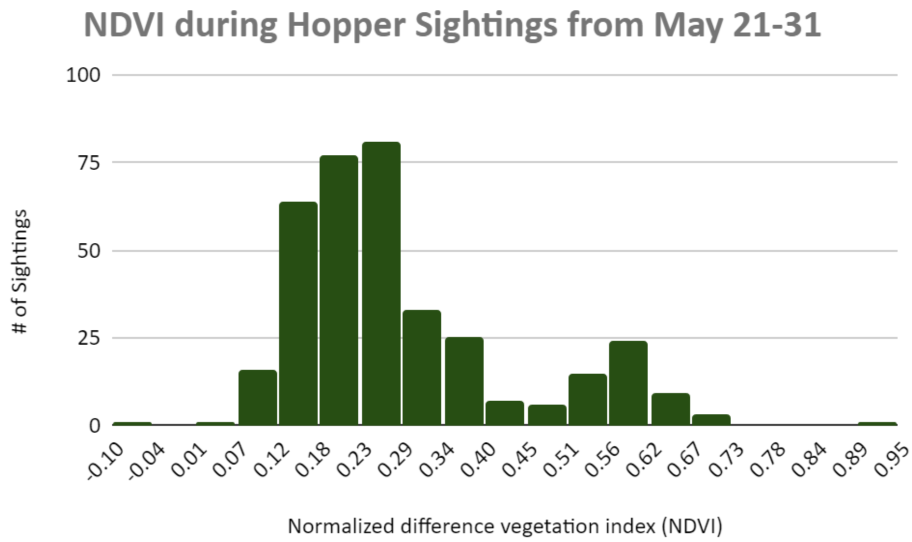


Figure 9: Seven weather variables overlaid with coinciding desert locust hopper sightings from May 21st - 31st in ten counties in Kenya.

Based on literature review of previous desert locust outbreaks, our observed characteristics either fall under these characteristics or just outside of the ideal range. Out of the seven characteristics observed, for hoppers only four are most favorable, which are wind direction, surface temperature, precipitation and NDVI (vegetation growth). Comparing the literature values to our observed characteristics, surface temperature needs to be considered since the warmer the temperature, the faster hoppers will mature and become adults which can be seen in Figure 6. Despite not being able to fly, hoppers have been found to travel in a downwind direction. Our observed characteristics indicate a south/southeast to north/northwest flow at relatively low speeds. Lastly, precipitation and NDVI also need to be considered based on the fact that hoppers need vegetation to eat in order to develop. The higher the precipitation amounts, the greater chance of vegetation growth which can translate to a higher NDVI value. According to literature, hoppers indirectly require rainy conditions since they need edible vegetation in order to survive. Even though the dekad with most hoppers observed also recorded 00 mm of precipitation (Annex 1), the observed NDVI index of 0.28 indicates that there was vegetation available for them to consume, most likely due to higher rainfall amounts a few dekads prior.



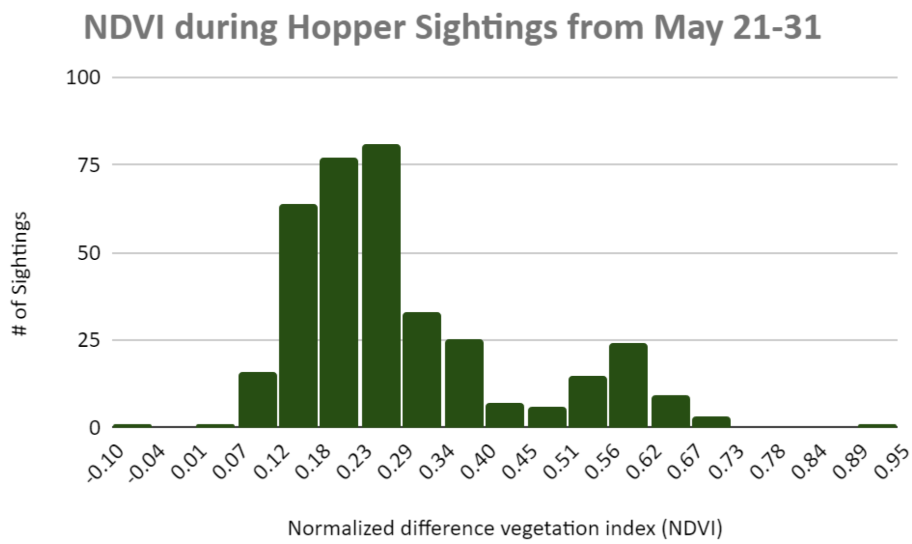


Figure 10: Distribution of dekadal NDVI values at all of the hopper sighting locations during the period of most hopper sightings from May 21-31, 2020.

To determine the impact of the hoppers during this period, NDVI and monthly precipitation anomaly for May was utilized. NDVI was used in this case study as an indicator of vegetation health and availability, and does not necessarily tell us what type of vegetation was present. Considering there is a lag between the hopper invasion and the impact on vegetation, the NDVI for the following dekad (June 1-10) were extracted. NDVI changed from 0.22 during the last dekad of May to (-) 0.4 in the 1st dekadal of June which indicates either dead or non-existing vegetation (Figure 10). This could either be due to the destruction caused by desert locust or the lack of precipitation observed (0 mm) during May. An extra addition to these points would be to create buffer zones to see how far hoppers will go to eat healthy vegetation.

While dekad 3 of May had the highest number of hoppers sighted, the soil moisture index at 0-5 cm was 0.10cm^3/cm^3, which depicts relatively low soil moisture. Thus, this characteristic was not a main factor in hopper behavior. However, the study determined the soil moisture values to coincide with NDVI values and see if vegetation growth matched with the moisture content in the soil. As water stays relatively longer in soil over a period of time, soil moisture from earlier in the month of May was collected as there was more precipitation across all of the hopper sighting points which the soil moisture and NDVI reflect. In this case study, it was assumed that sufficient rains were indicated by whether or not precipitation was at or above normal for the particular month in which the dekad of most frequent sightings occurred. Nearly 68% of hopper sightings from May 21-31, 2020 (Figure 11) and these earlier periods were sufficient in hopper and band developments as there was enough vegetation to provide food and shelter. This concludes that throughout the month of May, desert locust developed and a higher sighting was observed towards the 3rd Dekad of May.

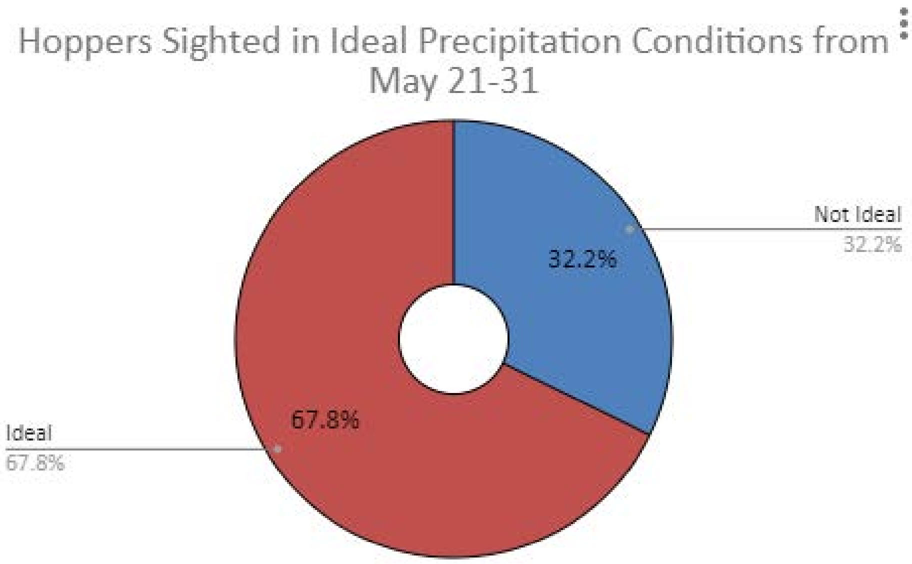


Figure 11: % of hoppers in ideal precipitation (positive precipitation anomaly) vs. not ideal (negative precipitation anomaly)

The majority of hopper sightings occurred at an average air temperature of 28.3°C (Figure 12). When compared to Figure 13 the relationship between hopper development and mean daily air temperature, we can see that the temperature they were most seen at in Kenya corresponds to about 34 days which is slightly faster than the average development period according to literature. Further, although there are no concrete thresholds for solitarious hopper movement based on cloud cover and wind direction, we could assume that any hopper bands in the vicinity were moving and roosting during the day in a north/northwest direction based on the mainly sunny conditions and light south/southeast winds during the May 21-31, 2020 (Annex 1). In our case study analysis, the mode for the hopper sightings coincided with average air temperature of 28.3C which corresponds to a development period of ~34 days.[44]

44 WMO & FAO, 2016.

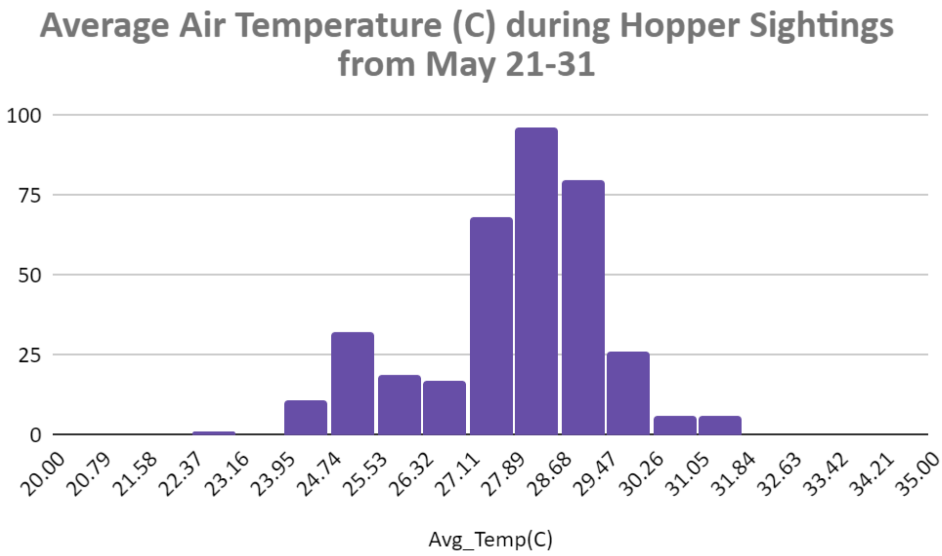


Figure 12: Distribution of the observed average daily temperature values at all of the hopper sighting locations during the period of most hopper sightings from May 21-31, 2020.

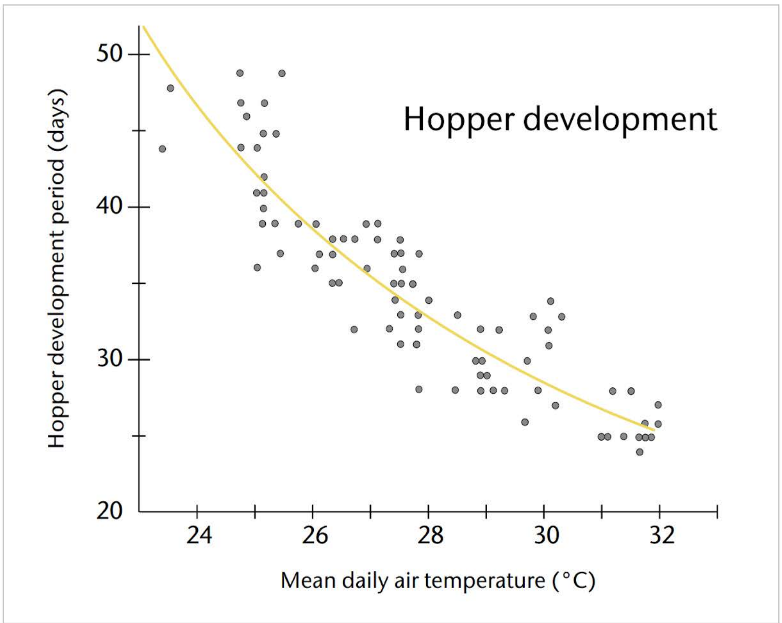


Figure 13: Relationship between rate of hopper development and mean daily air temperature based on literature.[45]

Temperature is a very important factor in determining how quickly desert locusts develop during the hopper stage. The hopper development period decreases with increasing air temperature from 24°C to 32°C (Figure 13). Over 56% of hopper sightings from April 21-29, 2020 were when average daily temperatures were greater than or equal to 28°C, which indicates a relatively 'faster' development period of around 34 days. On average, the hopper development period is 34 days long (Figure 13). According to our observations, hoppers developed a bit faster than the average rate.

45 WMO & FAO, 2016

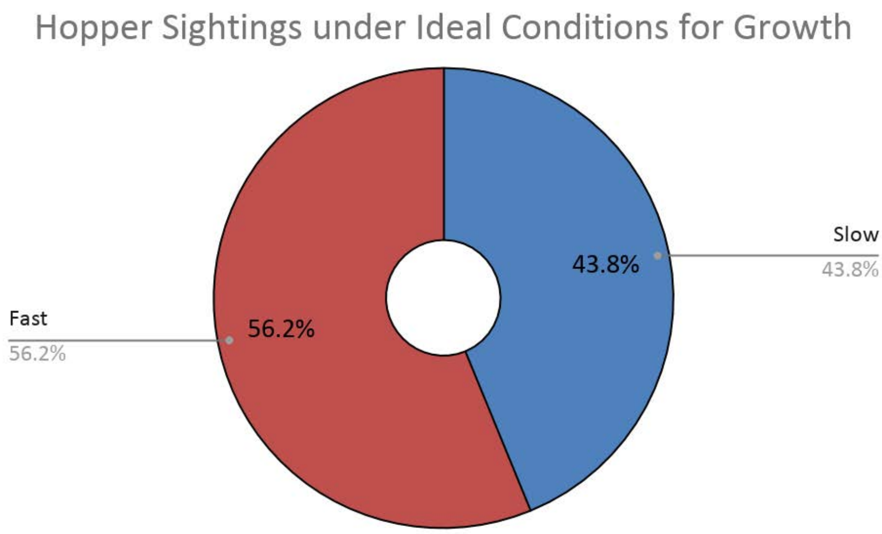


Figure 14: Hopper sightings under ideal conditions for growth; hoppers were considered to grow "fast" if average air temperature was greater than or equal to 28°C.

Based on the observational dataset of the highest frequency of hopper sightings (363 sightings), the average daily surface air temperature during a hopper sighting was 27.95°C. The most likely surface air temperature observed for hoppers during this period was 28°C at 27% (Figure 14 and 15).

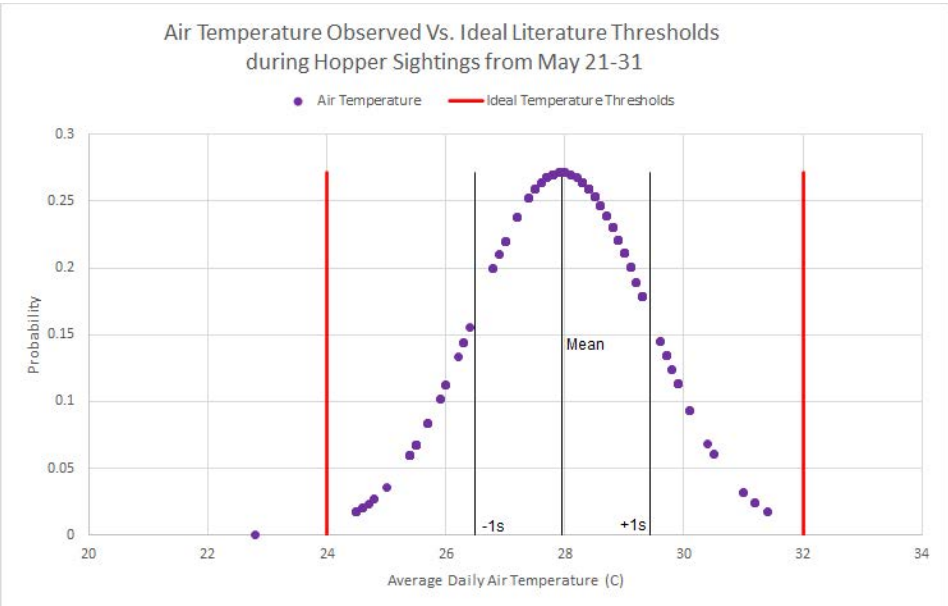


Figure 15: Hopper sightings based on average daily surface air temperature

5.2 Adults

Seven weather variables were overlaid with coinciding adult desert locust sightings in the ten counties. The most adult sightings recorded within the Dec. 2019 to May 2020 case study time period was during dekad 3 for May (21st to 31st May). The counties of Marsabit, Mandera, Wajir, and Turkana had the most adult sighting submissions (Figure 16). Based on literature review of previous desert locust outbreaks, *daily minimum surface temperature, soil temperature, and precipitation* should be considered for adult development and activity. They tend to mature rapidly in areas receiving recent significant rainfall and tend to mature slowly in cooler, drier conditions (See Appendix A). *Wind direction and speed* also play a role in the movement of adult desert locusts, as they have been found to only take off in a downwind direction when wind speeds are below 7 m/s. the average for soil temperature at the *ADULT* points is 33.3°C (Figure 17 and 18), average NDVI index of 0.36, average soil moisture index of 0.1 cm^3/cm^3 (10% saturation for that dekad), total precipitation of 0 mm, average air temperature of 27.3°C, an average cloud cover of 42.2% and average wind speed of 3.7 m/s from a south to southeast direction (Figure 19 and 20, Annex 4). Further, based on previous studies adult desert locusts tend to fly at night when air temperatures are at or above 21°C (see Appendix A).

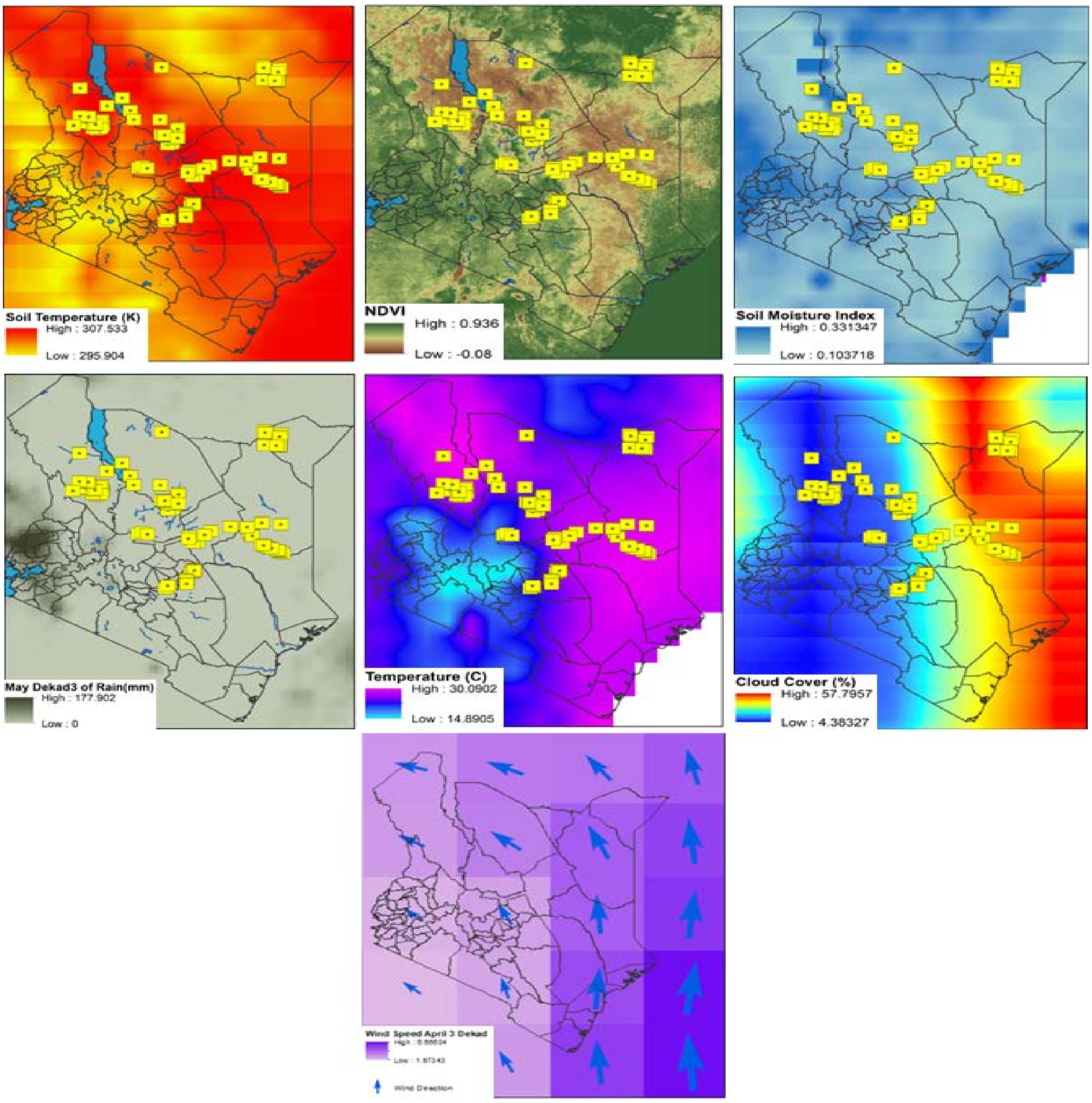


Figure 16: Weather variables overlaid with coinciding adult sightings from May 21st -31st in the ten counties in Kenya.

Figure 16 shows the seven weather variables in dekad 3 of May. These weather variables are overlaid with coinciding adult desert locust sightings in the ten counties of Kenya; the average for soil temperature at the *ADULT* points is 33.3°C, average NDVI index of 0.36, average soil moisture index of 0.1 cm3/ cm3 (10% saturation for that dekad), total precipitation of 0 mm, average air temperature of 27.3°C, an average cloud cover of 42.2% and average wind speed of 3.7 m/s from a south to southeast direction (see Annex 4).

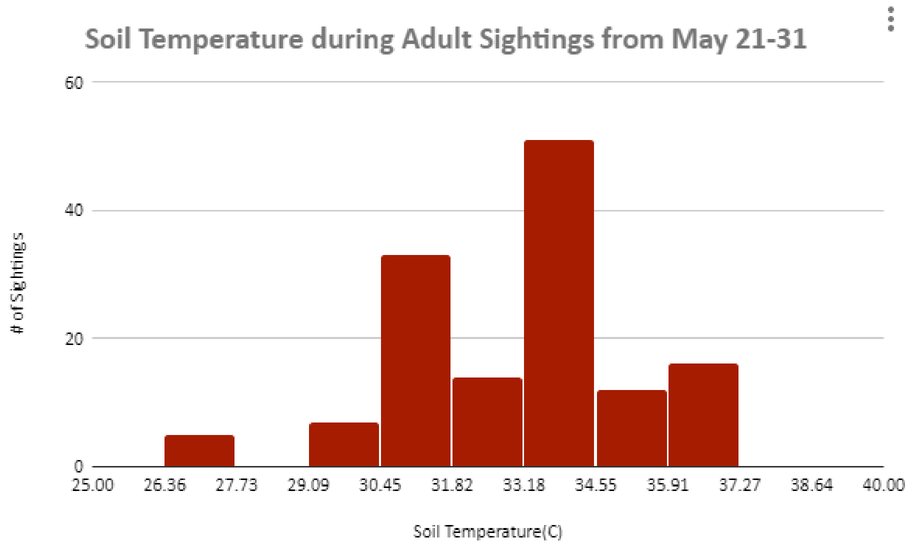


Figure 17: Distribution of daily soil temperature values during dekad 3 for May at adult desert locust sighting locations.

The average for soil temperature at the *ADULT* points is 33.3°C, average NDVI index of 0.36, average soil moisture index of 0.1 cm^3/cm^3 (10% saturation for that dekad), total precipitation of 0 mm, average air temperature of 27.3°C, an average cloud cover of 42.2 and average wind speed of 3.7 m/s from a south to southeast direction (Figure 18, Annex 4).

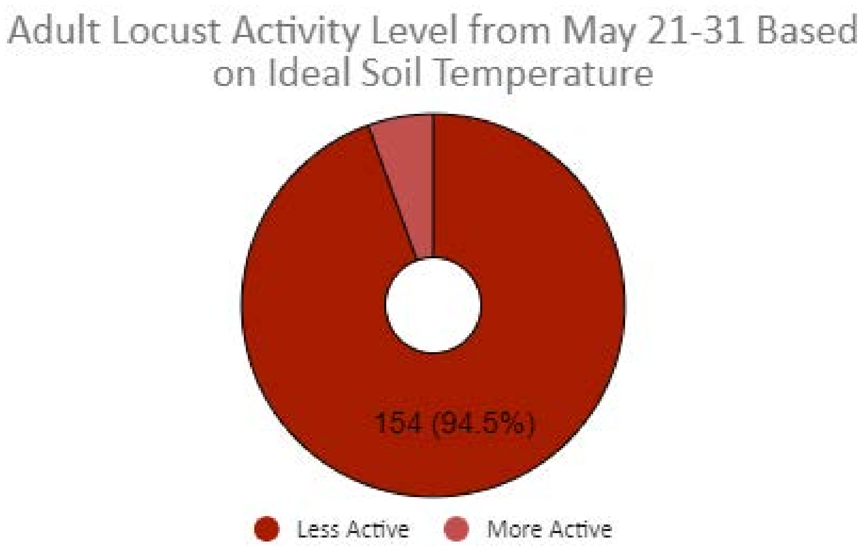


Figure 18: Adults sightings based on ideal soil temperature.

The established literature indicates that adult locusts are most active when soil temperature ranges from 25-30°C. Activity level of adult desert locust during dekad 3 for May at adult desert locust sighting locations. Over 94% of the adult locust sightings for this period occurred when the soil temperature was outside of the ideal-active range of 25°C-30°C found in literature (See Table 2 & 3). Having observed 94.5% of the adult locusts in this study at a soil temperature outside of that range could indicate a departure from literature.

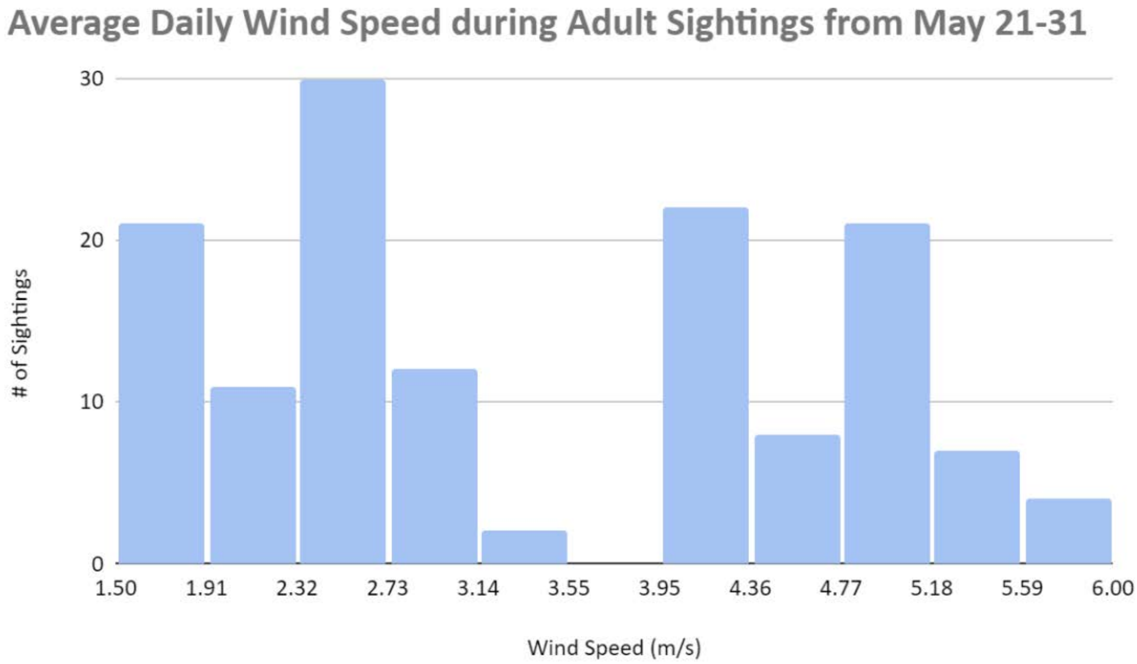


Figure 19: Distribution of daily average wind speed values during dekad 3 for May at adult desert locust sighting locations.

Wind speed is an important factor in determining whether or not desert locusts will take off and begin flying. If winds are faster than 7 meters per second, adults will not take off. All adults from May 21-31, 2020, were sighted when average daily wind speed was below this threshold, which indicates adults likely moved those days (Figure 20; Table 2 & 3).

Figure 20: Adult locust sightings in ideal wind speed conditions according to previous literature.

5.3 Bands

The most band sightings recorded within the Dec. 2019 to May 2020 case study time period was during dekad 3 for May in Turkana county and in western Marsabit county (Figure 21). Based on literature review from past desert locust invasions, cloud cover and surface temperature tend to dictate their movement. Bands tend to march on warm, sunny days; bands tend to not move on overcast days. Similar to hopper, band movement can be affected by wind direction, as they tend to move downwind. Additionally, precipitation and NDVI also need to be considered based on the fact that bands need vegetation to eat in order to develop. The higher the precipitation amounts, the greater chance of scattered green vegetation growth in sandy soil areas which is prime groundcover conditions for bands.[46] The average for soil temperature at the *BANDS* points is 35.3°C, average NDVI index of 0.23, average soil moisture index of 0.1 cm3/cm3 (10% saturation for that dekad), precipitation of 0 mm, temperature of 28.9°C, average cloud cover of 35.8% and average wind speed of 3.3 m/s from south to southeast direction (Figures 21, 22, 23 and 24)). The mainly sunny conditions from May 21-31, 2020 would indicate that the hopper bands were moving and roosting during the day in a north/northwest direction (Annex 2).

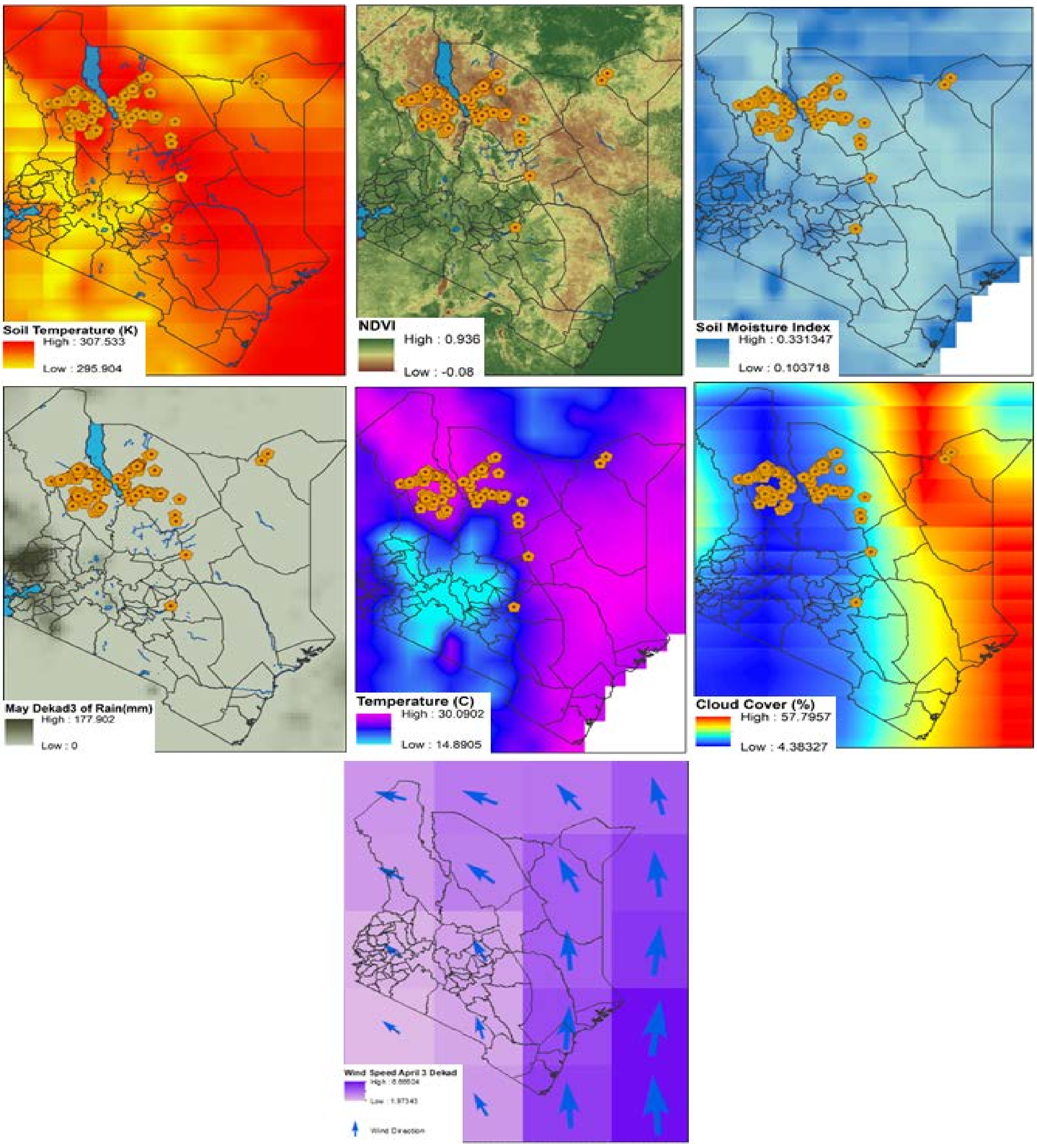


Figure 21: Weather variables overlaid with coinciding desert locust bands from May 21st -31st in ten coun ties of Kenya

46 WMO & FAO, 2016.

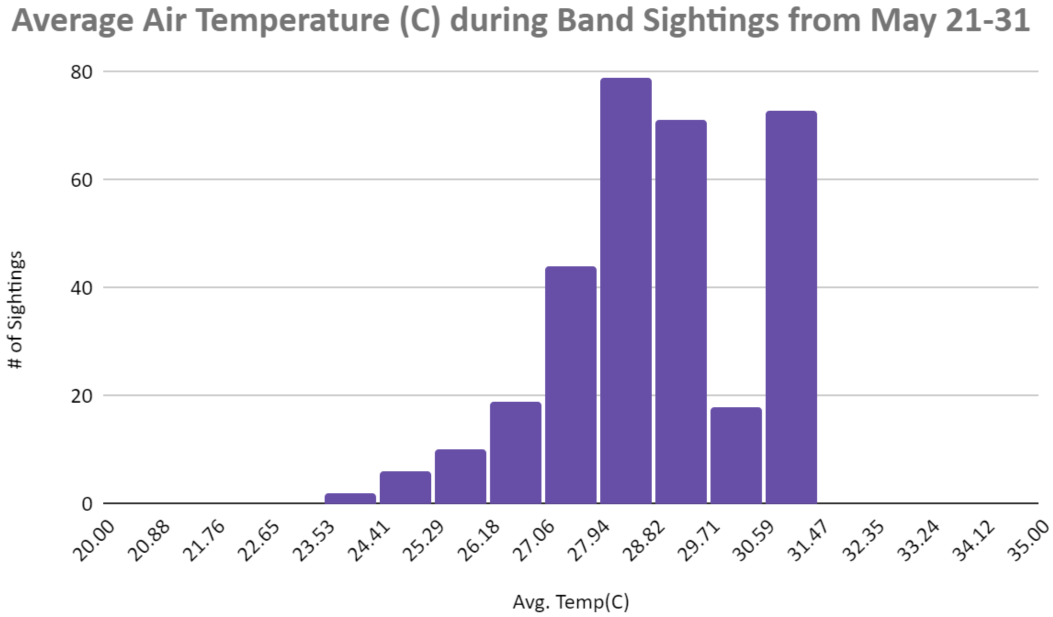


Figure 22: Distribution of average daily temperature values during dekad 3 for May at desert locust band sighting locations.

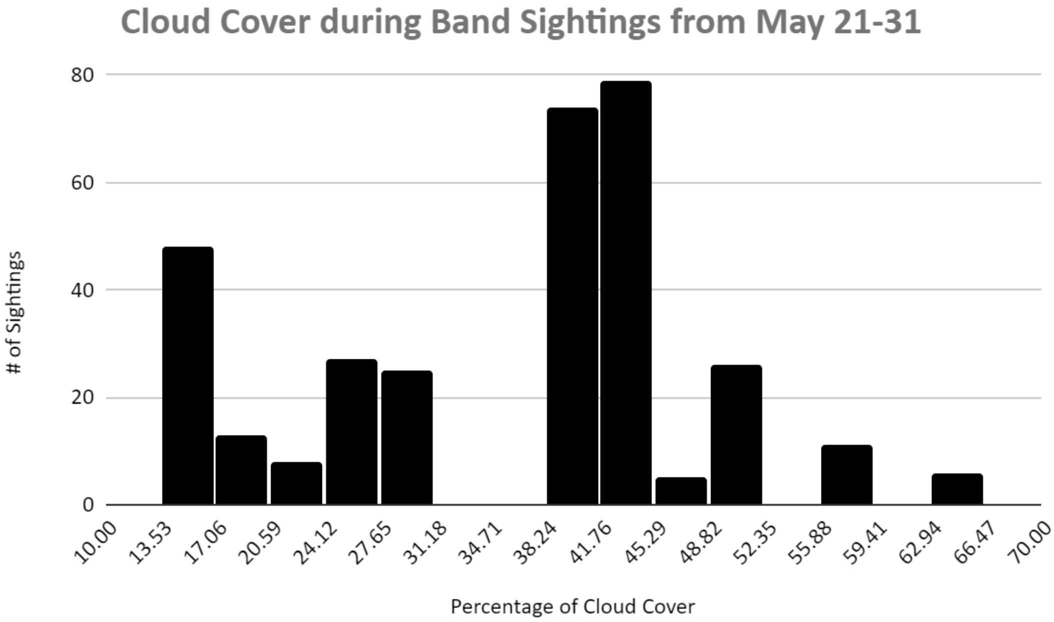


Figure 23: Distribution of % total air column cloud coverage values during dekad 3 for May at desert locust band sighting locations.

Cloud cover is an important factor in determining whether or not desert locust bands will move during the day. Bands tend to march on warm, sunny days and tend to stay in the same area on overcast days (See Appendix A). Nearly 98% of bands from May 21-31, 2020, were sighted when total air column cloud coverage was below 65%, which indicates adults likely moved/marched those days (Figure 24). Sunny days were identified as days in which total air column cloud coverage was below 65% (See Appendix B).

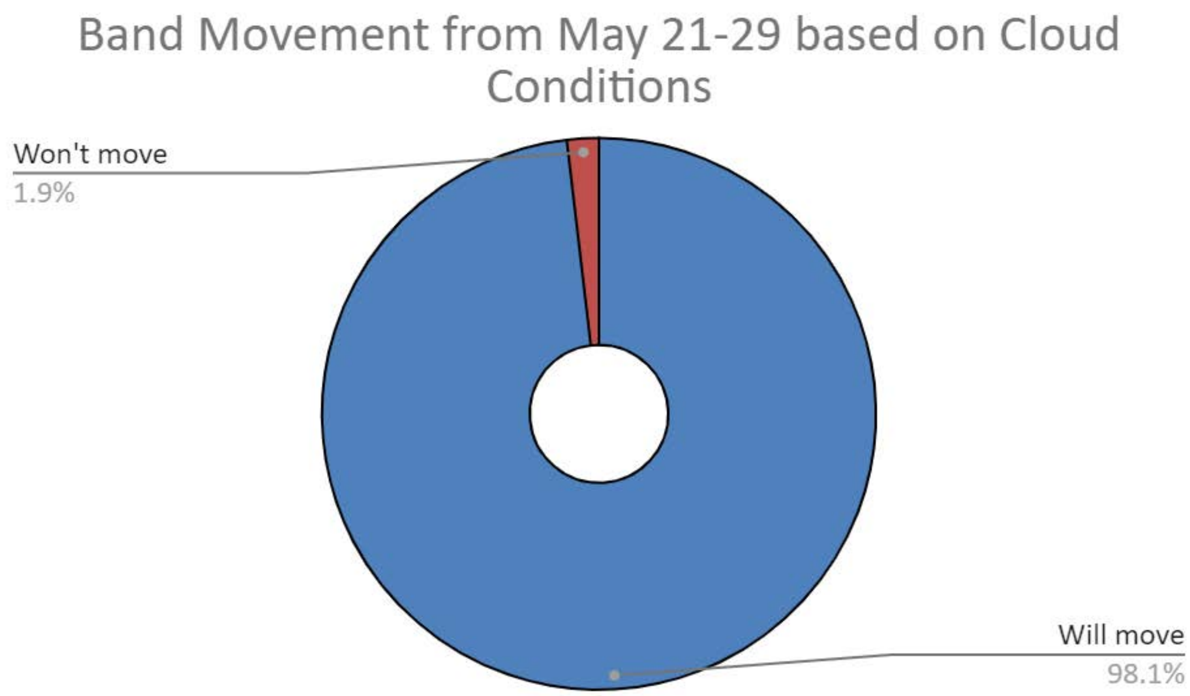


Figure 24: % of band movement based on cloud conditions from May 21 - 29.

5.4 Swarms

The most swarm sightings recorded within the Dec. 2019 to May 2020 case study time period was during dekad 3 for April in Isiolo and Samburu counties as can be seen in Figure 25. Based on literature of past desert locust upsurges, swarm movement tends to be linked to surface temperature and cloud coverage (combination of both). They tend to take off in sunny conditions at least 15°C–17°C; in cloudy conditions at 23°C–26°C. Similar to adults, wind direction and speed also play a role in the movement of desert locust swarms, as they have been found to only take off when wind speeds are below 10m/s. Moreover, movement tends to be in a downwind direction (See Appendix A).

The average for the soil temperature at the Swarms points is 28.4°C, average NDVI index of 0.46, average soil moisture index of 0.22 cm^3/cm^3 (22% saturation for that dekad), precipitation of 14.4 mm, temperature of 24.4°C, average cloud cover of 54% and average wind speed of 3.3 m/s from south to southeast direction (Figures 25, 26, 27 and 28). These values would indicate the swarms at these points during the April 21-29 period were not inhibited to take off in the morning based on wind speed and temperature and most likely moved in a north/northwest direction during flight (See Tables 2 and 3 and Annex 3). Wind speed is one of the factors that determines whether or not desert locust swarms will take off and begin flying. If winds are faster than 10 meters per second, swarms will not take off. All swarms from April 21-29, 2020, were sighted when average daily wind speed was below this threshold, which indicates swarms likely moved on those days (Figure 28).

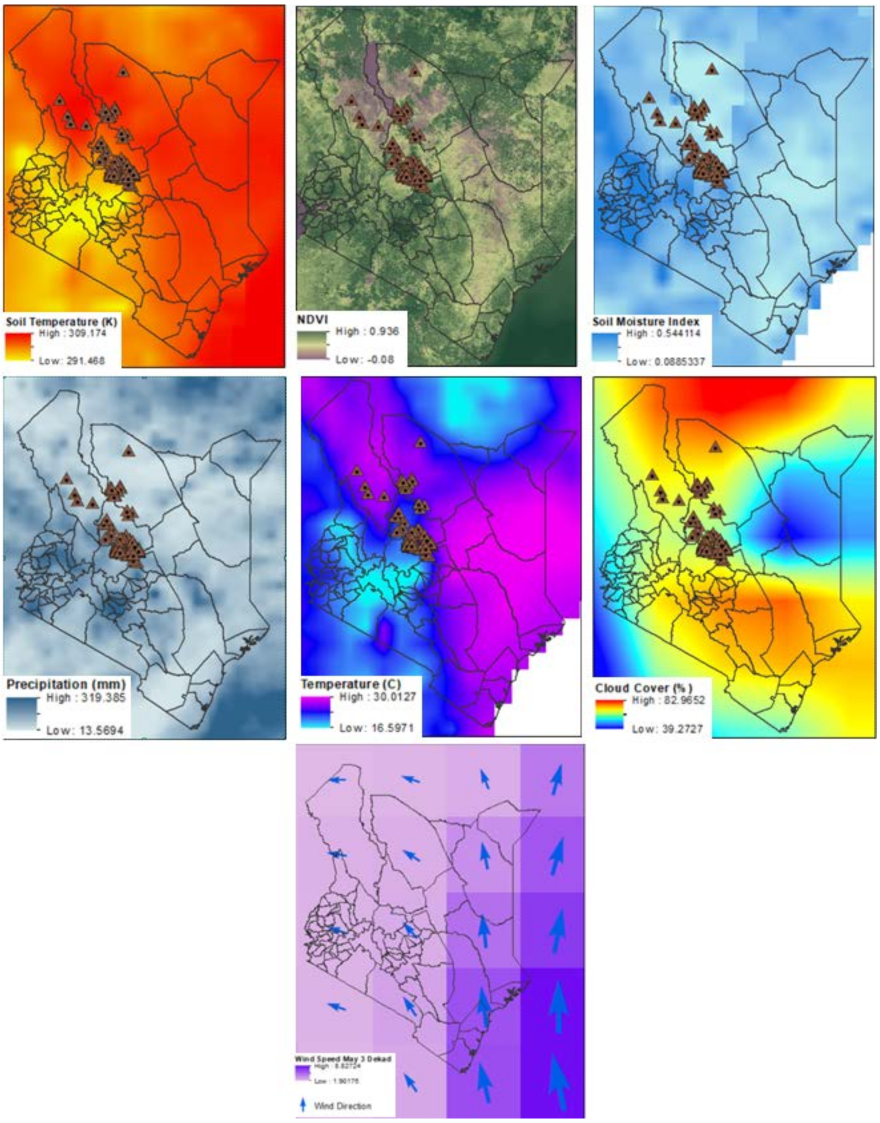


Figure 25: Seven weather variables overlaid with coinciding swarms seen in 10 counties in Kenya.

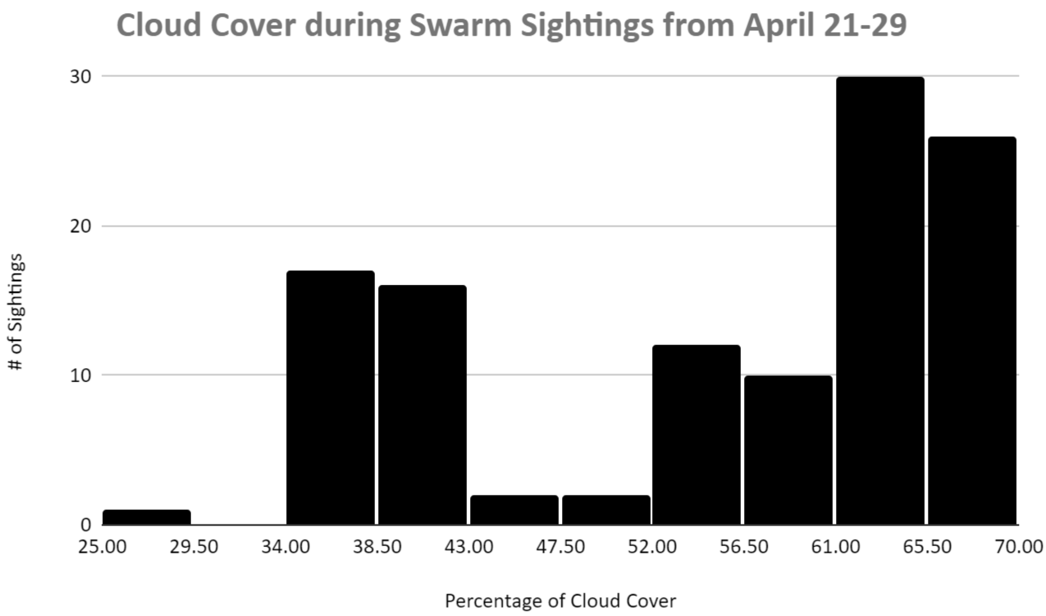


Figure 26: Distribution of % total air column cloud coverage values during dekad 3 for April at desert locust swarm sighting locations.

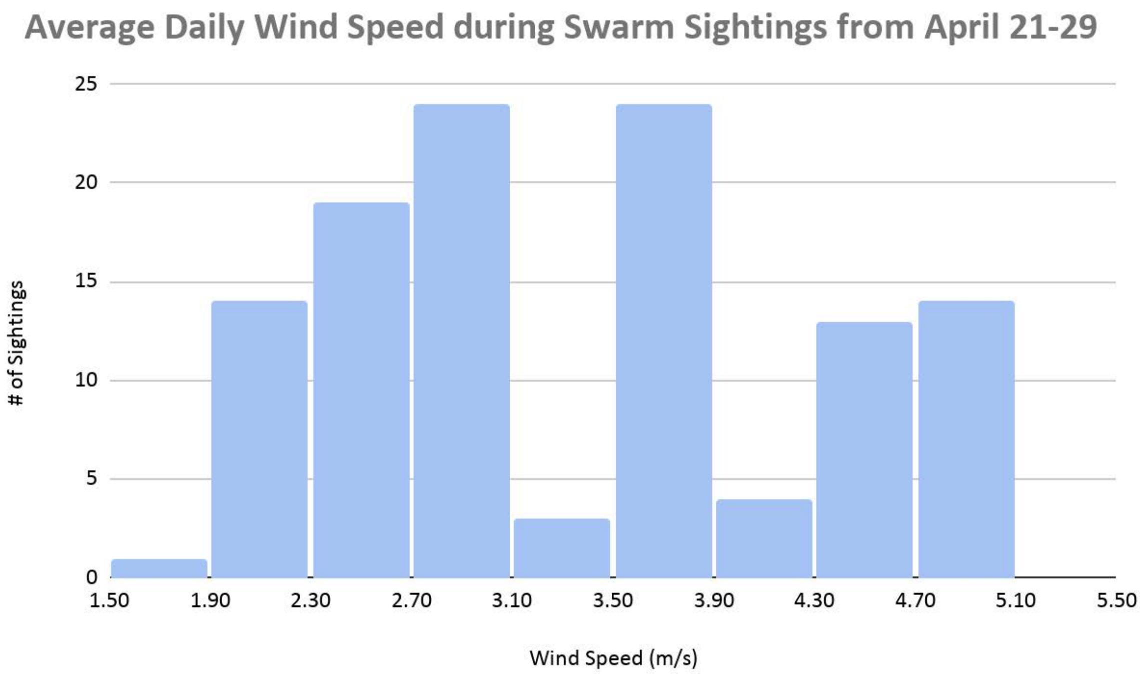


Figure 27: Distribution of daily average wind speed values during dekad 3 for April at desert locust swarm sighting locations.

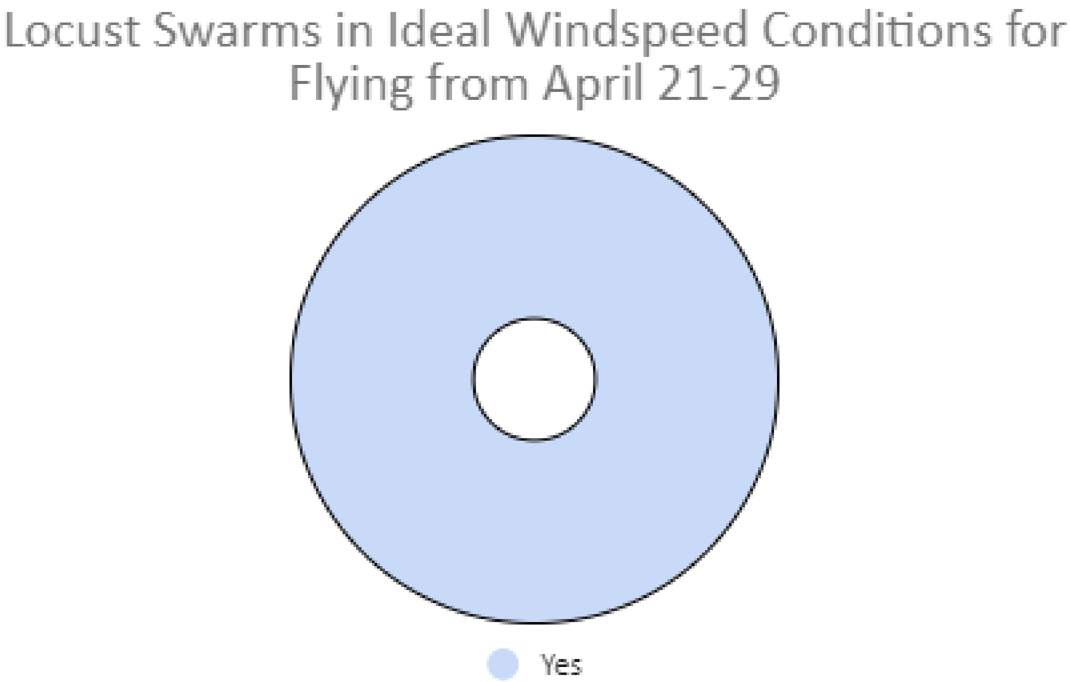


Figure 28: Locust swarm in ideal wind speed conditions for flying from April 21 - 29.

Based on the observational dataset of the highest frequency of swarm sightings (116 sightings), the average daily wind speed during a swarm sighting was 3.3 m/s. The most likely wind speed observed for swarms during this period was 3.4 m/s at 42% (Figure 29). However, as denoted by the red line (ideal threshold), all of the points fell within the ideal takeoff wind speed conditions from previous desert locust studies (See Table 2 & 3).

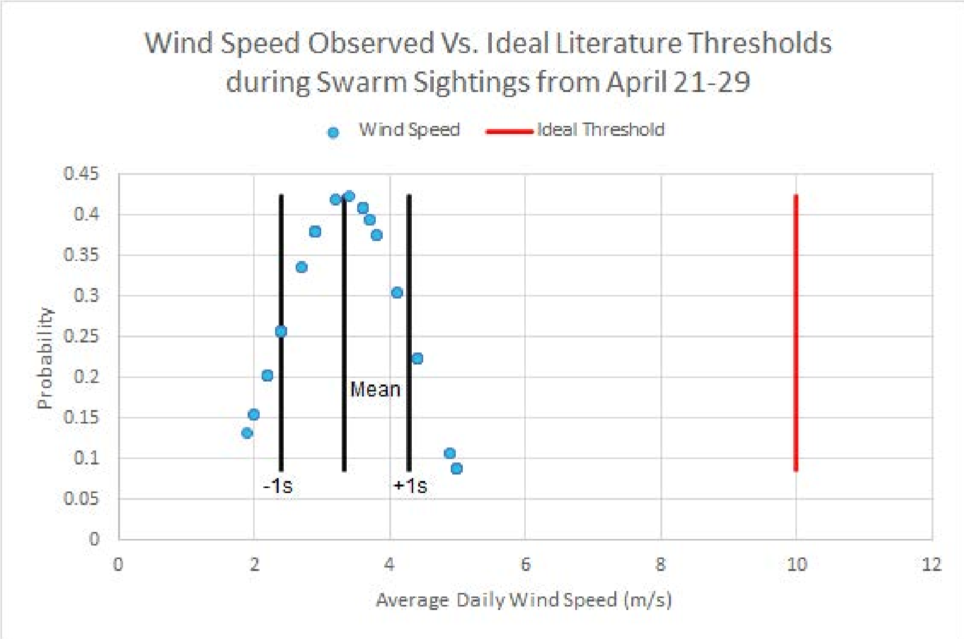


Figure 29: Wind speed observed vs. ideal literature thresholds during swarm sightings from April 21 – 29.

During the 3rd dekad of April, the total air column cloud coverage under 65% and average daily temperatures above 16°C was met 77% of the time. Sunny days were identified as days in which total air column cloud coverage was below 65%. Based on literature, 16°C is the minimum temperature needed for swarms to take off and move on sunny days as per literature (See Appendix A). Both of these conditions were met 77% of the time during our observational period and thus we presume that the swarms took off daily and flew approximately 77% of the time during the April 21-29, 2020 time period (Figure 30).

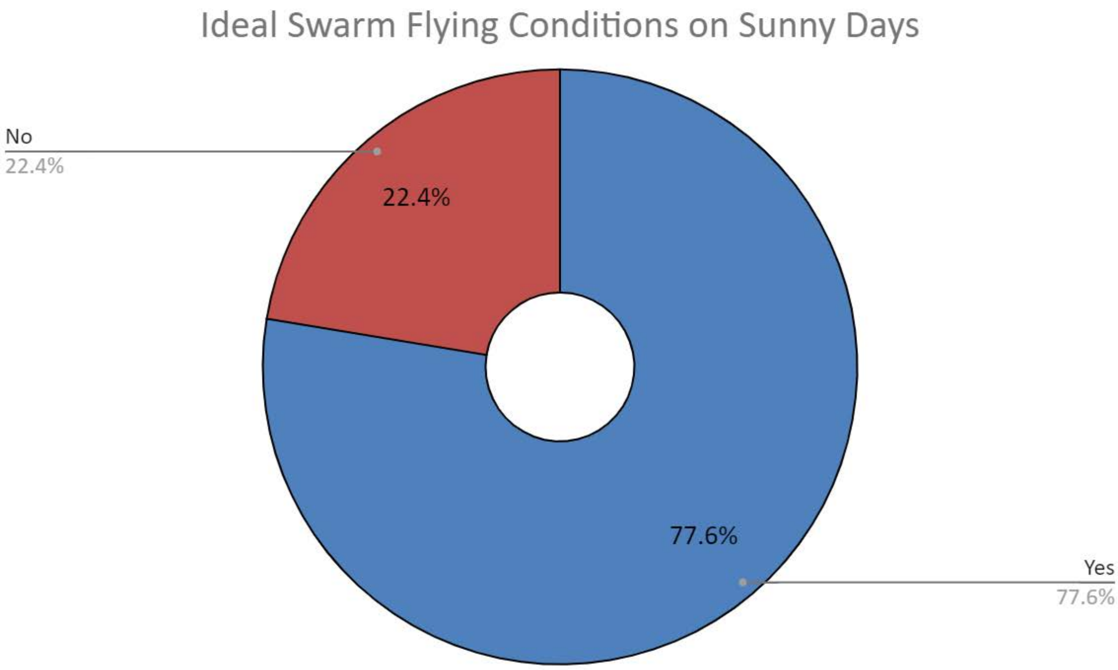


Figure 30: Combined sky condition with temperature thresholds for swarm movement.

Based on the observational dataset of the highest frequency of swarm sightings (116 sightings), the average daily surface air temperature during a swarm sighting was 24.5°C (Figure 31). Sunny days were identified as days in which total air column cloud coverage was below 65%. The most likely surface air temperature observed for swarms on sunny days during this period was 24.7°C at 16%. In sunny conditions, the temperature must be about 16°C or higher for swarms to take off, however sustained flight of swarms is rare if temperatures are below about 20°C (See Appendix A). All swarms sighted during this dekad were in the ideal temperature conditions needed to take off on sunny days (Figure 31).

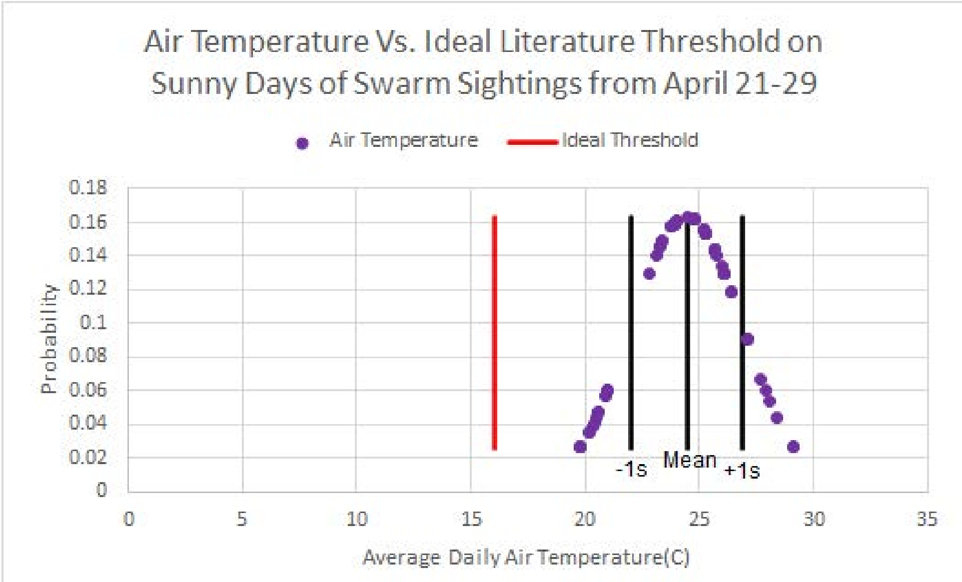


Figure 31: Swarm sightings on sunny days from April 21st - 29th.

Combined sky conditions and temperature thresholds for swarm movement during the 3rd dekad of April, the total air column cloud coverage above 65% and average daily temperatures above 24.5°C was met 88% of the time (Figure 32). Sunny days were identified as days in which total air column cloud coverage was below 65%. 24.5°C is the minimum temp needed for swarms to take off and move on cloudy days as per literature (See Appendix A). For the days that both of these conditions were met, we presume that the swarms took off daily and flew approximately 88% of the time during the April 21 – 29, 2020 time period (Figure 32).

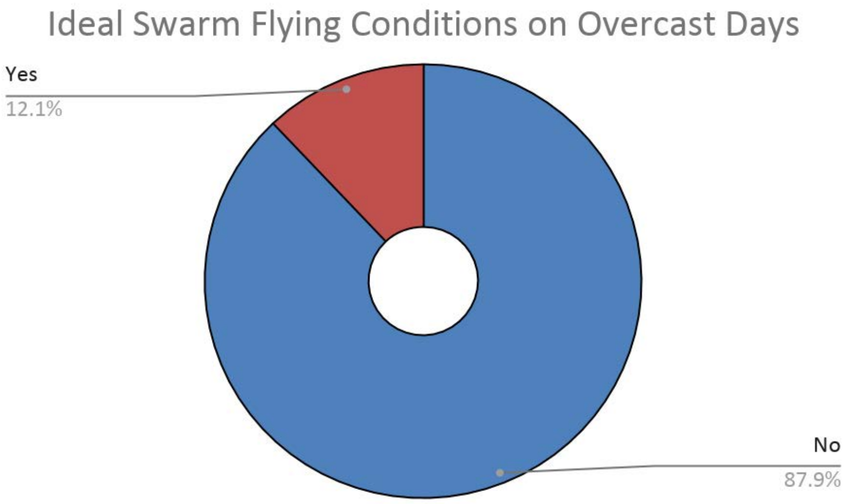


Figure 32: Ideal (24.5°C) swarm flying conditions.

Based on the observational dataset of the highest frequency of swarm sightings (116 sightings), the average daily surface air temperature during a swarm sighting was 24.6°C. Cloudy days were identified as days in which total air column cloud coverage was above 65%. The most likely surface air temperature observed for swarms on cloudy days during this period was 23.9°C at 15.6% (Figure 33). In cloudy conditions, the temperature must be about 24.5°C or higher for swarms to take off, keeping in mind that sustained flight of swarms is rare if temperatures are below about 20°C (See Table 2 & 3 and Appendix A).

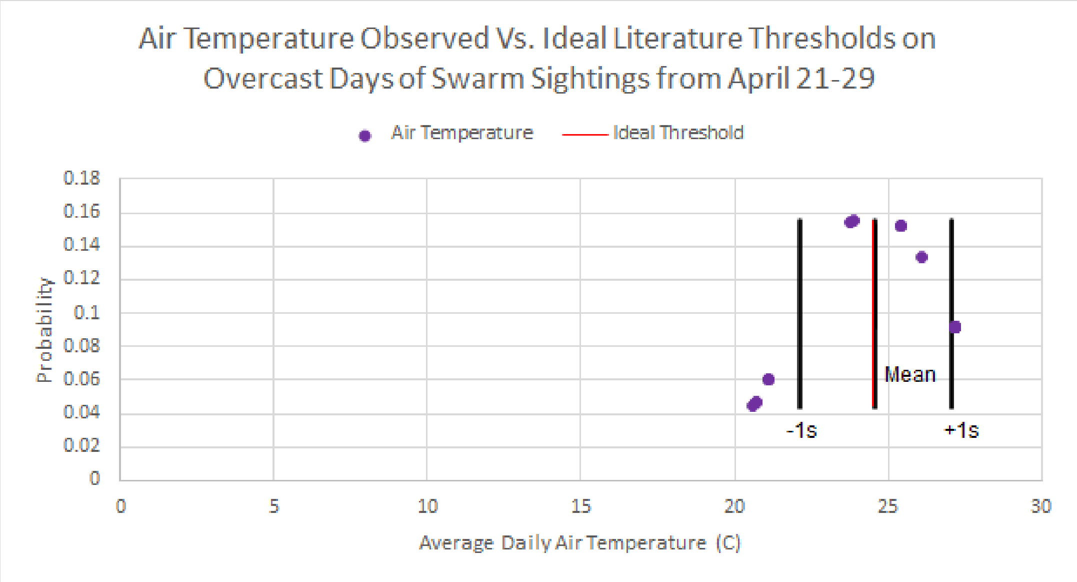


Figure 33: Swarm sightings based on the air temperature observed versus the ideal thresholds based on literature.

For a clearer understanding of the way in which the majority of locusts in the northern counties of Kenya behaved during the most recent plague, the mode was calculated from the already extracted dekads in which most locusts were seen at each stage. Figures 34-37 show the most frequent values for each variable at each stage.

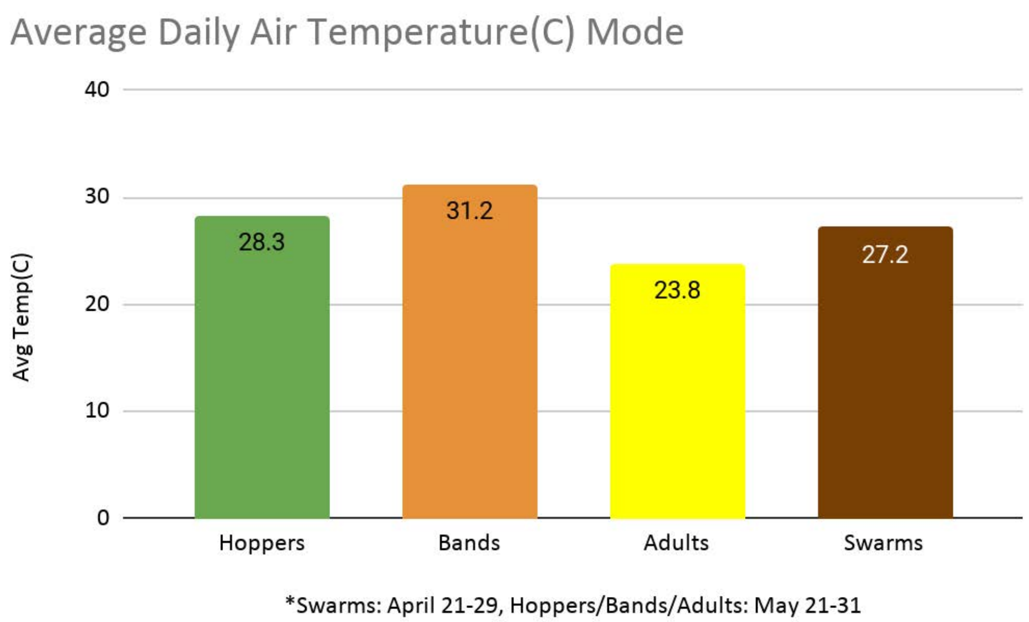


Figure 34: The mode for each stage in our case study analysis depicts the most frequent average daily surface air temperature value (°C) for all locations at which the majority of desert locusts were seen.

Hopper development period decreases with increasing daily air temperature from 24°C to 32°C. The most frequent average daily temperature value at the hopper sighting locations was 28.3°C. There is no specific threshold from literature that relates band development and movement directly to surface temperature. Solitarious adults tend to migrate at night about 20 minutes after sunset when the temperature is above 20–22°C.[47] Although minimum temperature would be a more reliable variable

47 All ideal values based on previous studies & literature. World Meteorological Organization, & Food and Agriculture Organization of the United Nations. (2016). Weather and desert locusts.

to use in this case, we found that the most frequent average daily air temperature at the adult sighting points was 23.8°C. In general, sustained flight of swarms is rare if temperatures are below 20°C. If there are overcast conditions, then the lower limiting temperature is about 23°C. Our case study analysis showed that the most frequent average daily air temperature at the swarm sighting points to be 27.2°C. This would imply that even if there were overcast conditions, the majority of swarms were likely to be moving/migrating during the day, throughout this dekadal time period at their sighting locations in Kenya. More detailed information on cloud cover/temperature and swarm behavior can be found in previous sections of this paper.

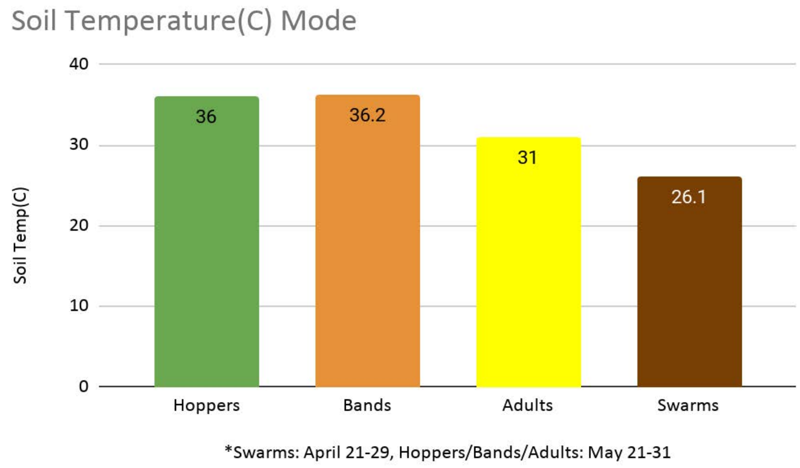
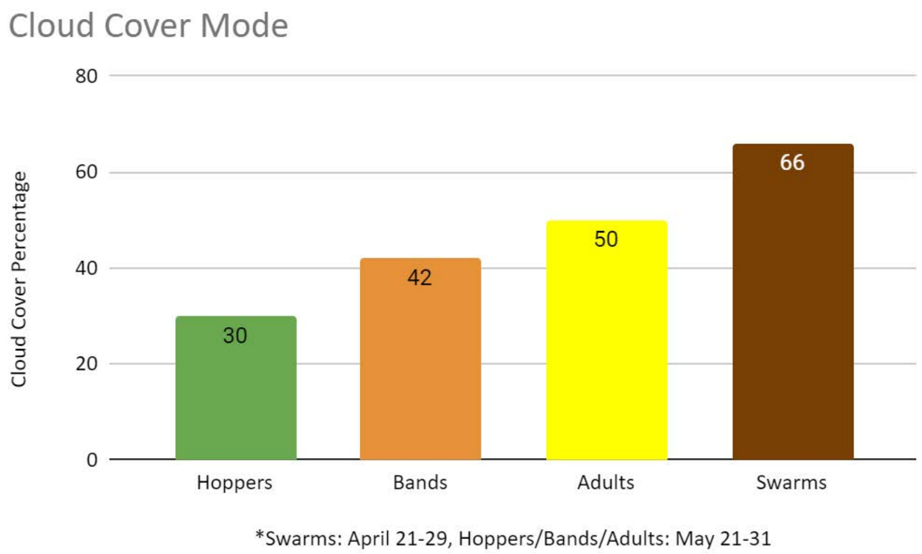


Figure 35: The mode for each stage in our case study analysis depicts the most frequent 0-5cm soil temperature value (°C) for all locations at which the majority of desert locusts were seen.[48]

Although now depicted in the graph, the ideal soil temperature for egg incubation tends to be anywhere from 15°C to 35°C. Although most eggs are laid at soil depths of 10-15 cm, it is interesting to note that based on the most frequent 0-5 cm soil temperature values for all of the locations at which the majority of desert locusts were seen, soil temperatures fall well within this and sometimes at the maximum of this range. There is no specific threshold from literature that relates bands, swarms, and hopper development and movement directly to soil temperature. Adult solitarious locusts have been found to be the most active when soil temperature ranges between 25°C and 30°C. Our case study analysis showed that the most frequent 0-5 cm daily soil temperature at the adult sighting points was 31°C, which would imply that adult locusts were slightly less active during this dekadal time period at their sighting locations in Kenya.



48 All ideal values based on previous studies & literature. World Meteorological Organization, & Food and Agriculture Organization of the United Nations. (2016). Weather and desert locusts.

Figure 36: The mode for each stage in our case study analysis depicts the most frequent percentage cloud cover value for all locations at which the majority of desert locusts were seen.[49]

Bands tend to march on warm, sunny days and have minimal movement on overcast days. Our case study analysis showed that the most frequent daily total air column cloud cover percentage at the band sighting points was 30%, which would imply that locust bands were moving/marching during this dekadal time period at their sighting locations in Kenya. Swarms will take off in the morning in sunny conditions at temperatures of at least 16°C or higher. During cloudy conditions, swarms will take off at temperatures of anywhere from 23°C – 26°C or higher. This mode chart only takes into consideration cloud cover so no implications can be made regarding swarm take off since temperature is not factored in. Lastly, there are no specific thresholds from literature that relates hopper and adult solitarious development and movement directly to cloud cover.

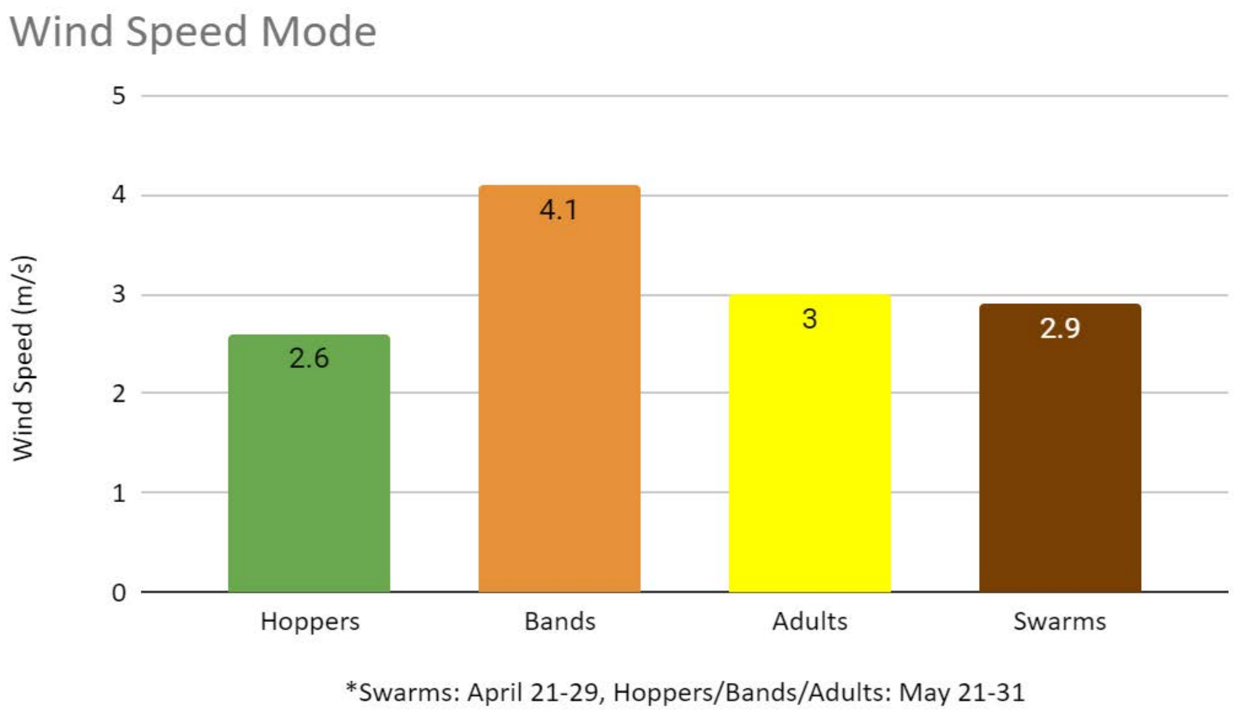


Figure 37: The mode for each stage in our case study analysis depicts the most frequent average daily wind speed value (m/s) for all locations at which the majority of desert locusts were seen

Regarding wind direction, hoppers and bands have been observed moving downwind in previous studies, but there are currently no specific thresholds from literature directly linking wind speed or direction to hopper movement or development. Solitarious adults have been seen to migrate (mostly at night) when the wind speed is less than 7 m/s. Swarms will usually not take off during the day if wind speeds are greater than 10 m/s.[50] Our case study analysis showed that the most frequent daily wind speed values (m/s) at the swarm and adult sighting points was 2.9 m/s and 3 m/s, respectively. This would imply that swarm and adult stage desert locusts were most likely flying/migrating during their respective flying times, during this particular dekadal time period at their sighting locations in Kenya.

49 All ideal values based on previous studies & literature. World Meteorological Organization, & Food and Agriculture Organization of the United Nations. (2016). Weather and desert locusts.

50 All ideal values based on previous studies & literature. World Meteorological Organization, & Food and Agriculture Organization of the United Nations. (2016). Weather and desert locusts.

5.5 Eggs:Potential oviposit sites between April 21st and May 31st, 2020

An approach to analyzing where eggs were laid (oviposition sites) is crucial in understanding where a new generation of desert locusts could develop. The creation of suitability maps is a way to forecast where favorable conditions will be for swarms to lay eggs and to verify if hopper sightings coincide with these particular locations. Regarding this case study, analyzing the highest frequency of swarm sightings in the third dekad of April and highest hopper sightings in dekad 3 of May (approximately a month later) could be a way of predicting the temporal and spatial development of a new generation. Literature suggests four bioclimatic factors that are key for the process of oviposition and the mortality of the eggs. These include precipitation, soil temperature, air temperature and soil type, which is a factor in determining soil saturation (soil moisture).[51]

Based on the FAO's classification soil types, clay and silt are the soil types with the highest saturation levels.[52] To create the areas in Figure 38, clay and silt soil areas were spatially analyzed along with precipitation, air temperature, and soil temperature data. The resulting areas indicate regions that have suitable egg-laying qualities.

Figure 38 shows the dekad 3 of April where most swarms were sighted, with the pink square areas showing areas with suitable conditions for eggs to be laid and buffer zones of flying distance to account for the range of land areas for oviposit. Swarms can fly 5 - 200 km to lay their eggs, which develop and hatch in 10 - 65 days depending on these climatic drivers. The map on the right shows the month of May and areas swarms can oviposit in that time period. The buffer zones may also indicate areas where development of eggs has already started from previous swarm sightings.

Referring to Figure 38, the third dekad of April indicated more suitable sites for egg laying than the month of May. There was a significant amount of precipitation two months prior to this period in April, with an average temperature of 22.3 ºC and soil temperature of 26.35 ºC, which are all well within the threshold for faster development rate of eggs. The relationship between areas of high precipitation and lower NDVI values tend to indicate locations of bare sandy soils. The literature suggests that locusts will oviposit when the soil is moist, stating that "eggs require moist soil conditions after laying as they need to absorb moisture to complete their development".[53]

However, thus far no specific threshold of soil moisture has been established but further analysis on key questions like 'are certain levels of moisture crucial for egg-laying or do minimal levels of moisture suffice?' will determine a more reliable thresholds

The geospatial analysis in this case study suggests that eggs were laid when the soil was in low-medium moisture levels (27%). Knowing this information will be useful in beginning to establish a literature around soil moisture observed during oviposition. This will be important in desert locust management, preparedness, and response issues, given that preventing mature adult locusts from ovipositing is crucial to stopping a new generation from developing and a plague from spreading even further. Identifying locations where ovipositing is suitable (based on soil temperature, soil conditions, and soil moisture) will allow for preemptive action to be taken. Some examples of action that could be taken include (1) chemical spraying methods by farmers or government resources, (2) tilling in order to disrupt soil and thus expose locust eggs to the elements, or (3) laying down a granular pesticide that will leach into the soil and kill the larvae as they hatch.

51 Kimathi et al. 2020.

52 FAO, 2001.

53 WMO & FAO, 2016

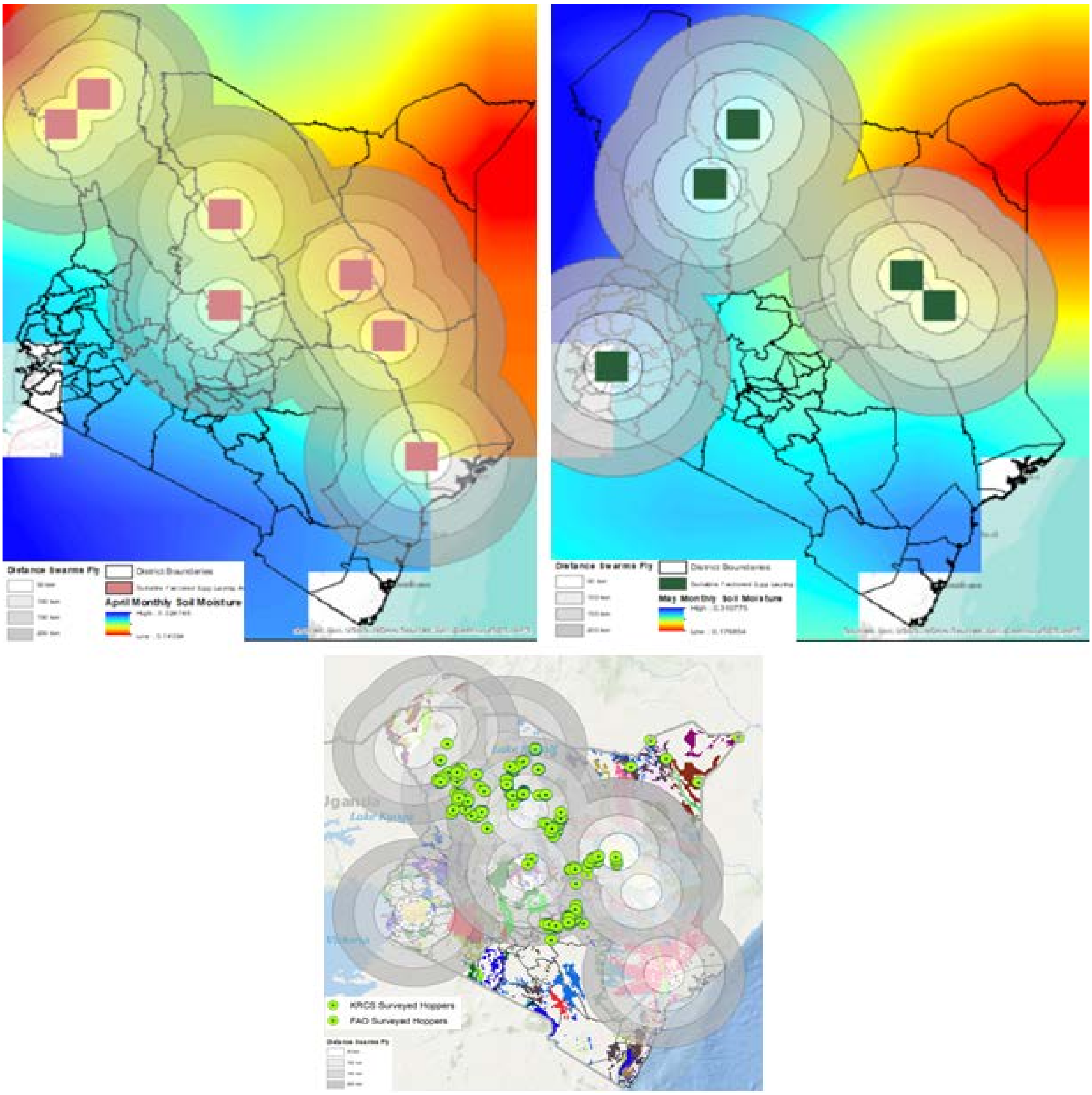


Figure 38: Oviposition sites with 50 to 200 km buffer zones; April 3 Dekad oviposition sites with soil moisture under laid (top left), month of May oviposition sites with soil moisture under laid (top right) and buffer zones combined April 3 Dekad and May with hopper points to show if Hoppers were seen in the sights around eggs laid (bottom).

The third map in Figure 38 shows the hopper points from FAO overlaid with the two collective buffer zone areas. This map further shows coinciding hopper points from their highest sighted dekad within these zones with a possible assumption that the new generation of hoppers are from the eggs laid by swarms in April, as the month had the most suitable conditions for eggs to be laid and the conditions in consequent months to develop the eggs. The conditions in May had low precipitation, high soil temperature and high air temperature as well but within the threshold to show a moderate to fast development as initial soil moisture was high enough in the beginning of the month of May and end of April for absorption by eggs, especially with 50% high saturation soil zones.

6. Conclusion and Recommendations

The critical context of this case study analysis involved different phases in the life cycle of desert locust starting from oviposition, egg development, hopper development, differing moulting and maturing rates of hoppers to adults, along with movement and momentum of hopper bands and adult swarms. Each stage has ideal meteorological conditions for survival and development, including rainfall, soil moisture, soil and air temperatures, surface and boundary winds, synoptic-scale patterns and the convective state of the atmosphere. To understand how the current desert locust plague in Kenya relates to the region's recent weather and climatic conditions, a literature-based typology of ideal desert locust proliferation conditions was compared to observed conditions during selected dekads defined by the most frequent sightings. The counties that were impacted the most during these time periods were Turkana, Marsabit, and Isiolo. The majority of the frequently observed characteristics in this case study were within the respective literature thresholds of the most influential bioclimatic variables; however, there were a number of minor deviations from the established thresholds that are worth exploring in the future to better understand locust behavior.

Based on the linear relationship between temperature and hopper development, observations in Kenya indicated conditions in which solitarious hoppers were able to develop in a period of 34 days, which is marginally faster than the literature-based average of 36 days. Both precipitation and temperature at observed hopper hotspots in the three counties depicted in this study were conducive to faster hopper development. Nearly 70% of the hopper sightings corresponded with ideal conditions suggested by the desert locust literature, indicating that along with these variables, there was enough green vegetation for hoppers to successfully develop and transition from solitarious to gregarious stages. The dekad of most hopper observations (May 21- May 31, 2020), had a combination of ideal conditions for temperature in the faster-growth range (56% of the time) and at or above normal precipitation for that particular month (68% of the time). This combination of favorable temperature and rainfall likely led to quicker hopper gregarization in Turkana and Marsabit counties. Furthermore, a noteworthy departure from literature was also observed regarding soil temperatures during adult locust sightings. Having observed 94.5% of the adult locusts outside of that range indicates that future studies should take note of soil temperatures. It would be worth exploring whether locusts are becoming more adapted to differing soil temperatures or if this situation is particular to Kenya.

With regards to swarms, clouds were the most inhibiting factor in our case study analysis. Wind speeds were generally favorable for swarm movements but on overcast days, temperatures were not warm enough for swarms to fly (not suitable for 88% of observations). Based on our data, on sunny days (when total air column cloud coverage was under 65%), 77% of the swarm observation points were over 16°C. According to the literature threshold, this is the minimum temperature needed for swarms to take off and move on sunny days. All of the swarms were seen at temperatures higher than 16°C so we presume that they took flight during the April 21-29, 2020 time period. Therefore, the situation in Kenya was highly favorable for swarm movement.

In order to prevent an outbreak, it is important to target transiens or gregarious hoppers and/or adults before they are able to breed and multiply. As stated previously, the majority of the available data did not identify whether an observed adult was in a solitarious or a gregarious phase. In future studies, it would be useful to distinguish between solitarious and gregarious adults, as these different phases cause the locusts to behave differently and therefore may also indicate different preferred bioclimatic and weather thresholds. We advise that future desert locust surveillance prioritize identifying which state the adult or hopper was seen at. This would help management and disaster relief organizations identify the areas in which locusts are most likely to form destructive bands or swarms. Since many countries in the region already do not have enough spraying units, focusing on gregarious adults would allow resources to be allocated more effectively.

Another relevant takeaway from reflections on desert locust data is that consistent and transparent reporting of locust sightings is pivotal for the accuracy of this desert locust and climate study. Only if locust reporting is coherent across the entire time period and all affected counties, do the observed weather conditions, linked to highest frequency sightings, allow for assumptions regarding locust favorable environments. It is recommendable to set up consistent time tables and regularly follow-up on the consistency of reporting strategies and timely reporting. The reporting strategy and routine should be identical and comprehensive across counties, which, admittedly can be difficult to attain in more remote regions of Kenya. If the reporting is not transparent and does not follow strict, comparable guidelines, biases are inevitable and will not lead to the most accurate results for the methods and type of analysis suggested in this study.

...consistent and transparent reporting of locust sightings is pivotal for the accuracy of this desert locust and climate study.

Generally, due to overall supply shortages and the increased likeliness of desert locust outbreaks and plagues in the future, it is also recommendable to scale up emergency supplies. With global supply chains being disrupted by the current COVID-19 pandemic, Kenyans' flexible access to necessary equipment is highly restricted. In order to implement spraying operations and future adaptation measures, it is advisable to rely on a bottom-up multi stakeholder dialogue in order to build trust and transfer knowledge to the affected communities. Social media data revealed a pattern of mistrust in science and governmental agencies, which has to be addressed for the future implementation of adaptation strategies. There is also a growing notion of the nutritional value of locusts and while the Twitter community currently jokingly exchanges desert locust recipes, it is worth taking into account to which extent desert locusts could be effectively captured and turned into an alternative source of food during plagues. With a changing climate, it is important for future studies to re-examine the impacts on the hydrological cycle as well as climate drivers which heavily impact cyclone activity and precipitation in Kenya. A better understanding of the MJO (Madden Julian Oscillation) and the IOD (Indian Ocean Dipole) could contribute to a more advanced warning with regards to the likelihood of favorable desert locust egg hatching and overall development conditions.

This study concluded that heavier precipitation episodes certainly contribute to more favorable conditions for desert locusts to survive or be attracted to the Kenyan lands. This desert locust and climate case study analysis serves as a baseline for future analysis, which can be enhanced by finer resolutions and more dekads geospatially analyzed in order to corroborate our study. The data provided here hopes to show frequently observed characteristics of known and unknown (not already established in literature) weather variables thresholds in high sighted periods and location, but does not serve as a reflection of locust movements and development in general. Starting from this study, a much finer and nuanced understanding can be generated with future studies and research in the future.

This study concluded that heavier precipitation episodes certainly contribute to more favorable conditions for desert locusts to survive or be attracted to the Kenyan lands.

The added value to established literature and general locust knowledge that can be obtained from this case study is that seven weather/bioclimatic variables were identified and analyzed across all stages. Furthermore, the researchers acknowledged that according to literature review, some variables were particularly more important at different points in the desert locust life cycle than others. However, each variable (wind speed, air temperature, precipitation, soil temperature, soil moisture, cloud cover, NDVI) was analyzed for each of the five main stages (egg, hopper, band, adult, swarm). Therefore, this case study not only compared observed variable data to the important variable thresholds at each stage, it also provides new information regarding the most frequently observed characteristics for variables that were not previously deemed as relevant at certain stages. Annex 1 can be seen for more specific data.

As climate change continues, we know that temperatures will continue to rise, that more positive Indian Ocean Dipole events are likely to occur, and that this will bring increased convection and precipitation to Eastern Africa. The combination of increased soil moisture, increased vegetation in semi-arid and arid regions as a result of increased precipitation, and higher air temperatures creates the perfect concoction for locust breeding and development. For this reason, it is important to gain a deepened understanding of the complexities and nuances of weather and bioclimatic conditions that uniquely affect desert locusts at each stage of their lives. A way to take this study further would be to analyze the weather/bioclimatic variables during January and February, the two months following the December 2019 cyclone. We know that cyclones bring heavy rainfall which tend to create suitable, moist conditions for oviposition and locust development. As climate change is likely to increase the occurrence of cyclones affecting East Africa, we recommend further geospatial analysis utilizing the variables identified in this case study to predict which regions are likely to become oviposition and locust breeding areas. Gaining an accurate geographical understanding of egg-laying locations will allow for the most effective, anticipatory action. As climate change continues to exacerbate, locust upsurges and plagues are likely to occur more frequently. Exploring and analyzing all possible variables will allow for more precise forecasting and a better understanding of locust behavior so that appropriate preventative measures can be taken to minimize the impact these migratory pests have on human livelihood, poverty, and food security.

...it is important to gain a deepened understanding of the complexities and nuances of weather and bioclimatic conditions that uniquely affect desert locusts at each stage of their lives.

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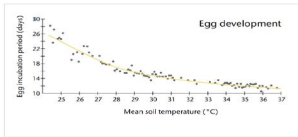
Appendix A

Table 1: DL Typology based on Literature Review

The table below shows the literature-derived "ideal" thresholds for different locust life cycle stages based on meteorological and ecological parameters such as rainfall, soil moisture, temperature etc. These thresholds have been determined by the World Meteorological Organization and the Food and Agriculture Organization. The literature suggests, for example, that solitarious adults migrate when the wind is less than 7m/s. Further, precipitation data can be used to identify which areas may become suitable for breeding or where green vegetation and locusts may be present.

	Stage Definition & Behavior	Wind	Temperature	Precipitation	Soil Conditions	Cloud Cover
Egg (10-65 days)	The development from eggs into hoppers (wingless larvae or nymphs) is a function of temperature (WMO & FAO, 2016: 4).	Eggs can dry up, especially if exposed to wind (WMO & FAO, 2016: 4).	Egg development rate increases with temperature. Eggs will hatch sooner under warmer conditions. High mortality of eggs may occur if soil temperatures are above 35°C (WMO & FAO, 2016: 4).  **Figure 3.** Relationship between egg development and temperature. Eggs will hatch sooner under warmer conditions. Air temperature range of 20°C–35°C for egg and hopper development (WMO & FAO, 2016: 13)	Eggs are usually laid in areas of bare sandy soil and require previous rainfall. Laying of eggs occurs when soil is moist 0 cm–15 cm (rainfall > 25 mm/month for 2 months) (WMO & FAO, 2016: 13).	The rate of development of the laid eggs is a function of the soil temperature at the depth where the eggs are laid. Soil temperature range for egg viability 15°C–35°C (WMO & FAO, 2016: 13). Eggs require moist soil conditions after laying as they need to absorb moisture to complete their development (WMO & FAO, 2016: 10).	

	Stage Definition & Behavior	Wind	Temperature	Precipitation	Soil Conditions	Cloud Cover
Hoppers (Solitary) (24-95 days; average 36 days)	In the early morning and late afternoon, hoppers bask on plant tops or the ground; at midday, they take shelter inside plants (WMO & FAO, 2016: 13) Hoppers are the wingless juvenile stage. In optimal conditions, hoppers can form bands and adults can form swarms (WMO & FAO, 2016: 1). A hopper moults 5-6 times and becomes an adult in about 4-6 weeks(WMO & FAO, 2016: 2). When solitarious hoppers increase in number, their behaviour changes, they become concentrated and can form groups. Grouping often occurs in open, less uniform, habitats, where there are patches of relatively dense vegetation separated by large areas of bare soil (WMO & FAO, 2016: 4).	Hopper band movement is usually downwind (WMO & FAO, 2016: 13)	The development from eggs into hoppers is a function of temperature. Hopper development period decreases with increasing daily air temperature from 24°C to 32°C. The warmer the temperature, the faster hoppers will mature and become adults (WMO & FAO, 2016: 4). The correlation with air temperature is less clear than with eggs because the hoppers can control their body temperature to a considerable extent by basking or seeking shade.	Hopper development indirectly requires rainy conditions, since the hoppers require edible vegetation for survival (WMO & FAO, 2016: 10). Rain needed for annual vegetation for food and shelter (WMO & FAO, 2016: 13)		

	Stage Definition & Behavior	Wind	Temperature	Precipitation	Soil Conditions	Cloud Cover
Adults (Solitary) (2.5-5 months)	Adults mature from 3 weeks to 9 months (2–4 months is average) (WMO & FAO, 2016: 13) Adults can fly and reproduce (WMO & FAO, 2016: 1) Adults that can fly are initially sexually immature, but eventually become sexually mature and can copulate and lay eggs (WMO & FAO, 2016: 3)	Solitarious adults migrate when the wind is less than 7 m/s. They usually take off about 20 minutes after sunset and can fly for up to 10 hours, usually flying for only a few hours at a time. Individuals have been detected by radar up to heights of 1 800 m(WMO & FAO, 2016: 5). Adults fly downwind during the night at heights up to 1 800 m (generally < 400 m) with ground speed of 25–65 km/h for up to 10 hours (2-hour average) (WMO & FAO, 2016: 13).	Solitarious adults migrate at night about 20 minutes after sunset when the temperature is above 20–22°C and wind < 7 m/s (WMO & FAO, 2016: 5). Sustained flights are rare at temperature < 20°C (WMO & FAO, 2016: 13).	Mature rapidly in areas receiving recent significant rains; mature slowly in low temperatures or dry habitats (WMO & FAO, 2016: 13). Adults start to mature when they arrive in an area that received significant rains recently (WMO & FAO, 2016: 10). Downwind displacement tends to bring locusts into an area during the season when rain is most likely, for example, the Sahel of West Africa and the Sudan in the summer and the Red Sea coast in the winter. Once rain falls, locusts will mature and breed (WMO & FAO, 2016: 6).	Solitarious locusts are most active when soil temperature ranges between 25°C and 30°C (WMO & FAO, 2016: 30).	

	Stage Definition & Behavior	Wind	Temperature	Precipitation	Soil Conditions	Cloud Cover
Hopper Bands (Gregarious)	The non-flying hopper (or nymphal) stage can form cohesive masses that are called hopper bands. As hoppers continue to concentrate, they become more gregarious and the groups fuse to form bands (WMO & FAO, 2016: 4).	Band movement is usually downwind (WMO & FAO, 2016: 13).		When plentiful rain falls and annual green vegetation develops, Desert Locusts can increase rapidly in number and, within a month or two, start to concentrate and become gregarious. Unless checked, this can lead to the formation of small groups or bands of wingless hoppers and small groups or swarms of winged adults (WMO & FAO, 2016: 1). During warm and sunny days, hopper bands follow a pattern of behaviour alternating between roosting and marching throughout the day (WMO & FAO, 2016: 4).	If the vegetation is very dry, bands may continue moving at night in search of green vegetation (WMO & FAO, 2016: 4).	Bands march on warm, sunny days; bands do not move on overcast days (WMO & FAO, 2016: 13).

	Stage Definition & Behavior	Wind	Temperature	Precipitation	Soil Conditions	Cloud Cover
Swarms (Gregarious)	Bask to warm up in the sun from sunrise to mid-morning (WMO & FAO, 2016: 13). Swarms can occur as low-flying sheets (stratiform) or may pile high in the air (cumuliform), with the top level as much as 1 500 m above the ground. Stratiform swarms are flat, usually tens of metres deep, and often occur during cool, overcast weather or in the late afternoon. Cumuliform swarms are associated with convective updrafts on hot afternoons, especially common during the warmer and drier months of the year (WMO & FAO, 2016: 5). Swarms are usually stratiform in the morning and become cumuliform in the heat of the day, when convection takes place from the hot ground (WMO & FAO, 2016: 13).	In the absence of wind, locusts fly at about 3–4 m/s. Swarms may fly up to nine or 10 hours in a day, moving downwind, although mature swarms may sometimes move a short distance upwind if the wind is light. It is not clear with cumuliform swarms which wind level determines displacement. Swarms start to settle about an hour before sunset as convection dies away. (WMO & FAO, 2016: 6). Will not take off in winds > 10 m/s (19.4 knots) (WMO & FAO, 2016: 13). Fly downwind during the day at heights up to 1 700 m with ground speed of 1.5–16 km/h until 2 hours before sunset or 0.5 hours after sunset (WMO & FAO, 2016: 13).	Sustained flight of swarms is rare if temperatures are below about 20°C. If there are overcast conditions, then this lower limiting temperature is about 23°C. (WMO & FAO, 2016: 6). Take off about 2–3 hours after sunrise in warm weather (4–6 hours after sunrise in cool weather) and wind < 6 m/s (WMO & FAO, 2016: 13).			Take off in sunny conditions at least 15°C–17°C; in cloudy conditions at 23°C–26°C (WMO & FAO, 2016: 13).

Fig. 1: Vegetation Classes and NDVI Value

Table 1 Urban vegetation classes and NDVI value

Bil	Vegetation Classes	Description	NDVI Value
1	Non-Vegetation	Barren areas, build up area, road network	: -1 to 0.199
2	Low Vegetation	Shrub and grassland	: 0.2 to 0.5
3	High Vegetation	Temperate and Tropical urban forest	: 0.501 to 1.0

Source: Hashim, H. & Abd Latif, Zulkiflee & Adnan, Nor. (2019). URBAN VEGETATION CLASSIFICATION WITH NDVI THRESHOLD VALUE METHOD WITH VERY HIGH RESOLUTION (VHR) PLEIADES IMAGERY. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. XLII-4/W16. 237-240. 10.5194/isprs-archives-XLII-4-W16-237-2019.

Appendix B

- **Data Type: Locust Sighting Data**
  - Agency: FAO Locust Hub
  - Source: https://locust-hub-hqfao.hub.arcgis.com/
  - Instructions: We found this valuable datasource via emailing eclo@fao.org for the FAO Atlas of Desert Locust Breeding Habits. Keith Cressman, the Senior Locust Forecasting Officer at FAO responded and suggested we obtain data from the Locust Hub. The FAO Locust Hub contains datasets on locust sightings segmented by adults, bands, hoppers and swarms. The dataset is updated weekly, every Thursday. We downloaded the datasets as shapefiles and cropped them in ArcMap to fit our parameters –Kenya country boundary and time period from December 1st 2019 to May 31st 2020.

- **Data Type: Daily Soil Temperature**
  - Resolution: 36 km
  - Temporal Resolution: 1 day
  - Source: https://nsidc.org/data/SPL3SMP/versions/6
  - Parameters: The main output of this data set is 0-5 cm surface soil temperature (C) presented on the global 36 km EASE-Grid 2.0. Also included are Brightness Temperature (Tb) measurements (K), representing the weighted average of SMAP Level-1B brightness temperatures whose boresights fall within each 36 km EASE-Grid 2.0 grid cell.

- **Data Type: Daily Soil Moisture**
  - Resolution: 36 km
  - Source: https://nsidc.org/data/SPL3SMP/versions/6
  - Parameters: The main output of this data set is 0-5 cm surface soil moisture (cm3/cm3) presented on the global 36 km EASE-Grid 2.0. Also included are Brightness Temperature (Tb) measurements (K), representing the weighted average of SMAP Level-1B brightness temperatures whose boresights fall within each 36 km EASE-Grid 2.0 grid cell.

- **Data Type: Monthly Soil Moisture 0-10cm**
  - Agency: IRI Data Library
  - Service: NOAA NCEP-NCAR CDAS-1 Reanalysis
  - http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/.CDAS-1/.MONTHLY/.Diagnostic/.0-10_cm_down/.soil/.moisture/index.html#info
  - Resolution: 210km
  - Instructions: Parameters were set in the IRI Data Library Expert Mode to choose for the coordinates that would encompass Kenya from 33-42E and 5.5N to 5S. To obtain monthly data, the month/year can be set by changing it manually here. To download the data in a GIS-compatible format, click on "Entire Dataset", navigate to the "Data Files" tab and select "netCDF" under the section titled "Other Available File Formats". Download the file and open it in ArcMap.

Use the Make NetCDF Raster Layer tool to convert the data into a format that can be visualized.

- **Data Type: Avg. Relative Humidity Data (0-30mb)**
  - Agency: IRI Data Library
  - Source: NOAA NCEP-NCAR CDAS
  - Resolution: 275km
  - http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/.CDAS-1/.DAILY/.Intrinsic/.30-0_mb_above_gnd/.rhum/
  - Instructions: Parameters were set in the IRI Data Library Expert Mode to choose for the coordinates that would encompass Kenya from 32-42E and 5N to 5S. To obtain daily data, the date can be set by changing it manually here. To download the data in a GIS-compatible format, click on "Entire Dataset", navigate to the "Data Files" tab and select "netCDF" under the section titled "Other Available File Formats". Download the file and open it in ArcMap. Use the Make NetCDF Raster Layer tool to convert the data into a format that can be visualized.

- **Data Type: NDVI**
  - Source: Copernicus Global Land Service, European Commission Joint Research Centre VITO Vegetation Indicators
  - Resolution: 300m
  - https://land.copernicus.vgt.vito.be/PDF/portal/Application.html#Browse;Root=513186;Collection=1000063;Time=NORMAL,NORMAL,-1,,,-1,,
  - Normalized Difference Vegetation Index (NDVI) is an indicator of the greenness of all florae on Earth. It is not necessarily a physical property of vegetation; rather, it's based on a formula that consists of the spectral reflectances measured in the near infrared and red wavebands. Further, it is related to Fraction of Absorbed Photosynthetically Active Radiation (FAPAR). (Copernicus Global Land Service, European Commission Joint Research Centre (2020). NDVI. Retrieved from https://land.copernicus.eu/global/products/ndvi
  - Instructions: Dekadal periods chosen for the months of April and May 2020. netCDF files of global NDVI were downloaded and opened in GIS. The netCDF to raster tool was used to convert to the data for use/analysis in GIS. This new raster layer was exported with its features (right click layer, DATA, Export Features) When exporting, spatial parameters were set to encompass Kenya from 33E-42E latitude and 5.5N to 5S longitude. This minimizes the amount of data and makes it easier to load and analyze as you work with it in GIS.
  - For the NDVI values downloaded from this site, the physical min displayed is -0.08 and the physical max displayed is 0.92.

- **Data Type: Dekadal Precipitation**
  - Agency: IRI Data Library
  - Service: NOAA NCEP-CPC FEWS, Africa Rainfall Climatology Version 2 (ARC2) precipitation estimates
  - Resolution: 11km
  - http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.CPC/.FEWS/.Africa/.TEN-DAY/.RFEv2/.est_prcp/

- Instructions: Parameters were set in the IRI Data Library Expert Mode to choose for the coordinates that would encompass Kenya from 33-42E and 5N to 5S. To obtain dekadal data, the date can be set by changing it manually here. To download the data in a GIS-compatible format, click on "Entire Dataset", navigate to the "Data Files" tab and select "netCDF" under the section titled "Other Available File Formats". Download the file and open it in ArcMap. Use the Make NetCDF Raster Layer tool to convert the data into a format that can be visualized.

- **Data Type: Daily Precipitation**
  - Agency: IRI Data Library
  - Service: NOAA NCEP-CPC FEWS, Africa Rainfall Climatology Version 2 (ARC2) precipitation estimates
  - Resolution: 11km
  - http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.CPC/.FEWS/.Africa/.DAILY/.ARC2/.daily/.est_prcp/
  - Instructions: Parameters were set in the IRI Data Library Expert Mode to choose for the coordinates that would encompass Kenya from 33-42E and 5N to 5S. To obtain daily data, the date can be set by changing it manually here. To download the data in a GIS-compatible format, click on "Entire Dataset", navigate to the "Data Files" tab and select "netCDF" under the section titled "Other Available File Formats". Download the file and open it in ArcMap. Use the Make NetCDF Raster Layer tool to convert the data into a format that can be visualized.

- **Data Type: Total Air Column Cloud Cover**
  - Agency: IRI Data Library
  - Source: NOAA NCEP-NCAR CDAS-1
  - Resolution: 210km
  - http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/.CDAS-1/.DAILY/.Diagnostic/.total_air_column/.cld/
  - Instructions: Parameters were set in the IRI Data Library Expert Mode to choose for the coordinates that would encompass Kenya from 32-42E and 5.5N to 5S. To obtain daily data, the date can be set by changing it manually here. To download the data in a GIS-compatible format, click on "Entire Dataset", navigate to the "Data Files" tab and select "netCDF" under the section titled "Other Available File Formats". Download the file and open it in ArcMap. Use the Make NetCDF Raster Layer tool to convert the data into a format that can be visualized.
  - Thresholds for cloudy vs sunny conditions used in our analysis found at: https://www.weather.gov/media/pah/ServiceGuide/A-forecast.pdf

- **Data Type: Surface Air Temperature**
  - Agency: NOAA Physical Sciences Laboratory, CPC Global Daily Temperature
  - Source: NOAA/OAR/ESRL PSL, Boulder, Colorado, USA
  - Resolution: 55km
  - https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html
  - Min and Max temperature derived separately using the Download/Plot data, Maximum-Daily, then choose years.

- Download the netCDF file and open it in ArcMap. Use the Make NetCDF Raster Layer tool to convert the data into a format that can be visualized. This is a multidimensional raster.
- "Note: the daily average temperature can be generated from tmax and tmin by adding the values together and dividing by 2. You should be able to do this in any data analysis package that supports netCDF files.

- **Data Type: Monthly Precipitation Anomaly**
    - Agency: IRI Data Library
    - Source: NOAA NCEP-CPC CAMS OPI
    - Resolution: 275km
    - http://iridl.ldeo.columbia.edu/maproom/Global/Precipitation/Anomaly.html?bbox=bb%3A-20%3A-40%3A55%3A40%3Abb
    - Instructions: Instructions: Parameters were set in the IRI Data Library Expert Mode to choose for the coordinates that would encompass Kenya from 32-42E and 5.5N to 5S. To obtain monthly data, the month/year can be set by changing it manually here. To download the data in a GIS-compatible format, click on "Entire Dataset", navigate to the "Data Files" tab and select "netCDF" under the section titled "Other Available File Formats". Download the file and open it in ArcMap. Use the Make NetCDF Raster Layer tool to convert the data into a format that can be visualized.

- **Data Type: U-Wind Speed and Direction at 1000mb**
    - Agency: IRI Data Library
    - Service: NOAA NCEP-NCAR CDAS-1 Reanalysis
    - http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/.CDAS-1/.DAILY/.Intrinsic/.PressureLevel/.u/
    - Resolution: 275km
    - Instructions: Parameters were set in the IRI Data Library Expert Mode to choose for the coordinates that would encompass Kenya from 33-42E latitude and 5.5N to 5S longitude, and pressure leve, P at 1000mb. To obtain daily data, the date can be set by changing it manually here. To download the data in a GIS-compatible format, navigate to the "Data Files" tab and select "netCDF" under the section titled "Other Available File Formats". Download the file and open it in ArcMap. Use the Make NetCDF Raster Layer tool to convert the data into a format that can be visualized.

- **Data Type: V-Wind Speed and Direction at 1000mb**
    - Agency: IRI Data Library
    - Service: NOAA NCEP-NCAR CDAS-1 Reanalysis
    - Resolution: 275km
    - http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/.CDAS-1/.DAILY/.Intrinsic/.PressureLevel/.v/
    - Instructions: Parameters were set in the IRI Data Library Expert Mode to choose for the coordinates that would encompass Kenya from 33-42E latitude and 5.5N to 5S longitude, and pressure leve, P at 1000mb. To obtain daily data, the date can be set by changing it manually here. To download the data in a GIS-compatible format, navigate to the "Data Files" tab and select "netCDF" under the section titled "Other Available File Formats". Download the file and open it in ArcMap. Use the Make NetCDF Raster Layer tool to convert the data into a format that can be visualized.

- **Computing wind direction and speed in GIS from u and v components:
- In ArcGIS Pro, open the raster calculator tool within the project that contains the u and v component rasters. To compute and create the wind direction layer, use the expression (ATan2(u, v) / (2*3.14159265) + 0.5) * 360, where u is the u raster input and v is the v raster input. This will give you wind direction in degrees, relating to the direction from which the wind is coming from. To compute and create the wind speed layer, use the expression SquareRoot((u * u) + (v * v)), where u is the u raster input and v is the v raster input. You can then use your point sightings layers to extract this wind speed and direction data from the resultant rasters and into the attribute table of the point sighting layer.
- Once wind direction (in degrees) is calculated, the expression

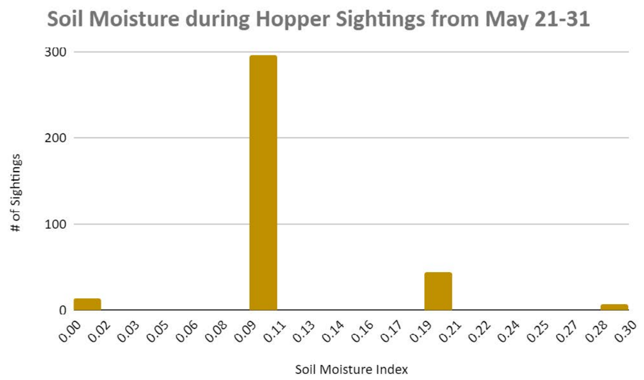
=LOOKUP(MOD(A1,360),{0,22.5,45,67.5,90,112.5,135,157.5,180,202.5,225,247.5,270,292.5,315,337.5},

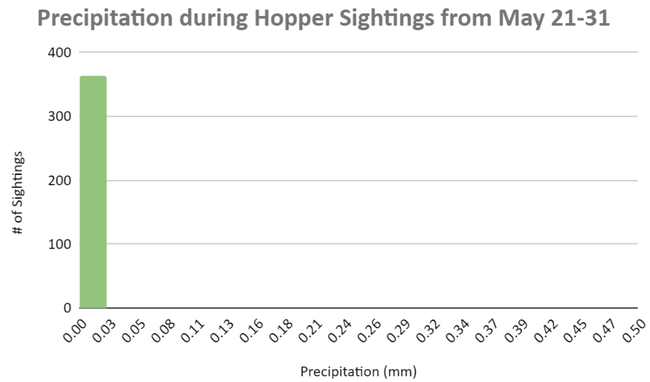
{"N","NNE","NE","ENE","E","ESE","SE","SSE","S","SSW","SW","WSW","W","WNW","NW","NNW"}) can be used in a program such as Excel in order to convert degrees to compass direction.

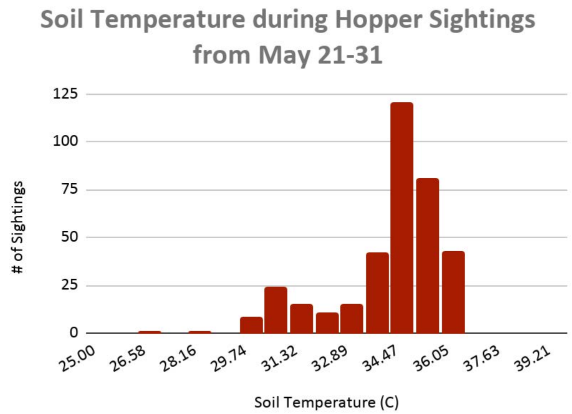
- **Data Type: Soil Type**
  - Agency: ISRIS
  - Service: KENSOTER 2.0
  - https://data.isric.org/geonetwork/srv/api/records/73e27136-9efe-49e4-af35-fd98b841d467
  - The Soil and Terrain database for Kenya (KENSOTER), version 2.0, at scale 1:1 million, replaces version 1.0 . The update includes changes in the GIS file and in the attribute database. The topographic base of KENSOTER was adapted to a version congruent to the Digital Chart of the World. The KENSOTER attribute database has changed with respect to the number of pedons stored and pedon attributes. The KENSOTER version 2.0 database contains a number of measured soil moisture contents at various tensions.

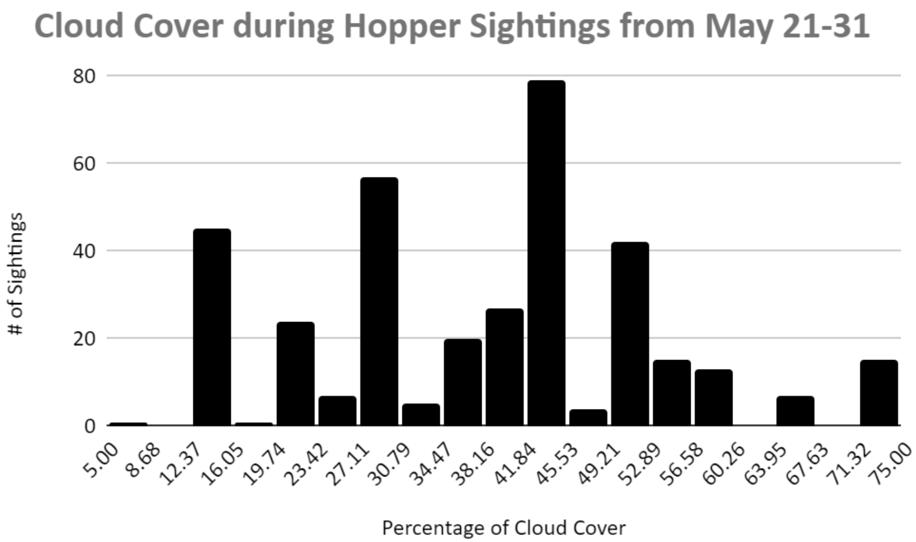
- **Data Type: Dekadal Wind Speed and Direction 1000mb**
  - Agency: IRI Data Library
  - Service: NOAA NCEP-NCAR CDAS-1 Reanalysis
  - http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/.CDAS-1/.DAILY/.Intrinsic/.PressureLevel/.u/
  - Resolution: 275km
  - Instructions: Parameters were set for the coordinates that would encompass Eastern Africa and the Arabian Peninsula from 20-55E latitude and 25N to 10S longitude, and pressure level P at 1000mb. To obtain dekadal data, the date can be set by changing it manually here. To download the data, click on the download icon on the top right of the map and click JPEG.

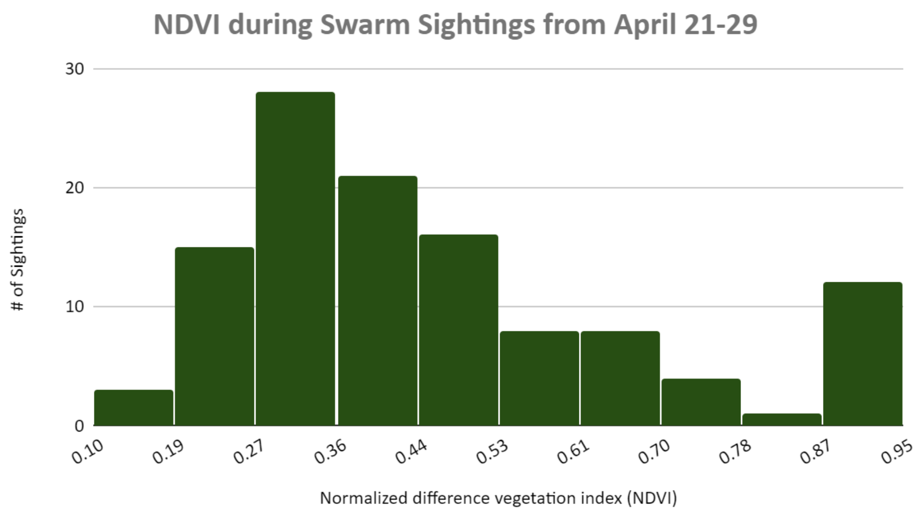
Annex 1: Kenya Case Study Hopper Data



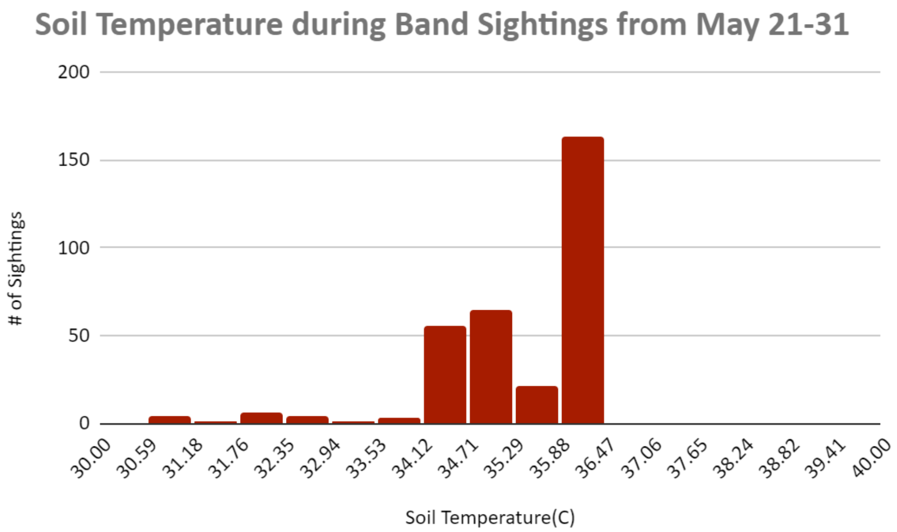


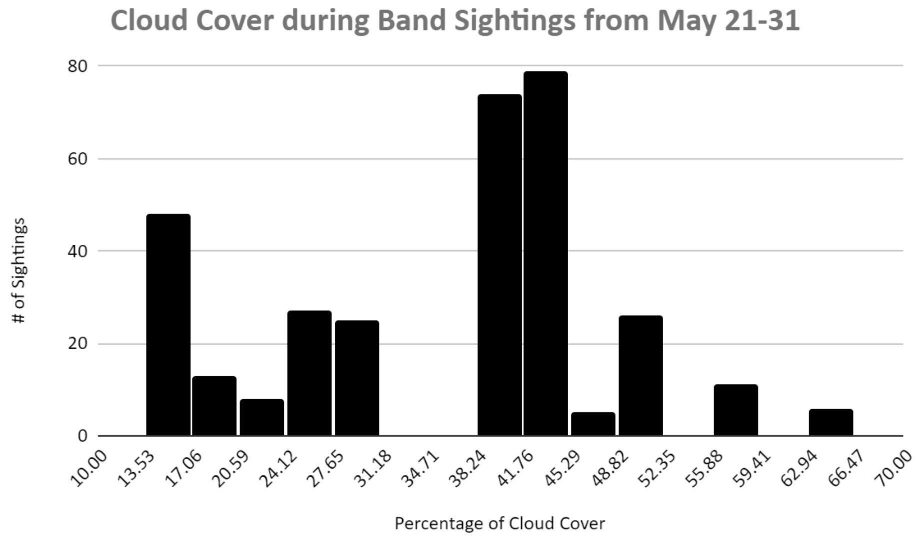


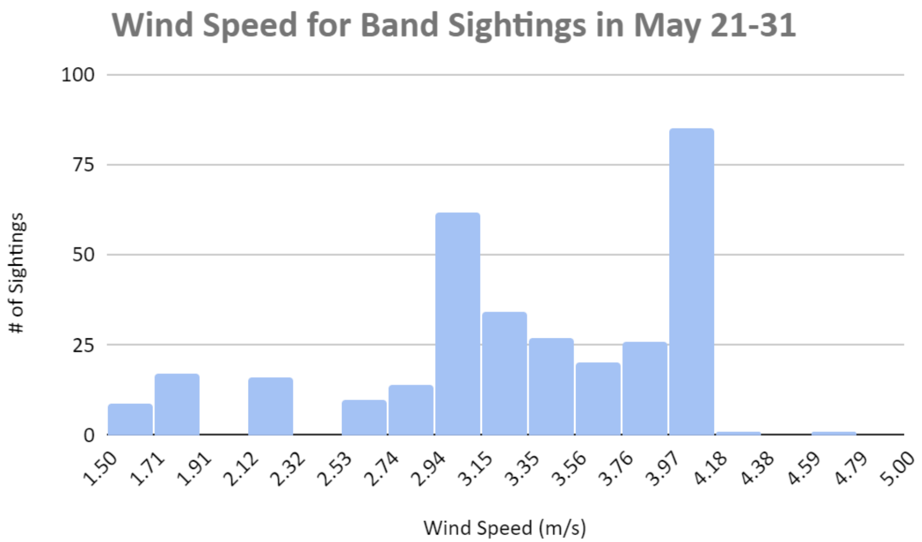


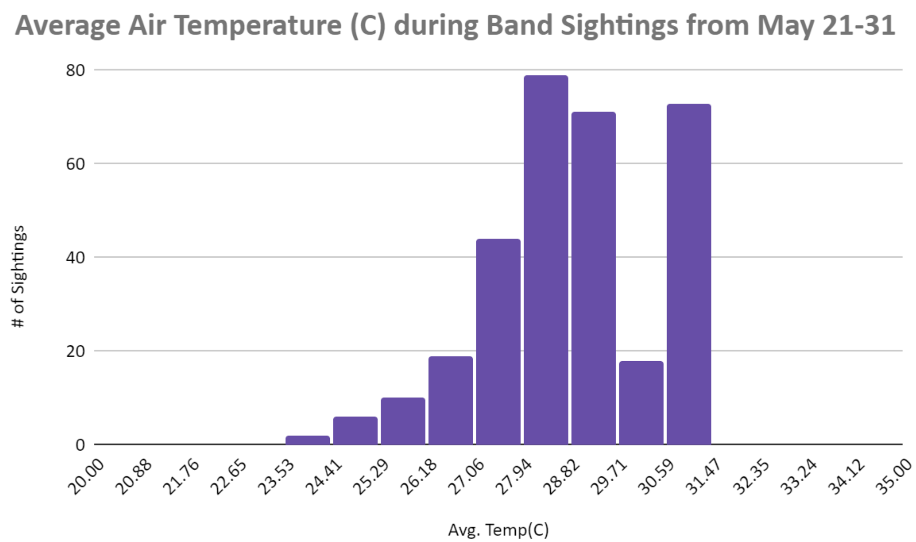


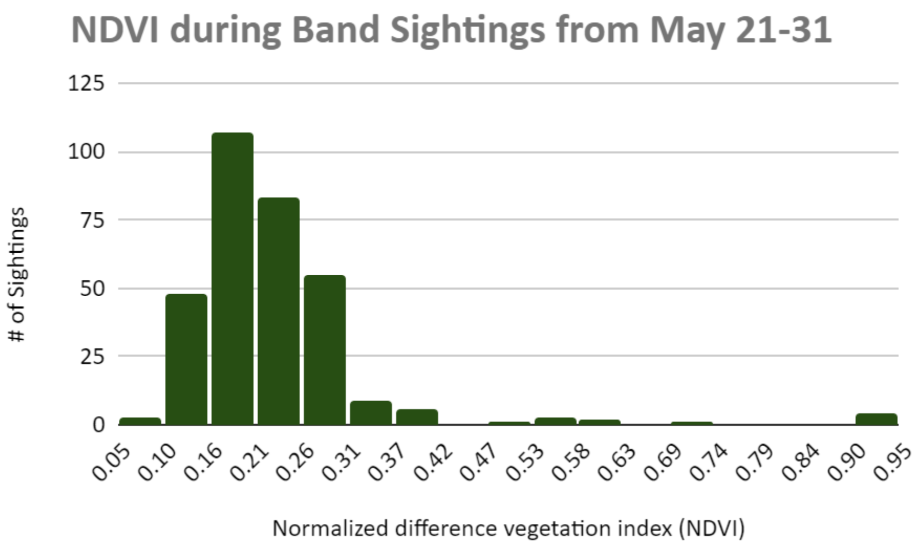
Annex 2: Kenya Case Study Band Data

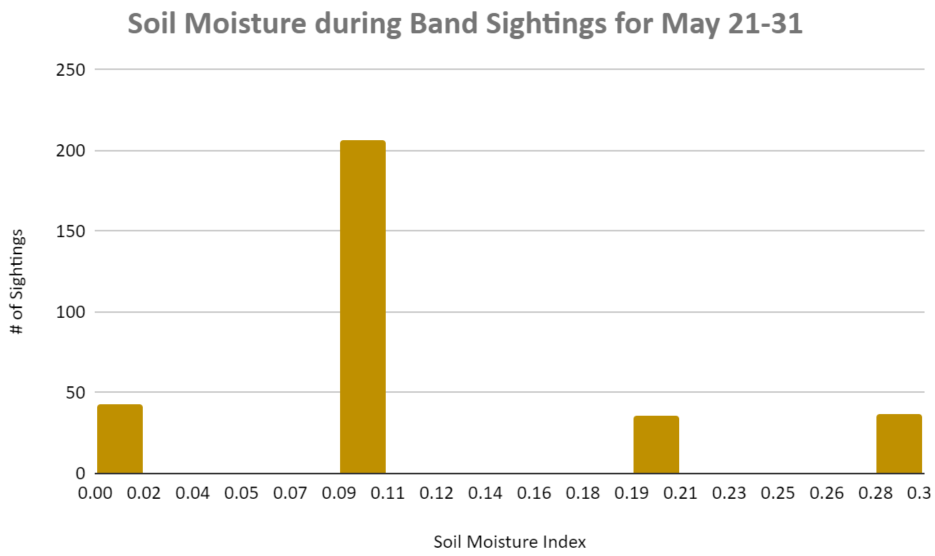


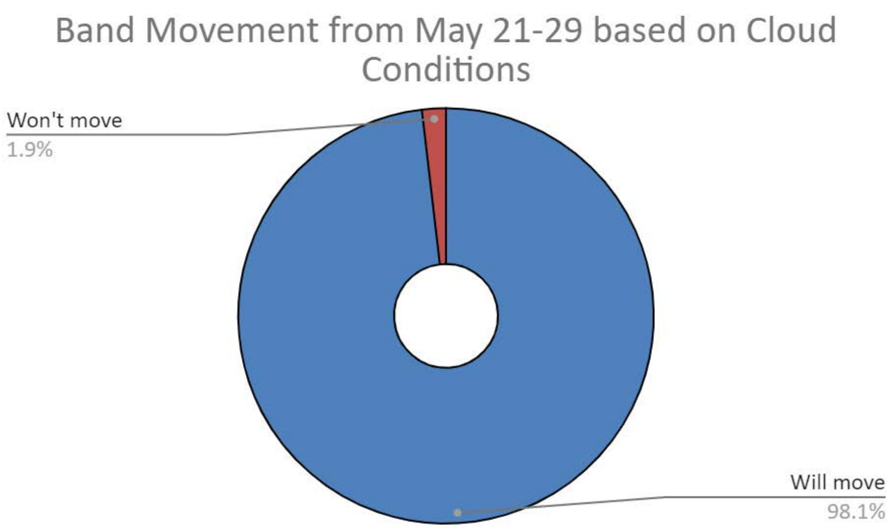


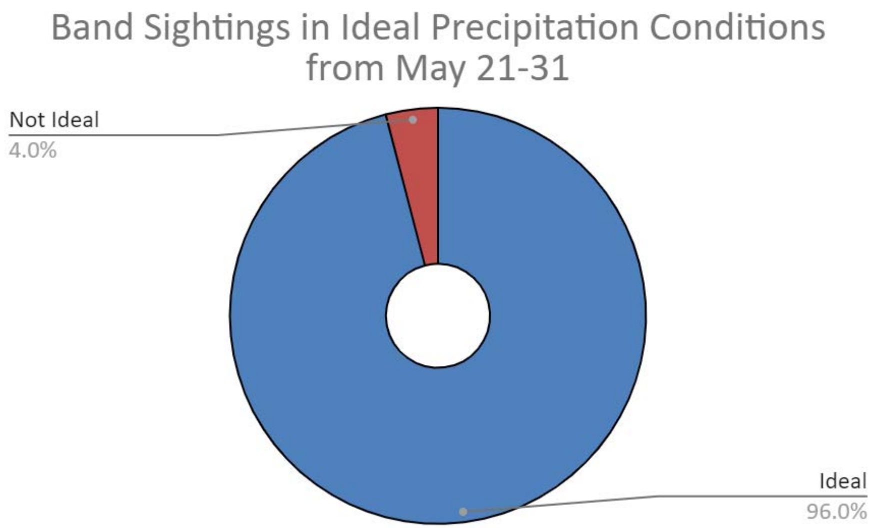




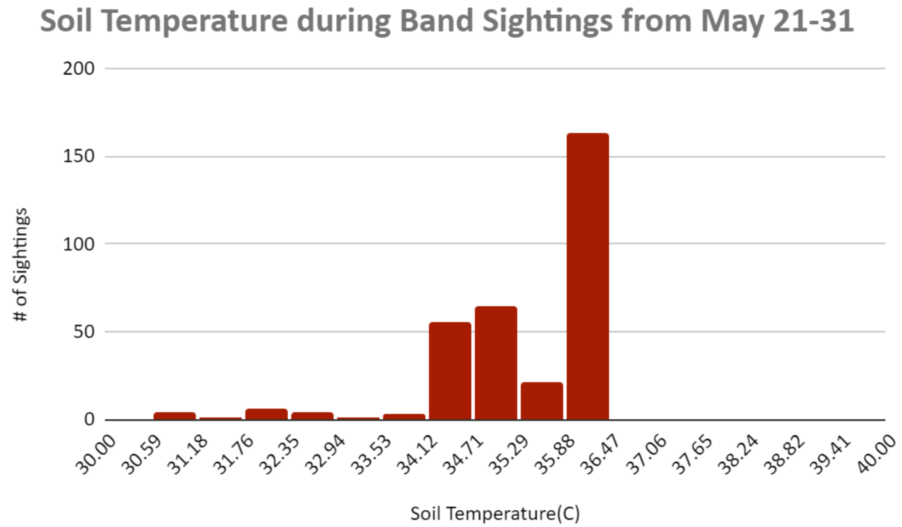

NDVI during Band Sightings from May 21-31
125
100
75
50
25
0
# of Sightings
0.05
0.10
0.16
0.21
0.26
0.31
0.37
0.42
0.47
0.53
0.58
0.63
0.69
0.74
0.79
0.84
0.90
0.95
Normalized difference vegetation index (NDVI)

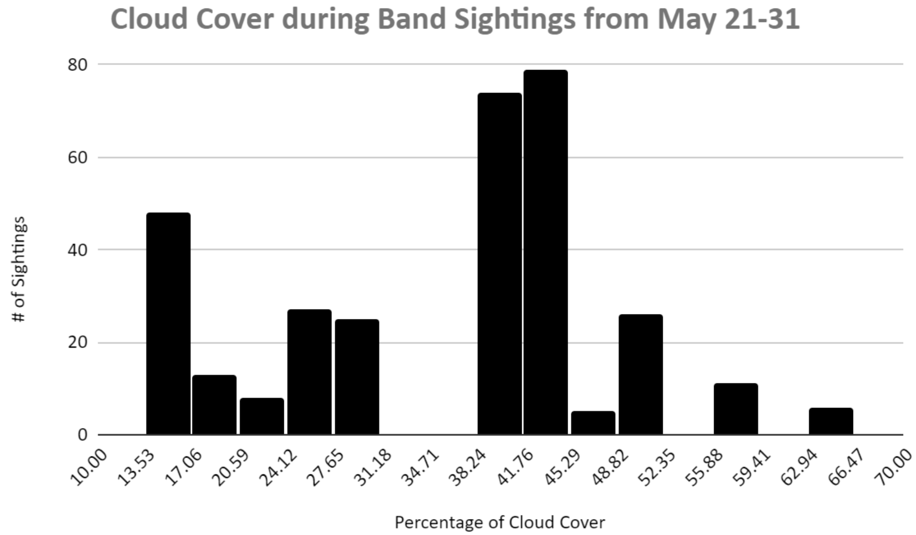

Soil Moisture during Band Sightings for May 21-31
250
200
150
100
50
0
# of Sightings
0.00
0.02
0.04
0.05
0.07
0.09
0.11
0.12
0.14
0.16
0.18
0.19
0.21
0.23
0.25
0.26
0.28
0.3
Soil Moisture Index

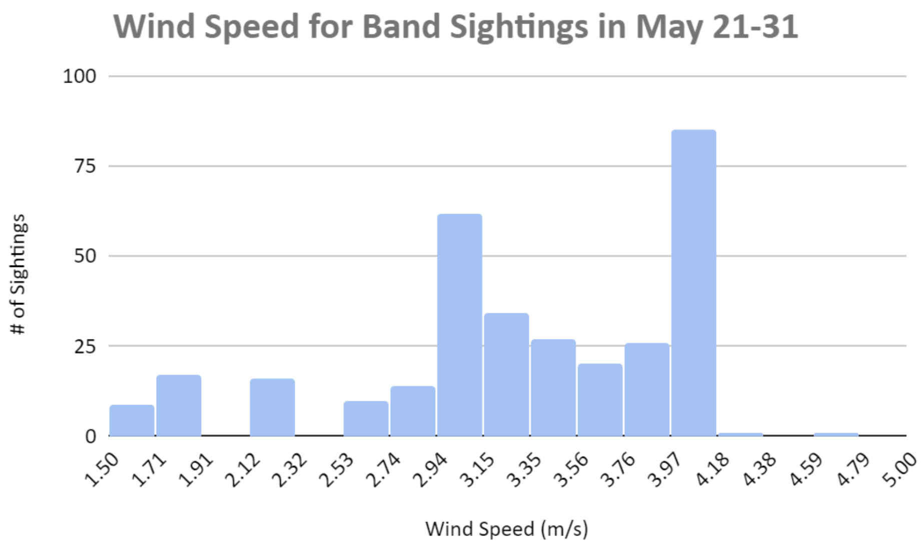

Band Movement from May 21-29 based on Cloud Conditions
Won't move
1.9%
Will move
98.1%

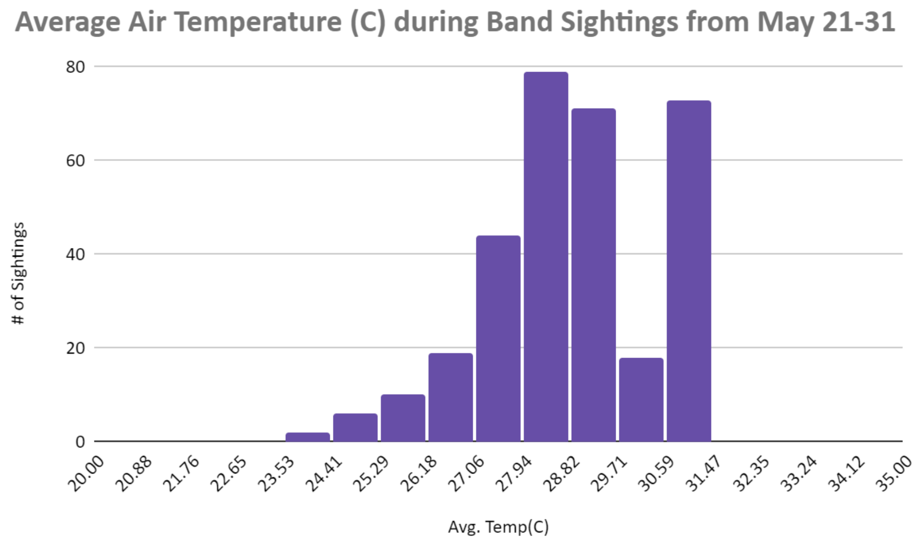

Band Sightings in Ideal Precipitation Conditions from May 21-31
Not Ideal
4.0%
Ideal
96.0%

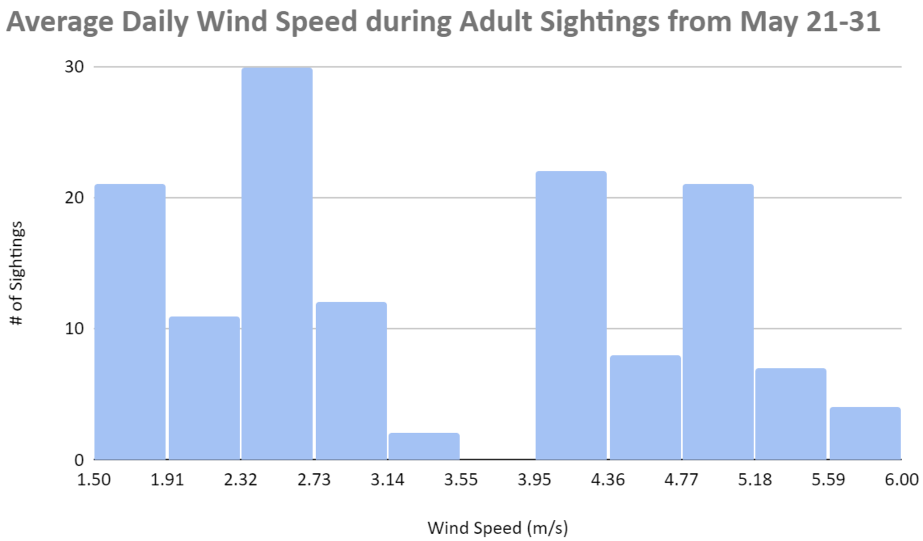
Annex 3: Kenya Case Study Swarm Data

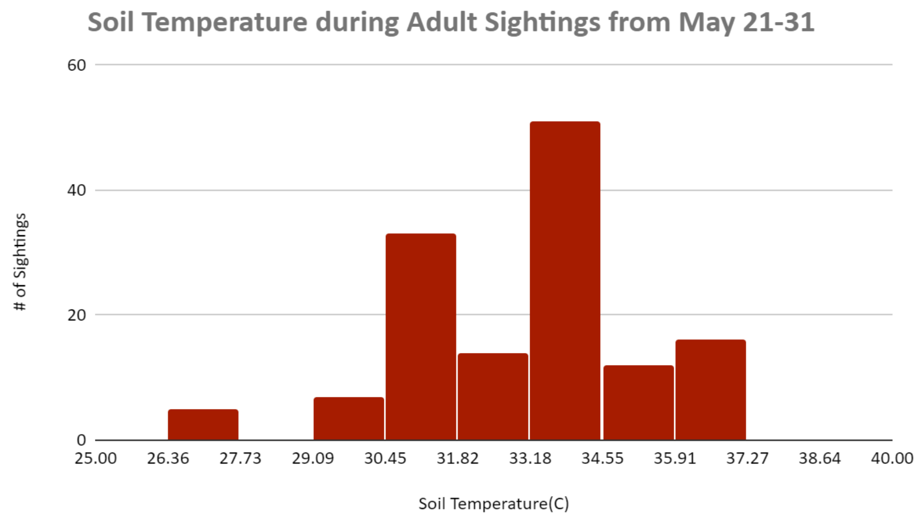




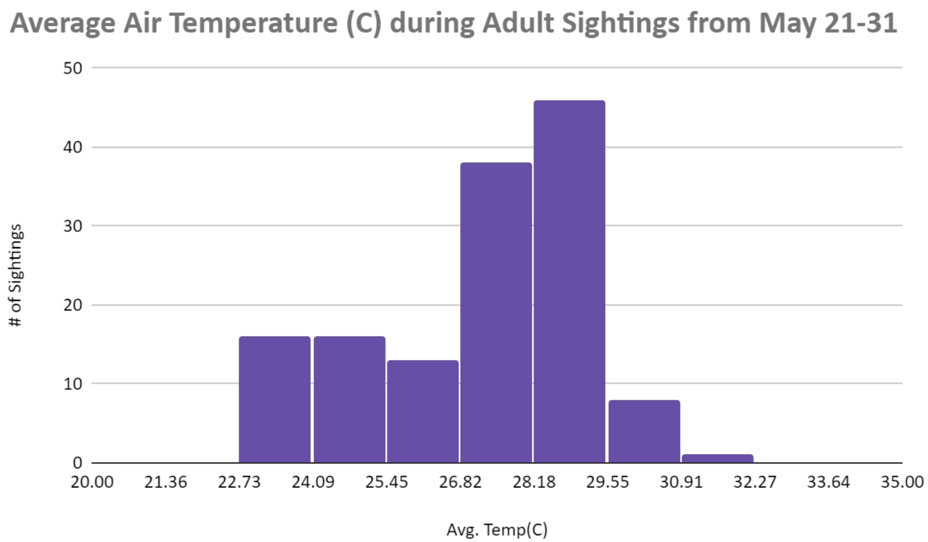


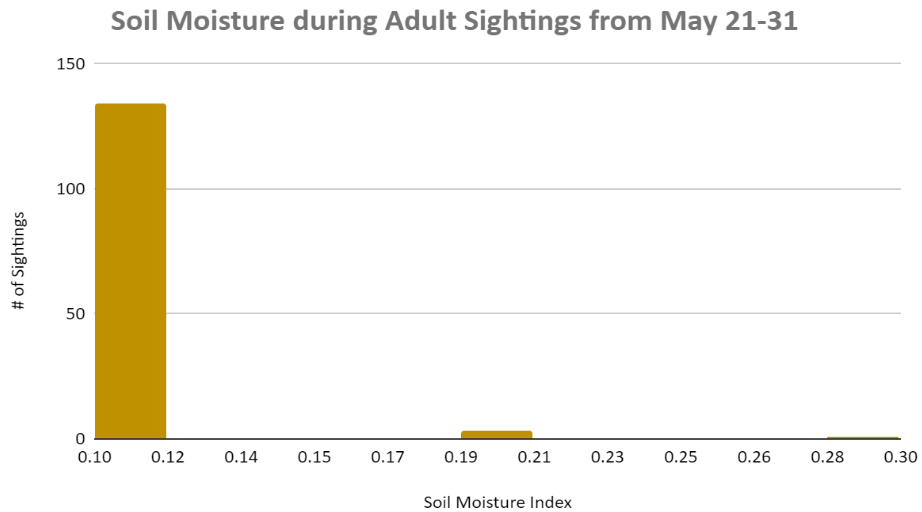


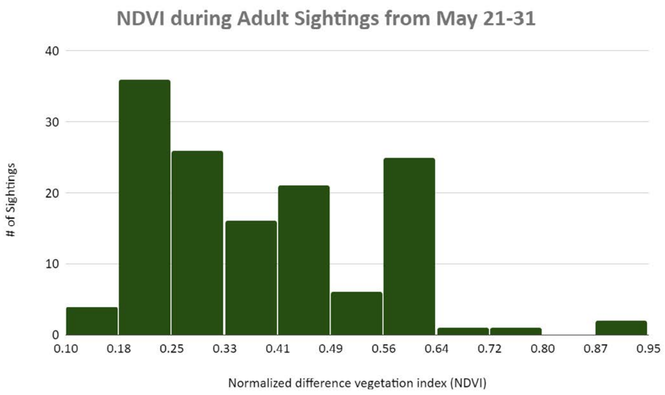


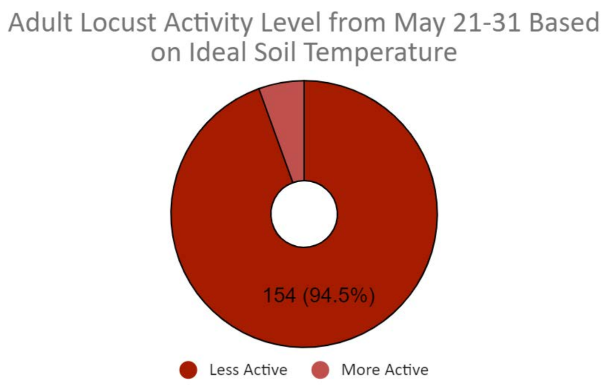


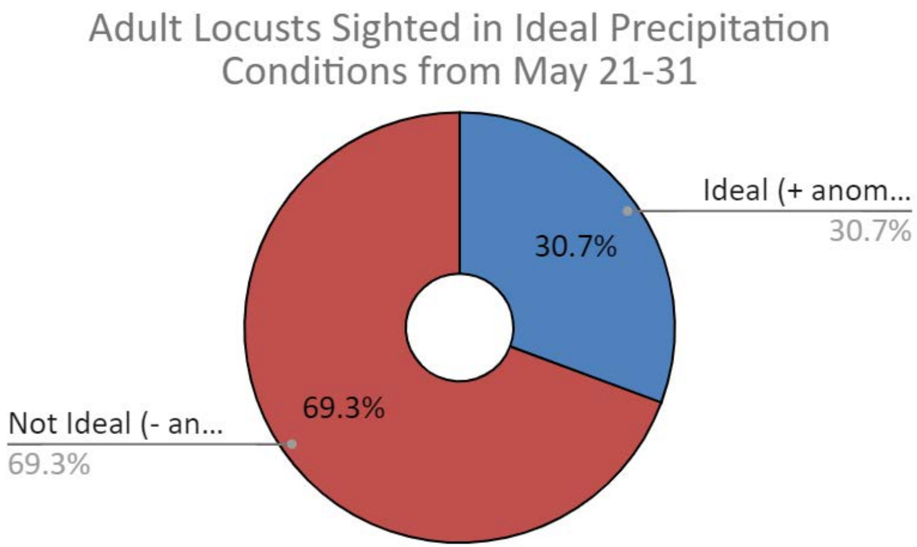
Annex 4: Kenya Case Study Adult Data











South "C" (Bellevue) Red Cross Road, Off Popo Road
P.O Box 40712, 00100 - GPO, Nairobi, Kenya
Tel: (254-20) 3950000/ 2355062/3 Fax: (254-20) 3950444
Mobiles: 0722-206958, 0703037000, 0733-333045
Email: info@icha.net, Website: www.icha.net

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At the Kenya Red Cross Society
Inquire • Understand • Influence