ASSESSMENT OF THE EFFICIENCY OF DRONES IN SURVEILLANCE AND CONTROL OF DESERT LOCUST, *Schistocerca gregaria*

BY

VIOLET AWINO OCHIENG'

I56/35936/2019

A thesis submitted in partial fulfilment of the requirements for award of the Degree of Master of Science in Agricultural Entomology of the University of Nairobi

DEPARTMENT OF BIOLOGY

FACULTY OF SCIENCE AND TECHNOLOGY

UNIVERSITY OF NAIROBI

November, 2022

DECLARATION

Candidate

I, Violet Awino Ochieng', hereby declare that this thesis is my original work and has not been presented elsewhere for award of a degree. Where other people's work have been used, this has been properly acknowledged and referenced in accordance with the University of Nairobi requirements.

Signature ___________ ________________ Date: ___15/10/2022________________

Violet Awino Ochieng'

I56/35936/2019

Supervisors

This proposal is submitted with our approval as the supervisors

Dr. George O. Ongamo

Department of Biology, University of Nairobi

Signature ___________________________ Date: _25/10/2022__________________

Prof. Paul N. Ndegwa

Department of Biology, University of Nairobi

Signature ________ Date: ___19/10/2022_____

Dr. Ivan Rwomushana

Centre for Agriculture and Bioscience International (CABI), Africa

Signature _ __________________________ Date: ___20/10.2022_

DEDICATION

This thesis is dedicated to my mother; Rose Atieno who has been giving me endless support, guiding light and my source of strength and my father; late Joseph Ochieng' whose spirit has guided me throughout the study period; and siblings for being my cheerleaders.

ACKNOWLEDGEMENT

First and foremost, I thank GOD Almighty for giving me strength, endless love, grace and favor throughout the study period. I am grateful and thankful to my internal school supervisors Dr. George Ongamo and Prof. Paul Ndegwa both of Faculty of Science and Technology, department of Biology, for their constructive criticism, immense guidance, mentorship, encouragement, and advice throughout the study period.

I appreciate my external supervisor Dr. Ivan Rwomushana of Center for Agriculture and Bioscience International (CABI) for providing facilitation to conduct this work and for ensuring that I promptly got all materials required for research. It was an honor and great privilege to study and work under your supervision.

I acknowledge CABI for the financial support and Carol Ellison Science for the Award I was given in 2021. This journey would not have been possible without the generous financial support received Foreign Commonwealth and Development Office through Frontier Technologies Hub. I acknowledge the invaluable help I received from Astral Aerial Solutions whose cordial collaboration with CABI provided conducive environment for this work. I also acknowledge KALRO, Muguga station for giving me a conducive environment to conduct my field and lab experiments.

I am pleased to acknowledge the University of Nairobi for allowing me to register my Master of Science programme under the support of University of Nairobi Scholarship. I also thank my family for the love, encouragement and support throughout the study period.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

ABBREVIATION AND ACRONYMS

ASALs -	Arid and Semi-Arid areas
CABI-	Centre for Agriculture and Bioscience International
EC-	Emulsifiable Concentrates
FAO-	Food and Agriculture Organisation
GCS-	Ground Control Points
GPS-	Global Positioning System
JPEG-	Joint Photographic Expert Group
KALRO-	Kenya Agriculture and Livestock Research Organisation
MODIS-	Moderate Resolution Imaging Spectroradiometer
PRG-	Pesticide Reference Group
TIF-	Tag Image Format
UAV-	Unmanned Aerial Vehicle
ULV-	Ultra-Low Volume
VAR-	Volume Application Rate

ABSTRACT

Desert locust is a migratory pest with ability to change from solitary to gregarious phase in response to suitable ecological conditions and has been listed as one of the most destructive pest in the world. Current methods of surveillance and control rely on the use of ground and aerial methods which presented some challenges despite being used successfully during the recent upsurge, hence the need to supplement them with suitable and affordable alternatives. Successful use of drones to manage other pests makes it an attractive and potential technology for desert locusts' management. However, the available studies have neither optimized the key parameters nor addressed the standard operating procedures for desert locusts management. This study bridged the existing gaps by establishing the key parameters for surveillance and spraying of desert locusts using a drone. For surveillance, Dji Mavic 2 pro, was launched at five different heights (30 m to 110 m) to capture the images of locusts in the field and time taken, speed of the drone, spatial resolution and distance covered at each height was generated from the drone. AGISOFT software was used to stitch the images together to form Orthomosaic maps which were compared at different heights and generated parameters tested for correlation. To test the optimum height for spraying *Metarhizium* on the locusts using a drone; drone was flown at five different test heights; 2.5, 5, 7.5, 10 to approximate the droplet density and compare it to the standard droplet density recommended for desert locusts control. To assess the efficiacy of M. acridum and the effectiveness of drones in its application, 500 grams of *Metarhizium* (Novacrid) spore was mixed in 20 litres of diesel and 1 litres sprayed at different heights on the caged live locusts of different stages (3rd and 4th as well as the adults) arranged systematically in one hectare. They were monitored for twenty one days in a controlled room and their mortality determined. Except for the resolutions of pictures (cm/pixel) taken, other generated parameters were negatively correlated

with flight heights. The results confirmed that orthomosaic images are clearer and well defined at a lower (30 m) compared to images obtained at flight height of 50 and 70m. Images obtained at higher flight height (90 and 110 m) are blurred with less defined details. This study confirms variation of droplet density between the tested heights ($F_{4,40}$ = 7.2; p<0.001). Droplets density observed at 5m (75.3± 11.1), 7.5m (96.0± 29.4), 10m (40.2± 10.1) and 12.5m (24.8 ± 6.51) had a significant variation while the droplets density observed at 2.5m (152.2 ± 4.8) was significantly different from the droplets densities observed at all tested heights except for 7.5m. There was evidence of variation of standard droplet density and mean droplet densities recorded at different heights. Height of 10m agreed with VAR as recommended standard droplets density within 45 droplets/ cm^2 range. Mortality varied among the locusts development stages within heights ($F_{2,30}$ =25.71; p<0.0001) and between heights ($F_{4,30}$ =143.39; p<0.0001). Interaction between stage-height also had a significant effect on mortality ($F_{8, 30}$ =3.6745; p=0.004). Survival probability varied between heights for third instar (χ^2_4= 56.84; p<0.0001), fourth (χ^2_4= 54.17; p<0.0001) and adults (χ^2_4= 47.57; p<0.0001). The study contend that relatively low flight heights (30–50m) and high flight heights (90 to 110m) above the ground are advisable for intensive and extensive surveillance respectively. Spraying desert locusts using a drone at any height below 10.0 m may lead to over-deposition of the pesticide, while heights above 10.0 m may lead to under-application. This study demonstrated that spraying a control agent from a specific height (10 m) is more effective than other heights tested. Despite all the developmental stages of the desert locust being susceptible to Novacrid®, the recommended target stage for management using this biopesticide is the 3rd instar stage because of the higher mortality rate and lower survival probability at this stage.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Desert locust, *Schistocerca gregaria* Forskål (Orthoptera: Acrididae) is the most destructive migratory pest in the world (FAO, 2020d). Desert locusts exhibit two different phases that vary in distribution, biology and behaviour (Symmons and Cressman, 2001). The non–migratory solitary phase inhabit recession areas in the arid and semi-arid lands (ASALs) including Sahel regions, Arabian Peninsula and western parts of Asia (Cressman and Stefanski, 2016). However, desert locust populations build-up rapidly and transform from solitary phase to gregarious phase after occurrence of ecologically suitable conditions characterised by vegetation flushes triggered by the rainfall (Symmons and Cressman, 2001). Persistence of favourable ecological condition favour a series of desert locust concentration and multiplication that go on for two or more generations which may define the beginning of an outbreak (Cressman and Stefanski, 2016).

The outbreaks in several breeding sites in the recession areas develop into an upsurge and eventually swarm from recession areas to invasion areas in search of food (vegetations) (FAO, 2016). The recent upsurge started in 2018 after two cyclones that occurred in the months May and October 2018, brought heavy rains that gave rise to favourable breeding conditions in the Empty Quarter of the southern Arabian Peninsula for at least nine months from the month of June (FAO, 2020d). As a result, three generations of breeding occurred that was undetected and not controlled. The first swarms left the Empty Quarter in January 2019 for Yemen and Saudi Arabia. Widespread spring breeding occurred in Yemen and Saudi Arabia between the months of February and June causing formation of large numbers of swarms. Due to prevailing insecurity, control operations were less successful in Yemen (FAO, 2020c). Swarms formed in Yemen, between June and December and moved to Northern Somalia and Ethiopia where breeding occured and more swarms formed (FAO, 2020a). Between the months of October and December, swarms moved from Ethiopia and Northern Somalia to Eritrea, Djibouti, Eastern Ethiopia, the Ogaden, Central and Southern Somalia and finally North Eastern Kenya (FAO, 2020d).

Swarms continued to invade and spread in Kenya in month of January 2020 during which they matured and layed eggs. Widespread hatching and bands formed in northern counties of Kenya in the month of February (FAO, 2020f). Widespread hatching caused a new generation of swarms to form in Kenya in late March with more swarms forming during the month of April. Another generation of hatching and band formation in Kenya continued in month of May. This second-generation swarms formed mainly in Turkana, Samburu, Isiolo and Marsabit counties (FAO, 2020e). The government with support of stakeholders and development partners spearhead control campaigns in an effort to limit impacts of invasion on crops, pastures and livelihood in general (Retkute *et al.*, 2021). Food and Agricultural Organisation of the United Nations (FAO), the main stakeholder, promote sustainable and ecological approaches to prevent impacts of desert locust invasion. This is achieved through continuous monitoring, early warning and promotion of sustainable preventive control strategies (Shuvo *et al.*, 2020)

During outbreak and upsurge, information provided by FAO is used by the individual countries to conduct search and assessment surveys. This is done by ground teams that move through the country by foot, vehicles or aerial teams that use aircraft (Cressman, 1996; Kuandykova *et al.*, 2015;Mroczkwoski, 2018). Data gathered during survey is used to make decision on appropriate control equipment and platform depending on size of the target area (Cressman, 2001). Ground control is conducted using motorized or manual knapsack sprayers and vehicle mounted sprayers while aerial control is conducted by the aircraft and helicopters when the target exceed the capacity of ground control (Dobson, 2001). These equipment were successfully used in the recent desert locust upsurge though the teams experienced some challenges (FAO, 2018).

The challenges of the existing management methods daunted the regional efforts of mitigating the scourge (Fischer *et al.*, 2020). For instance, manual spraying despite being cheap, was slow and exposed operator to the insecticides. On other hand, vehicles were restricted to motorable terrains only. Aircraft are expensive, unsustainable, require highly trained personnel (FAO, 2018). Modern innovative approaches and technologies are needed to complement the existing methods of managing desert locusts (FAO, 2020d). One such technology is the use of unmanned aerial vehicles (UAV) which are aircraft that fly without human onboard (Shuvo *et al.*, 2020; Subramanian *et al*., 2021). Advances in instruments and sensors installed on UAVs have resulted in innovative changes in pest management (Matthews, 2021). Drone has a potential to complement the existing methods of surveillance and control of desert locusts (Fischer *et al*., 2020).

1.2 Problem statement

Presence of desert locust in remote, inaccessible and insecure areas affected ability of teams to rapidly monitor potential breeding areas and adequately control targets (FAO, 2016; Mroczkwoski, 2018). Satellite imagery suffer from omissions errors and the resolution is insufficient to detect thin annual grasses preferred by locusts. Further, the imagery may arrive too late to be of use to survey teams and national locust control units since the satellites don’t sample frequently. Aerial surveys and control using aircraft are expensive and unsustainable while ground survey and control are labour intensive, time consuming and expensive (FAO, 2018). It is therefore important to complement the existing methods of survey and control with innovative efficient technologies such as drones to improve desert locust management (Fischer *et al.*, 2020; Matthews, 2021).

Use of drone has been identified as one of the innovative ways for improving surveillance and control of desert locusts especially in innacessible areas (Pramod *et al.*, 2020). However, there are parameters that need to be optimized for the drone to be used succesfully in desert locusts management. Existing studies dwelt on the use of drones' for detection and spraying of other priority pests and optimized key parameters in those studies may not apply to desert locusts because of the difference in biology and behavior. The purpose of this study was therefore to establish the key parameters for surveillance and spraying of insecticides on desert locust control using drones.

1.3 Justification and significance of the study

Challenges of current methods for surveillance and control of desert locusts exist and drones has the potential to be used as a complementary technology. However, key parameters that must be established and optimized to ensure efficiency of drones' operation are not well studied in the existing trials. This study proved the potential of drone to complement and fill the gaps presented by the existing methods of survey and control of desert locusts. These study also established and optimized key parameters that must be considered for effective surveillance and control of desert locusts using drones. The results contribute extra knowledge and will spur future research. Further, results serve as a framework for policy formulation that will provide basis for implementing drone technology for management of desert locusts and other pests. Complementing drones with current management methods will enhance efficiency and timeliness of desert locust survey and control.

1.4 General Objective

The overall aim of this study is to determine the key parameters for surveillance and spraying of desert locusts using drones

1.4.1 Specific objectives

i). To determine key parameters for surveillance of desert locusts using drones

ii). To establish key parameters for spraying biopesticide (*Metarhizium acridum*) for desert locust control using drones

1.5 Research hypothesis

i. Flight height has a significant effect on the surveillance parameters

ii. Flight height has a significant effect on droplet density of deposited pesticides

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 General Overview

Desert locust is the most destructive pests in the world and have ability to change their behavior from non-migratory and non-destructive solitary phase to migratory most-destructive gregarious phase (FAO, 2020d). Solitary locusts are found in the recession areas and when the conditions become favourable, they build up in number and stretch to the invasion areas during outbreak and upsurge (Cressman and Stefanski, 2016). The recent upsurge was as a result of unusual cyclones that occurred in the remote, insecured and inaccessible recession areas that brought favourable breeding conditions for desert locusts (FAO, 2020d) Remoteness and political instability in the recession areas hindered timeliness management and contributed to formation of hopper bands and adults swarms. The gregarious swarms migrated to different countries with the aid of metrological and ecological conditions destroying pasture, fodder and crops (FAO, 2020b).

The migrating nature of desert locusts make them dangerous transboundary pests and therefore their control is a co-operation between different governments and organizations such as Food and Agriculture Organization (FAO, 2016). FAO provide information on general situation of locusts to all the affected countries and give timely early warnings and forecasts in danger of invasion (Mroczkwoski, 2018). These updates guide the teams on how to conduct the ground (foot and vehicles) and aerial (helicopters and aircraft) survey to assess the size of infestation, nature of the area infested, stage of locusts among others (Cressman, 2001). Information collected during surveys is used to make the decision on whether to use ground (hand held and vehicle mounted sprayers) or aerial (aircraft) control (Dobson, 2001). The existing methods were used successfully to manage the locusts but they presented some challenges and gaps that should be filled for future timeliness control (FAO, 2018). Successful use of drone to manage other pests makes it an attractive and potential technology for desert locusts management (Pramod *et al.*, 2020). However, the available studies have neither optimized the key parameters nor mentioned the standard operating procedures for desert locusts management. This study therefore established the key parameters for surveillance and control of desert locusts using a drone.

2.2 Biology and behaviour of locusts

Desert locusts' life cycle pass through three stages; eggs, nymph and adult (Symmons and Cressman, 2001). Eggs are laid in sandy moist soils at about 5-10 cm below the surface to allow absorption of enough moisture for successful development (Sharma, 2014). Eggs are oviposited in 2-3 pods at intervals of 6-11 days, each containing 80 eggs in the gregarious phase and 3-4 pods each containing 90 to 160 eggs in solitarious phase (Cressman, 1997). The numbers of eggs pods depend on the lifespan of the female and the time it takes to develop the pod. The development rate is dependent on the soil temperature at the pod depth and air temperature. Eggs hatch after 14 days and the number that survives up to hatching widely varies and depend on environmental conditions and availability of egg predator and parasites (Cressman and Stefanski, 2016)

During hatching, hoppers emerge and immediately moult to the first instar (Symmons and Cressman, 2001). Hoppers pass through five to six instars depending on the phase and the fledglings emerge at the final moult. Development rate of hoppers is a function of air temperature even though they can control their body temperature by seeking shade and basking. Rain associated with laying of eggs generally produce enough green vegetation for hoppers to develop. Only a fraction of the first instar hoppers survive to fledge because of cannibalism, inadequate water reserves and predation (Cressman, 2016)

It takes ten days after fledgling for the adults' wing to harden sufficiently enough to sustain flight and to become fully mature. Adults remain immature until they encounter the conditions that stimulate maturation and this period is dependent on the habitat conditions. Rainfall in infested area triggers maturation of the adults and they can also mature when they invade an area where it has recently rained. Mature adults lay eggs within three weeks of fledging when the area has good vegetation, rain to maintain the growth of this vegetation and a maximum temperature of above 35°C (Symmons and Cressman, 2001).

Locusts exhibit two different phases with differences in behaviour and morphology. They exists in solitary phase when the population density is low in the arid and semi- arid (ASALs) regions of Northern Africa, parts of Asia, Arabian Peninsula and Western Asia and present no economic threat (Cressman and Stefanski, 2016). When there is growth of vegetation in major desert breeding areas after drought period, rapid population build up through multiplication causes the transformation from solitary to gregarious. Unfavorable conditions force the locusts to migrate to other regions in search of suitable breeding areas and green vegetation. The gregarious phase migrate long distances by flying downwind during the day for up to 150km while a hopper band match about 1.5km per day (Cressman, 2015). Locusts' migration to new regions is a behavior that threaten livelihood of people, environment, food security and economic development because they feed on large quantities of any kind of green vegetation and crop (FAO, 2020d)

2.3 Invasion of desert locust

Climate change contributed to the recent upsurge and nature of the recession areas hindered timely management of desert locusts (Shrestha *et al*., 2021). The upsurge of desert locust started to develop slowly in 2018 as a results of two unusual cyclones that brought heavy rainfall to the Empty Quarter in the Arabian Peninsula (FAO, 2020d) .This enabled unprecedented three generations of locusts breeding to occur in a nine-month period resulting in an 8,000-fold increase in the number of locusts. Control and survey operations were not adequately conducted since aerial and ground teams could not reach the recession area which is insecured, remote and inaccessible regions with endless towering sand dunes (FAO, 2020c).

When the vegetation started to dry out in the recession area, swarms moved from this area northwards in the Arabian interior to invade Iran and southwards to invade eastern Yemen. The swarm that invaded Iran spread out and two breeding generation occurred during spring along the whole southern coast of Iran from Iraq to Pakistan (FAO, 2020b). Many spring bred swarms moved east and invaded the desert along indo-Pakistan border despite the massive control operations. The swarm met heavy monsoon rain in 2019 that lasted longer than normal by one month enabling three generation of breeding. In late 2019, summer-bred swarms moved back to Iran while other remained in Pakistan. With the onset of rains, breeding occurred in wide areas throughout southern Iran and southwest Pakistan. The swarms that moved southwards to the interior of Yemen found favourable breeding conditions because of heavy rains (FAO, 2020e). Security issues prevented at least one breeding generation from being detected and controlled resulting in a swarm that migrated to northern Somalia, eastern Ethiopia and Kenya in 2019 (FAO, 2020f). Heavy rainfall in both countries enabled breeding and formation of swarms despite the control measures that were put into practice.

The unusual cyclone Pawan brought heavy rains and favourable conditions in the horn of Africa unlike in the normal situation where ecological conditions in the horn of Africa dry out by the end of the year thus reducing the population of locust. This cyclone suddenly caused the breeding conditions to remain favourable in Somalia and Ethiopia and the swarms in these areas gave rise to sizeable new generation of swarms that came to Kenya (FAO, 2020c). Different management methods were put into practice to contain adult swarms and hopper bands in various affected countries (Retkute *et al.*, 2021).

2.4 Current methods of managing desert locust

Desert locusts were successfully managed through co-operation between governments, government agencies and international organizations in surveillance, monitoring and control because they are transboundary pests. National agencies and international organization jointly launched various efforts to monitor and advice on early control measures concerning desert locusts (Matthews, 2021). The Food and Agriculture Organization of the United Nations (FAO), operates a centralized Desert locusts information system at Rome, Italy and all the countries affected with locusts transmit locusts' data. FAO analyses the data together with habitat and weather data and satellites imagery to assess the current situation of desert locusts, provide forecasts up to six weeks in advance and issue early warnings (Mroczkwoski, 2018).

The warning received by each country pushes for the survey operations to identify the places understated with desert locusts. According to Mroczkwoski (2018), desert locust migrate to areas where it has recently rained with green vegetation. Informed by this research, the current preventive measures and survey are thus based on the identification of these green areas and action directed to those infested with the locusts. The locusts management teams use Moderate Resolution Imaging Spectroradiometer) MODIS), a scientific instrument aboard the Terra (originally known as EOS AM-1) and Aqua (originally known as EOS PM-1) satellites to estimate estimating rainfall and green vegetation (Magor and Pender, 1997; Cressman, 2015). Satellites images are analyzed to identify areas where conditions are favourable for locust so that intensive survey and data collection can be done (FAO, 2016).

Once the area with green vegetation and favourable condition is identified, the phase of data collection usually follows. This phase aims to find out if the areas with green vegetation identified using the satellite imagery contain locusts or not. In practice, the survey is conducted by the land teams moving through the country using the vehicles and by air (aircraft) inspecting the areas for the presence of locust (Cressman, 2001). Assessment survey is conducted in areas that have a history of desert locusts and where rain or the locusts have been reported, to monitor the locust population and asses the suitability of habitats for breeding. Search surveys are performed in areas known to contain a significant population of desert locusts, to estimate the total infested area to help make the decision on how the control can be done (Cressman, 2001). These teams currently use the eLocust3 suites-based on a hand held smart phones that enable the user to log in details about vegetation, soil, habitat, rainfall, locusts, and control. These tools transmit the survey information via the satellites in real time to the desert locust information officers in the respective countries who clean the data and send to Rome for processing (Cressman, 2014)

After processing the survey data, the defined areas are noted and control conducted accordingly using the suitable chemical products for each country, region or zone. The commonly used method for controlling locust is spraying with the appropriate and approved pesticides using a sprayer to atomize a liquid pesticide which is then distributed over the target area with locusts (Dobson, 2001). Extensive spraying is performed with trucks or small airplanes but it is not most appropriate for precision application of pesticides since there is no adequate chemical control, pesticides are wasted and untargeted or sensitive areas can be sprayed which can result in undesired effects on the environment (Mroczkwoski, 2018). Intensive control method is carried out by a team equipped with chemical backpack sprayers and since it is more targeted the spraying accuracy is notably and pesticide wastage is reduced although the operation is slow and difficult to conduct over extensive or large areas. Several control products exists for the management of desert locusts.

2.5 Chemicals/pesticides used to control desert locust

Emulsifiable concentrates (EC) formulation products, Ultra low volume (ULV) products and bio-pesticides are currently used to manage the desert locusts (PFG, 1994). Emulsifiable concentrates are typically transparent oily liquid formulations that are prepared by dissolving a specific amount of pesticide in organic solvents and then diluted with water prior to spraying, which leads to the spontaneous formation of an oil-in-water emulsion that contains pesticides inside the oil droplets. In desert locust control, emulsifiable concentrate formulation is usually mixed with a hundred litres of water and applied to the target area. However, ECs are rarely used on a large scale against desert locust because of the slow work rate and also getting large volume of clean water in the most desert locust habitats is a challenge (Dobson, 2001). This resulted to the development of Ultralow Volume (ULV) technology.

ULV technology uses smaller volume of spray liquid called ultra-low volume spraying and is the most efficient and commonly used method in desert locust control with application rate between 0.5 to 1.0 litres per hectare (Dobson, 2001; Sharma, 2014; Matthews, 2021). The formulation is usually supplied ready to be sprayed but those in solid form are formulated or mixed with specific oil solvent. ULV formulations are oil based to prevent the small droplets evaporating in high temperatures during locust control. Many of the synthetic pesticides exists in form of ultra-low volume such as Fenitrothion, Malathion, Chlorpyrifos, and Deltamethrin among others. However, because of the concern of environment, human health and non-target organisms, safe biopesticide also exists for ULV application (Shuvo *et al.*, 2020).

Bio-pesticides are used to control desert locusts and they are based on fungus called *Metarhizium acridum* (Githae and Kuria, 2021). Bio-pesticides are attractive because they are specific to locust and have less impacts to livestock, human and environment. Fungi such as *Metarhizium anisopliae var. acridum* registered under ULV product have been tested to be effective against the desert locust (Lomer *et al.*, 2001). When the spores come into contact with the locusts, they penetrate and multiply inside the insects. Two products of this fungus, the Green Muscles and Novacrid, are available commercially. They are supplied in dry spores that are mixed with diesel or oil to obtain a suspension (Dobson, 2001).

2.6 Challenges of current survey and control measures

Challenges and gaps were realized with the existing methods of surveillance and control of desert locusts (FAO, 2018). For instance, satellite imagery used during locusts surveys to identify green vegetation and prioritize potentially large suitable areas, suffer from omissions errors. Moreover, the resolution may be insufficient to detect thin annual grasses that locust prefer and, it is often not available in time since the imagery may arrive late to be of use to survey teams and national locust control units. They have more days revisit period which makes them useless systems in emergent situation. Aerial surveys using aircraft and helicopters are usually not sustainable because of the high costs. Pesticides are distributed over large or vast areas and large quantity is lost to drift when aircraft are used to spray and this can seriously pollute the environment. Sensors on the aircraft and helicopters cannot identify locust swarms because of the poor spatial resolution and they cannot operate below a certain height. Ground control by vehicle or foot is time consuming and costly and is not effective when the level is infestation is high. Therefore, there was need to explore the potential of other technologies that can be complemented with the existing methods for timeliness management of desert locusts in future.

2.7 Unmanned Aerial Vehicle (UAV) technology (Drones)

Drones are aircraft that fly without human onboard composed of a flight platform comprising the drone, ground control system and a data link system (Filho *et al.*, 2019). Drones consists of GPS sensors for locating geolocation, a camera to capture the images and a charging port for recharging its batteries (Kulbacki *et al.,* 2018). Ground control stations are used to control the drones, display the data and information in a real time when the drone is on operation. It works as the interface for exchange of transmission and data relay. Ground stations is a communication protocol between the drone pilot and the drone for mission planning, flying and monitoring in real time. The drone app enable the operator to capture images and videos data, spray and see what the camera sees. It can also track the position of the drone and heading with glance at a map (Subramanian *et al.*, 2021). The drone can navigate autonomously to the desired location defined by the ground station and collect images via multi-spectral cameras (Psirofonia *et al.*, 2017). The data link system enables continuous communication between the unmanned aerial vehicle (drone), ground control stations, GPS satellites and ground control points. Data link system operates in the uplink mode-transmission from the ground control systems for controlling drone flights and downlink mode for sensors data transmission and module control. The advancement in drone navigation and obstacle avoidance technology, improvement of modularized and light weight payload enable target positioning in real time (Barbedo, 2019). The key advantages of operational flexibility, high spatial resolution of imagery, strong timeliness and lower operational costs widened the scope of UAV (Zhang *et al.*, 2021).

In the last few years, drones have been used to provide different services and tasks such as in aerial photography, remote aerial reconnaissance, search and rescue operations, security, land and water surveying, ecosystem monitoring and wildlife conservation, archeology and preservation of the natural heritage, environmental conservation, and precision agriculture among others (Beloev, 2016). Psirofonia *et al.*, (2017) reported that successful use of drones in these sectors is as a result of their ability to fly over the boundary of the target area under the supervision of the controller through the mobile application while identifying the relevant boundary geolocations and transferring data in real time. The central system directs the drone to scan and capture the high resolution aerial photographs which are analyzed by software to generates useful information (Martin *et al.*, 2019).

Development of UAV has become more practically feasible and affordable to collect aerial remote sensing data especially in precision agriculture (Barbedo, 2019). Several researchers have addressed the benefits of drone based remote sensing methods for the assessment of ecologically relevant data and detection of insects pests to undertake corrective timely measures (Filho *et al.*, 2019). Drone has been used to survey Grape *phylloxera* in vineyard (Vanegas *et al*., 2018), Sugarcane aphids (Stanton *et al*., 2022), Colorado potato beetles (Hunt and Rondon, 2017), Thrips in onions (Nebiker *et al*., 2016) Oak splendour beetles thrips infestation (Lehmann *et al.*, 2015) Pine processionary moth (Otsu *et al.*, 2018) Green peach aphids (Severtson *et al.*, 2016), Potato beetles (Bouroubi *et al.*, 2018) and invasive species-Brown marmorated stink bug (Stumph *et al.*, 2019). In these studies, the objective was to test the efficiency of the drone technology for pests detection and the operational parameters were not optimized (Subramanian *et al.*, 2021). However, Kaivosoja *et al.*, (2021) optimized the key parameters for surveillance of weeds. In addition, Ahmad, (2014); Seifert *et al.*, (2019); Çelik *et al.*, (2020); Chakra *et al.,* (2020); Long *et al.*, (2020) and Pramod *et al.,* (2020) optimized key parameters for surveillance using a drone but their studies were not targeting pests and may not apply for desert locusts. This study bridged the gap by optimizing the key parametrs for surveillance of desert locusts.

Aerial application of pest control products using a drone is also increasing over the years (Mogili and Deepak, 2018). Importance is ascribed to the correctness of the process and application taking into account the effects of sprayed liquid on environment (Qin *et al.,* 2016). The fundamental issue in these processes is the quality and efficiency since they determine the efficacy and deposition of the pesticide (Daniel *et al.,* 2019). Critical parameters to be optimized and considered for the effectiveness of drone enabled spraying is droplet deposition measured by droplets density measured using water sensitive papers (Subramanian *et al*., 2021). Researchers studied the efficiency of drone in spraying Aphids and Spider mites in cotton (Lou *et al.,* 2018), Brown plant hoppers (Qin *et al.*, 2016), Cowpea thrips (Yan *et al*., 2021), Rice plant hoppers (Chen *et al*., 2020) Fall armyworm in sugarcane (Song *et al*., 2020) and Wheat aphids (Wang *et al.,* 2019) . The parameters optimized in these studies may not apply for desert locusts because of difference in biology and behavior. Studies suggest that the drones can be used for spraying the desert locusts (Bright *et al*., 2016; Fischer *et al*., 2020). However, there are key parameters that must be established for succesful and safe application of drone for desert locusts management. This study established the key parameters for surveillance and spraying of desert locusts using a drone.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the field site

The performance testing of the drone was undertaken at a field site in Muguga Research Centre located in Kenya Agricultural and Livestock Research Organization (KALRO) Station. Muguga Research Center (S1° 13', E36° 38') lies 30km off the Nairobi-Nakuru highway at an altitude of approximately 2,150m above the sea level. Testing site was an open flat terrain with a few hilly outcrops and depressions not more than 1m in height or depth. There was a complete absence of buildings and animal in the testing area. Testing conducted during the second week of October on a day that the weather was sunny and cloudless with low relative humidity of 65%, with temperature varying between 26 and 29°C while wind speed varied between 3.0 and 3.6 m s^{-1}. Temperature and wind conditions as well as site characteristics were similar to conditions required during some actual locust survey and control operations.

3.2 Testing drone survey parameters

Drone (Dji Mavic 2 pro) from Astral Aerial Solutions was used during the experiment to test survey parameters. The drone was 214 × 91 × 84 mm in size using a 3-axis Gimbal equipped with a 20-megapixel dual camera and a take-off weight of 907g. A total of 270 dead locusts were spread in a zigzag pattern at 9 points, with 30 locusts per point. Flight mission parameters were set using autopilot mobile application, DJI pilot (Amarasinghe, 2018; Erich *et al.*, 2019; Tmusic *et al.*, 2020). The drone was launched to capture overlapping images at 30m, 50m, 70m, 90m, and 110m above the target areas where the locusts were spread. The flight heights were chosen so that the lowest was close to the ground but with sufficient distance that would guarantee safe flights without collisions from obstacles such as tall trees and power lines. The upper ceiling of 110m represent the legal maximum flight height for drones in Kenya. Images captured at different heights were imported to software for the analysis.

3.3 Parameters for spraying pesticides using a drone

A DJI Agras T20 drone fitted with an ultra-low volume (ULV) atomizer was used to assess the effect of spray application heights on droplet density on the ground. The drone was fitted with a Micronair 12 ULV spraying boom with three atomizers and a 20-liter spray tank. White A4 papers measuring 210 × 297 mm were used as spray cards to estimate the deposition of droplets at different spray heights. The spray tank was filled to its maximum volume with a mixture of water-soluble black ink and water in a ratio of 1:3 (*v/v*) to produce the payload of 20 L at the start of the trial and was reloaded when the tank was empty. The spray cards were placed and pinned on the ground at intervals of 1 m in three equal and parallel rows that were 50 m apart. The drone’s flight path bisected the three rows in the middle at right angles. A total of 61 spray cards were pinned on each row, 30 on the left and 30 on the right, with one card at the mid-line that marked the drone flight path (Figure 3.1). The spray cards were appropriately labelled according to the spray height tested and distance from the drone flight path. The flight trajectory was programmed using the drone’s software to spray the ink mixture at five different heights: 2.5 m, 5.0 m, 7.5 m, 10.0 m, and 12.5 m. At each height, the drone sprayed the ink mixture at a constant flow rate of 1 L/min at a constant speed of 14 km/h. After every flight, the pinned spray cards were collected sequentially for analysis. This procedure was repeated three times for each flight height. The sprayed papers were scanned using a scanner (LaserJet Pro MFP MI30NW, Hewlett Packard) at 600 dpi and stored in Joint Photographic Group (JPG) format. The images were imported to the Dropleaf app, which processed and analyzed droplet density through five steps: color space conversion to grayscale, binarization by threshold for noise removal, dilation and erosion, production of contours, and droplet identification. The spread factor was assumed to be such that the values calculated by the app were the ones used for analysis.

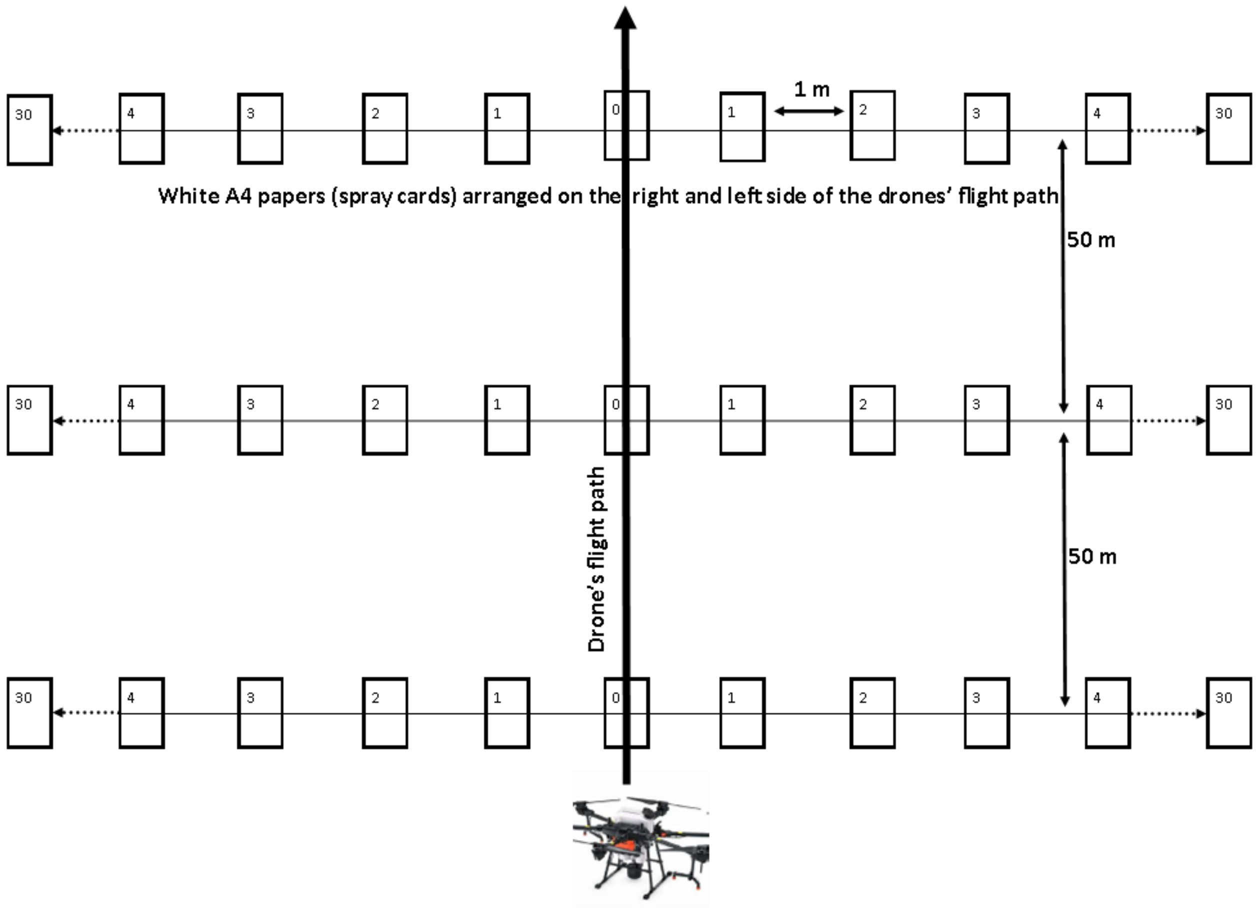


Figure 3.1; Illustration of the experimental layout of spray cards for establishing optimum droplet density by spraying at different heights using an Agras T20 drone fitted with a Micronair 12 ultra-low volume (ULV) spraying boom

3.4 Desert locust colony

A primary progeny of 140 desert locust hoppers in different developmental stages was obtained from the University of Nairobi, Department of Biology, and reared at the KALRO Muguga Center for six months, during which they were able to breed and generate a total of 1280 individuals in various developmental stages. A total of 324 individuals were selected for this experiment, comprising 108 individuals at the 3rd and 4th instars and adults. The temperature and relative humidity maintained in the insectary were 33 °C and 60%, respectively (Figure 3.2).

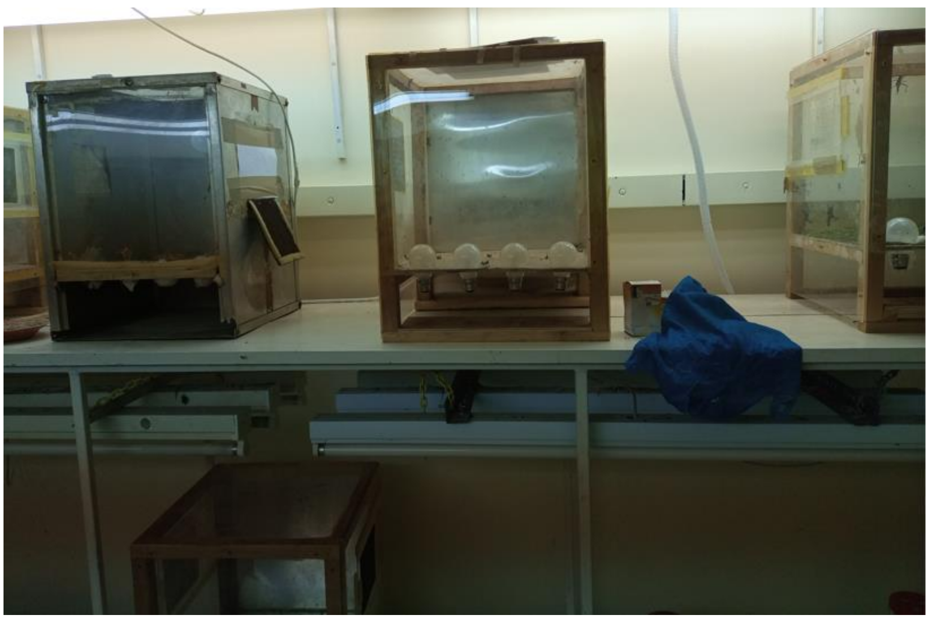


Figure 3. 2: Rearing of desert locusts in the laboratory

3.4 Spray of desert locusts with biopesticide

To test the efficacy of the Novacrid® biopesticide sprayed by a drone on live desert locusts, a total of 324 desert locusts were placed in 54 cages, each measuring 30 × 30 × 30 cm, with six locusts per cage. Each developmental stage had a total of 18 designated cages, of which 15 were for treatment (one treatment per drone flight height, repeated twice) and three were untreated controls.

A total of 500 g of Novacrid® biopesticide was mixed with 20 L of diesel to form a homogenous solution and loaded into the drone's container. At each of the five different flight heights, one cage for each developmental stage was randomly placed in a 1 ha area, parallel to the flight route (Figure 3.3 a). The drone was launched to spray at the selected height, and this process was replicated three times. After spraying, the labelled cages were transferred to a quarantine room at the insectary, while the untreated locusts (the control) were left at the main insectary for observation, with a daily mortality recorded for a period of 21 days (Figure 3.3 b). The dead locusts (Figure 3.3 c) were removed on a daily basis from the experimental cages and incubated in the laboratory at a temperature of 28 °C and 80% relative humidity to encourage external growth and sporulation of the fungus (Figure 3.3d).

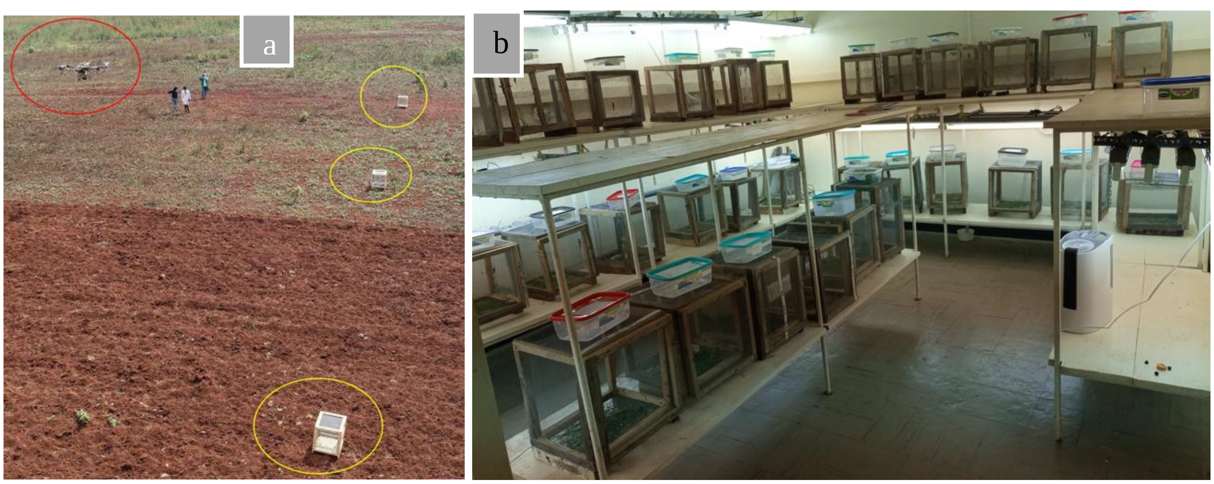


Figure 3. 3: Experiment layout (a) caged treated locusts in the laboratory(b), Infected red coloured desert locusts (c) and infected desert locusts with spores(d)

3.5 Data management and analysis

3.5.1 Surveillance of desert locusts

AGISOFT software was used to align and stitch photos to one orthomosaic image. The orthomosaic image was exported from the Agisoft as Tag Image Format (TIF) and imported to ArcMap to be compressed to Joint Photographic Expert Group (JPEG). The Orthomosaic image were compared at different heights. Information such as distance covered, number of waypoints, number of photos captured, area covered and take off speed generated during mapping were tested for correlation to determine if they violate the assumption of collinearity.

3.5.2 Optimum density droplets at different heights

Recorded density of drops were subjected to Hampel filter to identify outliers as part of the data management. Hampel filter consider outliers as the values outside the interval (***I***) formed by the median, plus or minus 3 median absolute deviations (***MAD***)

$$\boldsymbol{I} = [median - 3.MAD; median + 3.MAD]$$

where $\boldsymbol{MAD}$ is the median absolute deviation and is defined as the median of the absolute deviations from the data's median $\tilde{x} = median(x)$

$$\boldsymbol{MAD} = median(|x_i - \tilde{x}|).$$

To compute the optimum density of droplets, one litre, sprayed in one hectare, was converted to cubic micrometres (1.0×10^{15}). This is because it is known that during desert locust control, about 0.5-1.0 litre of ULV insecticide is optimally sprayed in 1 hectare using rotary atomizers (spinning discs or rotating cages) to produce droplets in a small size range (50-100*u*m) in diameter. For the purpose of optimization, a compromised diameter of 75 μm was used to estimate the volume of each droplet, $\text{Volume of each droplet} = \frac{4}{3}\pi r^3 = \frac{4}{3} \times \left(\frac{22}{7}\right) \times \left(\frac{75}{2}\right)^3 = 220{,}982 \mu m^3$

Estimated droplet volume was used to estimate the number of droplets in 1 litre

$$\text{No. droplets} = \frac{1 \text{ litre } (\mu m^3)}{\text{Droplet size } (\mu m^3)} = \frac{1.0 \times 10^{15}}{220{,}982} = 4{,}525{,}252{,}525$$

Assuming that droplets will be homogenously distributed in 1 ha. The area, one hectare, was converted into cm^2 resulting in 100,000,000 cm^2. Optimum density of standard droplets Ø75 μm in one hectare was estimated from the calculation resulting in 45 droplets/cm^2

$$\text{No. droplets } /cm^2 = \frac{4{,}525{,}252{,}525}{100{,}000{,}000} = 45 \text{ droplets}/cm^2$$

Effect of height on droplet deposition was tested by ANOVA. Tukey's honest significant difference (HSD) test was used where significant effects of flight heights on droplet density was observed ($p < 0.05$). One sample t- test was used to compare the standard calculated density against against densities in different spray heights.

3.5.2 Effects of heights on mortality of different development stages locusts

Mortality in respective cages were transformed into percentages and corrected using Abbotts's correction fomular to eliminate natural mortality as follows (Abbott, 1925); $Corrected\ mortality(\%) = \left(\frac{Trt - Co}{100 - Co}\right)$

Where *Trt* and *Co* are the daily treatment and control mortality respectively. Mortalities in 3rd instar, 4th instar and adults stages in all the cages were subjected to ANOVA to test the effect of spraying height on mortality. Cox proportion hazard model was deployed to assess statistical difference of survival probability of different development stages between heights. Survival distribution curves were generated using the Kaplan –Meier estimator.

CHAPTER FOUR

4.0 RESULTS

4.1 Optimum desert locust survey parameters

During programming of the drone, parameters such as flight time (s), number of photos captured, number of waypoints, resolutions (cm/px) and flight lengths (m) were automatically generated and displayed for each test height (Table 4.1).

Table 4. 1: Predetermined survey parameters

Heights (m)	Flight time (s)	No. of Photos	No. of Waypoint	Resolution (cm/px)	Flight length (m)
30	299	129	14	0.8	935
50	159	69	10	1.2	712
70	85	32	6	1.6	553
90	68	26	6	2.1	534
110	39	16	4	2.6	388

Generated parameters were tested for correlation to determine if they violate the assumption of collinearity. Except for the resolutions of pictures (cm/pixel) taken, other generated parameters were negatively correlated with flight heights (Fig. 4.1). Increase in height reduced the number of waypoints (R=-0.95; p<0.05). Up to 14 waypoints were generated for flight height of 30m compared to only 4 waypoints for flight height of 110m. Increased flight height above ground reduced the duration of mapping making it possible to cover larger area (R=-0.93; p<0.05). The longest duration of 5minutes was observed at 30 m flight height compared with 39 seconds at a flight height of 110 m. Flight height also affected number of photos captured (R=-0.93; p<0.05). More photos (129) were required at 30m compared with 16 photos at 110m. Nonetheless, the spatial resolution was positively correlated with flight height (R=1; p<0.001). High resolution, 0.8 cm pixel^{-1}, was generated for low flight (30m) compared with 2.6 cm pixel^{-1} for 110m.

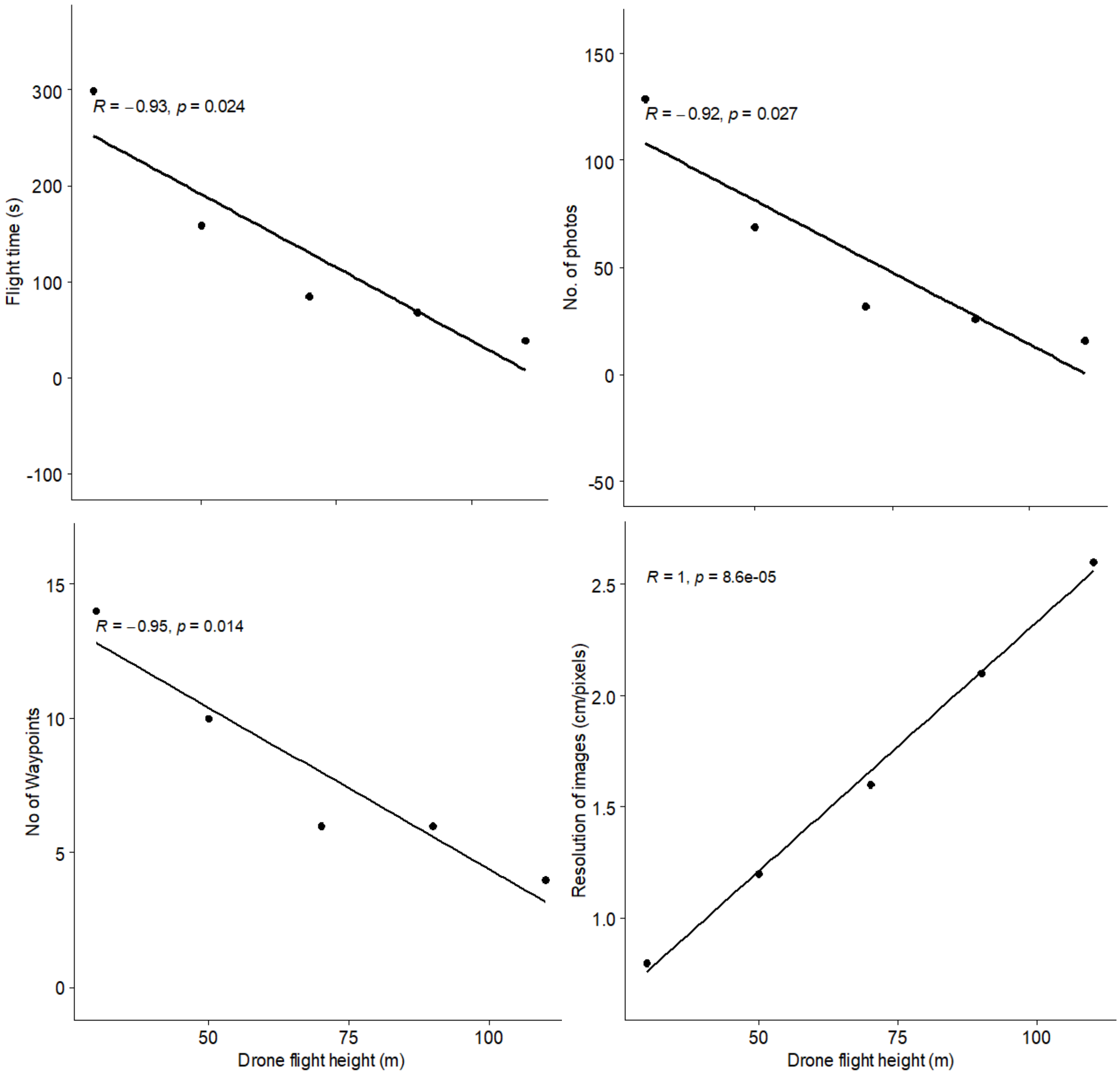


Figure 4. 1: Correlation between and various survey parameters.

4.1.1 Orthomosaic image

Descriptively, flight height had a significant effect on the clarity of Orthomosaic images. The Orthomosaic images were clearer and well defined at a lower (30 m) compared to images obtained at flight height of 50 and 70m (Figure 4.2). Images obtained at higher flight height (90 and 110 m) appeared blurred with less defined details.

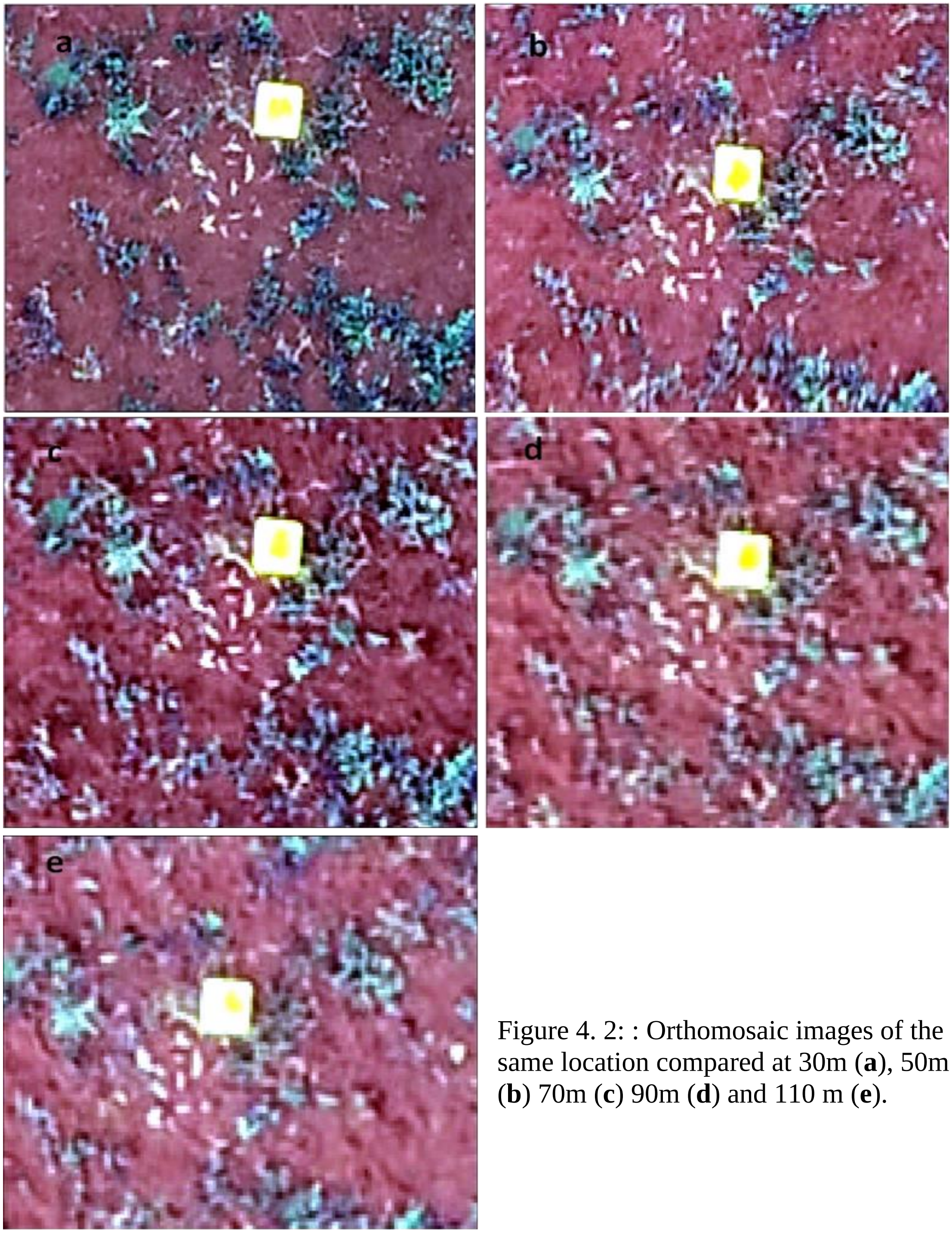


Figure 4. 2: : Orthomosaic images of the same location compared at 30m (**a**), 50m (**b**) 70m (**c**) 90m (**d**) and 110 m (**e**).

4.2 Optimum drone parameters for spraying pesticides for desert locust control

4.2.1 Variation in droplet density among different heights

Droplet density varied significantly between the tested heights ($F_{4,40} = 7.2$; $p < 0.001$). High mean droplet density (152.2 ± 24.8) was recorded at lowest height (2.5m) and lower mean droplet density (24.8 ± 6.51) was observed at highest height (12.5m). Droplets density observed at 5m, 7.5m, 10m and 12.5m had no significant variation while the droplets density observed at 2.5m was significantly different from other tested heights except for 7.5m (Table 4.2).

Table 4. 2: Mean droplet density among different heights tested

Height (m)	Mean droplet density ($\bar{x} \pm se$)
2.5	152.2 ± 24.8[b]
5.0	75.3 ± 11.1[a]
7.5	96.0 ± 29.4[ab]
10.0	40.2 ± 10.1[a]
12.5	24.8 ± 6.51[a]
$F_{4,40}$	7.2
p-value	0.0002

4.2.2 Optimum droplet density

Optimum density of standard droplets *Ø75* µm in one hectare was estimated from the calculation resulting in 45 droplets/cm^2

$$\text{No. droplets } /\text{cm}^2 = \frac{4{,}525{,}252{,}525}{100{,}000{,}000} = 45 \text{ droplets/cm}^2$$

4.2.3 Optimum ULV spraying heights

One sample comparison between standard droplet density and observed mean droplet density varied among different height (Table 4.3). Mean droplet densities were significantly more than the standard density (45 droplets/cm^2) at 2.5(t_{227}=6.02; p<0.01) and 5m (t_{289}=3.63; p<0.01). Mean droplet density at 10m was not different from the standard droplet density (t_{308}=1.031; p>0.05). Height of 10m agreed with VAR as recommended by the manufacturer because mean droplet density observed was within the range of 45 droplets/cm^2. The droplet density was lower than standard droplet density at 12.5m (t_{343}=6.39; p<0.01)

Table 4. 3: One sample t-test comparison of standard droplets density (45 droplet/cm^2) against droplets densities observed at different spray heights.

Spray heights	Mean droplet density	One sample t-test (Mu = 45 droplets/cm^2)		
(m)	($\bar{x} \pm se$)	t - value	Df	p-value
2.5	152.2 ± 24.8.	6.02	227	7.07E-09***
5.0	75.3 ± 11.1	3.63	289	0.0003***
7.5	96.0 ± 29.4	2.074	369	0.039*
10.0	40.2 ± 10.1	1.031	308	0.304
12.5	24.8 ± 6.51	6.39	343	5.61E-10***

4.2.4 Effects of spraying height on mortality

Mortality varied among the locusts' development stages within heights ($F_{2,30}$ =25.71; p<0.0001) (Table 4.4). Variation of mortality of different development stages was evident at 10m ($F_{2,6}$ =16.73; p=0.0035) and 12.5m ($F_{2,6}$ =27.97; p<0.0009). At 10m, mortality of 3rd and 4th instars were similar and high compared to adults while at 12.5m, mortality of third instar was high, followed by fourth and least in adults. Mortality of all the locusts' stages was similar at 2.5m ($F_{2,6}$ =1.22; p=1.00), 5m ($F_{2,6}$ =2.04; p=0.21) and 7.5m ($F_{2,6}$ =1.53; p=0.29).

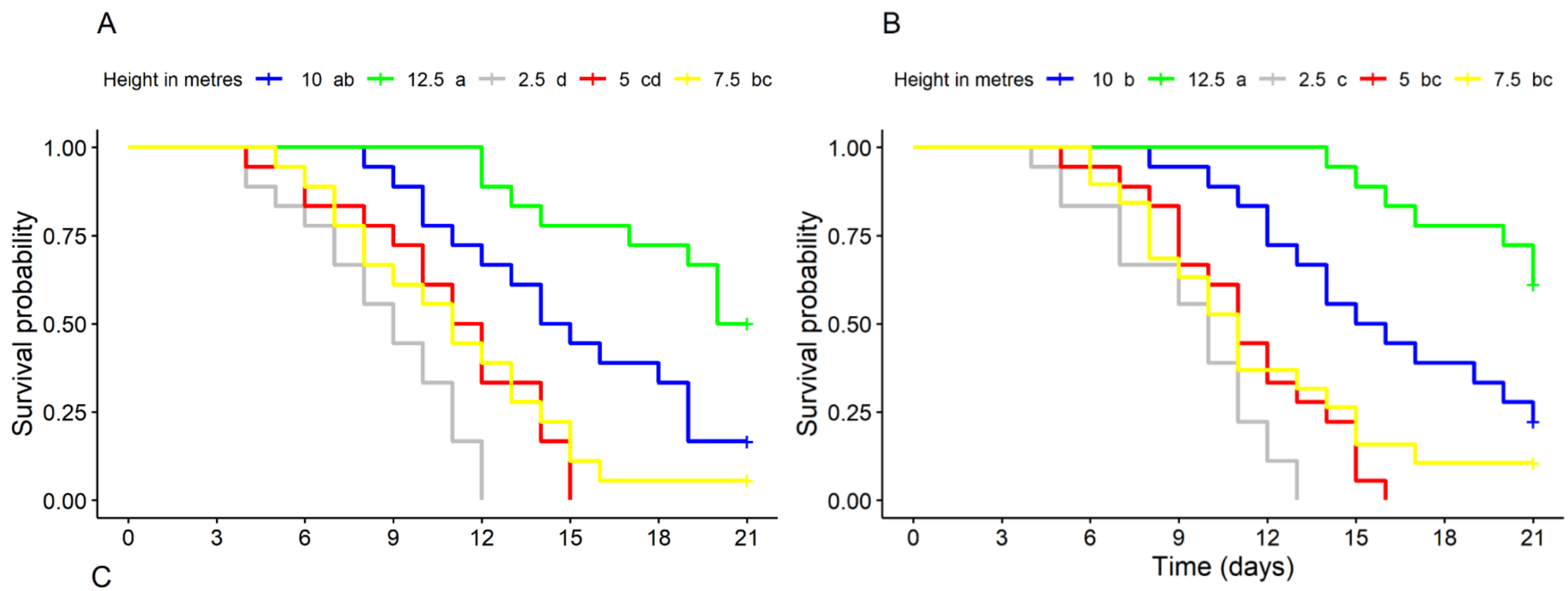
Mortality of all the locusts' stages varied between heights ($F_{4,30}$ = 143.39; p<0.0001) (Table 4.4). Variation of mortality between heights was evident in third instar ($F_{4,10}$=68.50; p<0.0001) with highest and similar mortality at 2.5m and 5m (100±0.00), followed by 7.5 (86.66±6.67), 10 m (80.00±0.00) and lowest at 12.5m (40.00±0.00). Similar variation was observed at fourth instar ($F_{4,10}$ =22.74; p<0.0001) and adults ($F_{4,10}$ =109.00; p<0.0001). Both forth instar and adults exhibited the same trend of reduction in mortality with increase in height except at 5 and 7.5m where mortality was the same. Interaction between stage-height also had a significant effect on mortality $F_{8,30}$ =3.6745; p=0.004271).

Table 4. 4. Mortality of desert locust within and between different heights

Stages of desert locusts	Heights (metres)						
	2.5	5	7.5	10	12.5	$F_{4,10}$	*p*-value
Third	100.00±0.00 cA	100.00±0.00 cA	86.66±6.67 bA	80.00±0.00 bB	40.00±0.00 aC	68.50	<0.0001
Fourth	100.00±0.00 cA	86.66±6.67 bcA	86.66±6.67 bcA	73.33±6.66 bB	26.66±6.67 aB	22.74	<0.0001
Adults	100.00±0.00 dA	83.33±8.33 cA	75.00±0.00 cA	50.01±0.00 bA	0.00±0.00 aA	109.00	<0.0001
$F_{2,6}$	1.22	2.04	1.53	16.73	27.97		
P-value	1.00	0.21	0.29	0.0035	0.0009		

Same lower case letters in the row indicate no significant difference in the mortality among different heights while same upper case letters in the column indicate no significant difference in the mortality across stages according to Turkey test at *p*=0.05

Survival rate of different locusts develoment stages (3^{rd}, 4^{th} and adults) varied between different heights (Figure 4.3). Survival probability varied between heights for 3^{rd} instar (χ^2_4= 56.84; p<0.0001), forth (χ^2_4= 54.17; p<0.0001) and adults (χ^2_4=47.57; p<0.0001). In third instar and forth instar, locusts treated at 2.5 and 5m did not survive and all died at 12^{th} and 15^{th} day respectively. High survival probability was observed at 12.5m, followed by 10m and least at 7.5m where some treated locusts remained alive after 21 days of monitoring. On the other hand, all the adults sprayed at 2.5m died while high survival rate was obseved at 12.5m, followed by 10m, 7.5m and 5m respectively.



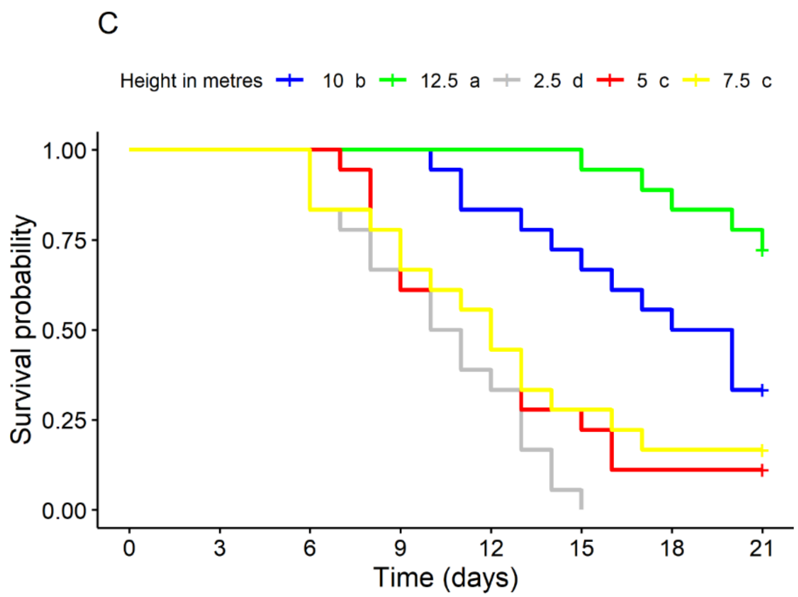


Figure 4. 3: Kaplan –Meier survival curves for different stages of desert locusts treated with *Metarhizium* at different heights. Same small letters adjacent to the legend indicates no significant difference in survival distribution curve at p> 0.05. A: Survival curve of 3rd instar, B: survival curve of 4th instar, C: survival curve of adults. "+" indicates right censorship

CHAPTER FIVE

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

5.1 DISCUSSION

5.1.1 Surveillance of desert locusts using a drone

Quality of orthomosaic images in drone surveys are significantly dependent on the height of the camera from the target (Çelik, *et al.* 2019; Seifert *et al.,* 2019), an observation confirmed during this study. A detailed orthomosaic images were observed at lower heights compared to blurred images at higher heights. This observation corroborate findings of studies by Chakra *et al*. (2020) ; and Long *et al*. (2020) where they reported accurate, sharper and high resolution images at lowest tested heights. High resolution of orthomosaic images at lower heights can be attributed to increased exposure of parts of sensors to the target coupled with ability of camera to match the lighting of the surrounding. Similar thought was presented by Pramod (2020) who argued that lower heights favour clearer images.

One other parameter that may have favored the observed high resolutions at lower height is the number of waypoints. There were more number of waypoints and distance covered at lower heights compared to higher heights, an observation that agrees with earlier report by Seifert *et al.* (2019). At lower height, the camera has short focal length, field of view and increasing number of viewing angles compared to higher heights. Many waypoints observed at lower height appears to gather more details of the target area coupled with capturing of more images per unit area, solving the aforementioned limitations of camera, hence avoiding the motion blur.

The drone was observed to move at higher speed at high height compared to lower height, taking less duration at higher height corroborating findings by Chakra *et al*. (2020) and Long *et al.* (2020). Such low speed results in collection of more details and overlapping images with more tie points coupled with capturing of more images that tend to take longer time. Flight height should be determined or set according to the terrain structure, accuracy, sensitivity, precision and time-cost balance expected from the mission and operation.

5.1.2 Optimum height for application of standard droplets density

According to the formula derived from the information provided by Dobson (2001), the recommended optimum droplet density for use in the management of desert locust is 45 droplets/cm^2. In this study, the droplet densities at the selected heights of 2.5 m, 5.0 m, 7.5 m, 10.0 m, and 12.5 m were 152.2 ± 4.8, 96.0 ± 29.4, 75.3 ± 11.1, 40.2 ± 10.1, and 24.8 ± 6.51, respectively. In reference to the optimum droplet density as provided by Dobson (2001), the droplets were deposited more uniformly and sufficiently at the flight height of 10.0 m (40.2 ± 10.1). When the flight height was lower or higher than 10.0 m, the droplet densities indicated either over- or under-spraying, respectively. At lower heights (2.5 m, 5.0 m, and 7.5 m), the droplet density was higher near the nozzle area, resulting in an uneven distribution of droplets. Additionally, the swirling airflow caused by the flight effect of the drone flying perpendicular to the ground resulted in increased downward pressure on the droplets when the flight height was too low.

The variation of droplet densities with spray heights reported in this study matches the findings of earlier experiments in which a higher density of droplets was reported at lower heights than at higher heights (Bock *et al.,* 2015; Wang *et al.*, 2018; Wang *et al.,* 2020; Lan *et al.,* 2021). High volumes and droplet densities at lower heights can also be the result of a strong downward swirling airflow that makes the air below sway substantially and affects the distribution and density of the droplets (Qui *et al.,* 2016; Lan *et al.,* 2021; OECD, 2021). Lower droplet density at 12.5 m can be attributed to the downwash wind field above the ground, which is weakened when this flight height is maintained. Additionally, the weakened wind field in a vertical orientation causes an increase in the horizontal wind field that aggravates droplet transfer and drift to non-target areas, resulting in a sharp reduction in the density of droplets deposited on the target. These results are similar to a recent observation that an increase in height changes the downwash wind field, leading to a gradual reduction in droplet deposition within the effective target area (Wang *et al.*, 2020; Lan *et al.*, 2021). The increased distance and time required for the spray to reach the targeted area also cause it to be dragged by the ambient air at higher heights compared to lower heights (OECD, 2021).

5.1.3 Control of desert locusts using a drone

Drones have been identified as a potential platform for the application of pesticides in pest and weed management (Filho *et al.,* 2019). Their use in the management of desert locusts has been challenged by a lack of data on optimum spraying height and the efficacy of biopesticides on different development stages of locusts in a field setting. This study demonstrated that although the application of Novacrid® at all the spraying heights tested caused mortality in the three different developmental stages of the desert locust, there were variances in the mortality rate and survival probability. In this experiment, lower spray heights produced a high rate of mortality and a lower survival probability in all the tested locust's lifecycle stages compared to higher spray heights (12.5 m), which was comparable to other similar studies conducted to assess effects of spraying heights on mortality of other pests upon application of synthetic pesticides using a drone (Qin *et al.,* 2016; Wang *et al.,* 2020; Qin *et al.,* 2014; Qin *et al.,* 2018). For example, a significantly higher mortality of wheat hoppers was reported when sprayed with chlorpyrifos pesticides at lower flight heights (Qin *et al*., 2016). The high concentration of conidia at a lower height can be attributed to reduced drift that maximized pesticide deposition in the target. Depending on the pesticide used, accuracy in deposition and distribution is dependent on application height (Lan *et al.,* 2021) which could affect the penetration of the active ingredients of the pesticides (Qin *et al.,* 2018). Furthermore, as the height increases, droplet dispersion increases and deposition decreases, causing pesticides to be carried to non-target areas (Wang *et al.,* 2020).

The findings on the mortality and survival of the desert locust can also be explained by the mode of action of *Metarhizium acridum*, which is through direct contact and germinates, invading the hemocoel within 24 hrs after application of conidia to the insect's cuticle. The rate of mortality achieved is dependent on the dosage of conidia that is in contact with the locusts (Kassimatis, 2000).

In this study, it was observed that at all heights, the 3rd instar was more susceptible to Novacrid®, followed by the 4th instar, and finally adults. The comparatively lower dose received at 12.5 m lengthened the infection period and lowered the mortality rate, leading to a high survival probability after 21 days of application. This finding was similar to other studies that treated desert locusts of different stages with *Metarhizium acridum* (Bashir and El Shafie, 2017; Youssef, 2014; Wakil *et al.*, 2022). For example, experimental studies in a laboratory setting have previously reported the highest mortality (50%) in the 3rd instar, followed by the 5th instar (43%), and adults (33%) (Bashir and El Shafie, 2017) . In this study, at the selected height of 10.0 m that deposited the standard droplet density, mortality was highest in the 3rd instar (80%), followed by the 4th instar (73%) and adults (50%). The high percentage of mortality observed at the 3rd nymphal stage could be due to a weakened immune system coupled with a soft exoskeleton that enabled the biopesticide to penetrate faster compared to the 4th instar and adults. At the hopper stage, their behavior includes banding and marching, and the band densities tend to reduce with the increase in size (30,000 hoppers per m^2 for the first instar and 50 to 100 hoppers per m^3 for the late instars)

(Symmons and Cressman, 2001). Therefore, targeting the most susceptible early stages is also cost-effective in terms of the density of bands that will be controlled at once unlike the female adult desert locusts which can lay at least one egg pod before dying after an estimated 21 days of Novacrid® application. Therefore, drones can be used to improve the control of desert locusts.

5.2 Conclusion and recommendations

5.2.1 Conclusion

Higher flight heights (90-110 m) should be selected for extensive surveillance where the drone is expected to cover larger areas within shorter time to identity suitable conditions such as green vegetation which shows the likeliness of locusts to be present in those particular areas. After knowing the specific places where the locusts are likely to occur, lower heights can be selected for intensive surveillance. The study contend that relatively low altitudes (30–50m) above the ground combination with the highest possible resolution and small areas are advisable for intensive surveillance, in order to harness the compound effect on image quality and accuracy with detailed information during intensive surveillance.

This study has demonstrated that spraying desert locusts using a drone at any height below 10.0 m may lead to over-deposition of the pesticide, while heights above 10.0 m may lead to under-application, which may limit exposure of the locusts to *Metarhizium* spores or pesticide molecules. This study demonstrated that spraying a control agent from a specific height (10 m) is more effective than other heights tested. Despite all the developmental stages of the desert locust being susceptible to Novacrid®, the recommended target stage for management using this biopesticide is the 3rd instar stage because of the higher mortality rate and lower survival probability at this stage.

5.2.2 Recommendation

1. Further researches are needed to examine the effectiveness of drone in reporting the locusts presence and absence and other key assessment information in real time when its integrated with eLocusts3 systems.
2. The promising results provides motivations for undertaking field trials of spraying and surveying gregarious hopper bands and settled adults swarms.
3. Further studies are required to repeat the experiments performed in this study but in different environments with different types vegetation. Efficiency of drones for spraying synthetic pesticides should also be examined
4. Future studies should test the effectiveness of using more than one drone – to understand the operations of drone swarms which allow for greater area coverage for the same time.

REFERENCES

Abbott, W.S. (1925) A Method of Computing the Effectiveness of an Insecticide. Journal of Economic Entomology, 18, 265-267.http://dx.doi.org/10.1093/jee/18.2.265a

Barbedo, J. G. A. (2019). A Review on the Use of Unmanned Aerial Vehicles and Imaging Sensors for Monitoring and Assessing Plant Stresses. *Drones*, *3*(40), 1–27. https://doi.org/10.3390/drones3020040

Bashir, E. M., & El Shafie, H. (2017). Laboratory evaluation of the effects of neem (Azadirachta indica) oil and Metarhizium anisopliae against some immature stages of the desert locust Schistocerca gregaria (Forskal) (Orthoptera: Acrididae) Ebtisam. *Journal of Agricultural and Veterinary Sciences*, *18*(2), 116–126.

Beloev, I. H. (2016). A Review on Current and Emerging Application Possibilities for Unmanned Aerial Vehicles. *Acta Technologica Agriculturae 3/2016*, 70–76. https://doi.org/10.1515/ata-2016-0015

Bock, C. H., Hotchkiss, M. W., Cottrell, T. E., & Wood, B. W. (2015). The Effect of Sample Height on Spray Coverage in Mature Pecan Trees. *Plant Dis*, *99*(7), 916–925.

Bouroubi, Y., Bugnet, P., Nguyen-xuan, T., Gosselin, C., Bélec, C., Longchamps, L., & Vigneault, P. (2018). Pest Detection on UAV Imagery using a Deep Convolutional Neural Network. *14th International Conference on Precision Agriculture*, 1–11.

Bright, L. Z., Handley, M., Chien, I., Curi, S., Brownworth, L. A., Sebastian, D., Bernier, U. R., Gurman, P., & Elman, N. M. (2016). Analytical models integrated with satellite images for optimized pest management. *Precision Agriculture*, *17*(5), 628–636. https://doi.org/10.1007/s11119-016-9434-0

Chen, P., Lan, Y., Huang, X., Qi, H., Wang, G., Wang, J., Wang, L., & Xiao, H. (2020). Droplet Deposition and Control of Planthoppers of Di ff erent Nozzles in Two-Stage Rice with a Quadrotor Unmanned Aerial Vehicle. *Agronomy*, *10*, 2–14. https://doi.org/10.3390/agronomy10020303

Cressman, K. (1996). *Currents methods of desert locust forecasting at FAO*.

Cressman, K. (1997). Swarms : A geographic Information System For desert locust forecasting. In *New Strategies in Locust control* (pp. 27–35).

Cressman, K. (2001). Survey. *Desert Locust Guidelines*.

Cressman, K. (2014). Desert Locust survey and control data recording and transmission by satellite in real time. *ELocust3*, 3–8.

Cressman, K. (2015). Role of remote sensing in desert locust early warning Keith Cressman. *Journal of Applied Remote Sensing*, *2013*. https://doi.org/10.1117/1.JRS.7.075098

Cressman, K. (2016). Desert Locusts. In *Biological and Environmental Hazards, Risks, and Disasters* (pp. 87–105).

Cressman, K., & Stefanski, R. (2016). *Weather and Desert Locusts* (Issue 1175).

Dobson, H. M. (2001). Control. In *Desert Locust Guidelines*.

FAO. (2016). *The potential use of drones in locust early warning and preventive control*.

FAO. (2018). *Potential of droes for locusts early warig and preventio control*. http://www.wipo.int/amc/en/mediation/rules

FAO. (2020a). Appeal for rapid response and anticipatory action in the Greater Horn of Africa. *Desert Locust Crisis*, *December*.

FAO. (2020b). Appeal for rapid response and anticipatory action in the Near East and North Africa January – December 2020. In *Desert Locust Crisis*.

FAO. (2020c). Desert locust crisis appeal in Greater Horn of Africa and Yemen. *Rapid Response and Sustained Action*.

FAO. (2020d). Desert locust upsurge; Global Response Plan, January–December 2020. In *Appeal for rapid response and anticipatory action*.

FAO. (2020e). Progress report on the response in the Greater Horn of Africa and Yemen. In *DESERT LOCUST UPSURGE Progress*. http://www.wipo.int/amc/en/mediation/rules

Locust Upsurge, *April*.

FAO. (2020f). DESERT LOCUST OUTBREAK RAPID NEEDS ASSESSMENT DESERT LOCUST OUTBREAK RAPID NEEDS ASSESSMENT. *Desert Locust Background*, 2019–2021.

Filho, F. H. I., Heldens, W. B., Kong, Z., & Lange, E. S. De. (2019). Drones : Innovative Technology for Use in Precision Pest Management. *Journal of Economic Entomology*, *113*(1), 1–25. https://doi.org/10.1093/jee/toz268

Fischer, N., Koning, R. de, Ngwenyaman, B., Slenders, L., & Wools, L. (2020). *Detecting desert locusts the UAV way.pdf* (p. 1).

Githae, E. W., & Kuria, E. K. (2021). Biological control of desert locust (Schistocerca gregaria Forskål). *CAB Review*, *16*(013), 1–8. https://doi.org/10.1079/PAVSNNR202116013

Hunt, E. R., & Rondon, S. I. (2017). Detection of potato beetle damage using remote sensing from small unmanned aircraft systems. *Journal of Applied Remote Sensing*, *11*(2), 1–10. https://doi.org/10.1117/1.JRS.11

Kaivosoja, J., Hautsalo, J., Heikkinen, J., Hiltunen, L., Ruuttunen, P., Näsi, R., Niemeläinen, O., Lemsalu, M., Honkavaara, E., & Salonen, J. (2021). Reference Measurements in Developing UAV Systems for Detecting Pests , Weeds , and Diseases. *Remote Sensing*, *13*(1238), 1–21. https://doi.org/doi.org/10.3390/rs13071238 Academic

Kassimatis, E. J. M. (2000). Evaluation of Metarhizium anisopliae mycoinsecticide as an alternative locust control measure in southern Africa by. *University of Pretoria*, 1–80.

Kuandykova, A., Uskenbayevaa, R., Chob, Y. I., Kozhamzharovac, D., Baimuratovd, O., Chinibayeva, Y., & Karimzhana, N. (2015). Multi-Agent Based Anti-Locust Territory Protection System. *Procedia Computer Science*, *56*, 477–483. https://doi.org/10.1016/j.procs.2015.07.238

Kulbacki, M., Segen, J., Kniec, W., Kulbacka, J., Klempous, R., Kluwak, K., Nikodem, J., & Serester, A. (2018). Survey of Drones for Agriculture Automation from Planting to Harvest. *International Conference on Intelligent Engineering Systems*, 353–358.

Lan, Y., Qian, S., Chen, S., Zhao, Y., Deng, X., Wang, G., Zang, Y., Wang, J., & Qiu, X. (2021). Influence of the Downwash Wind Field of Plant Protection UAV on Droplet Deposition Distribution Characteristics at Different Flight Heights. *Agronomy*, *11*(2399), 1–13. https://doi.org/doi.org/10.3390/ agronomy11122399

Lehmann, J. R. K., Nieberding, F., Prinz, T., Knoth, C., & Jokela, E. J. (2015). Analysis of Unmanned Aerial System-Based CIR Images in Forestry—A New Perspective to Monitor Pest Infestation Levels. *Forests*, *6*, 594–612. https://doi.org/10.3390/f6030594

Lomer, C., Bateman, B., Johnson, D., Langewald, J., & Thomas, M. (2001). Biological Control of Locusts and Grasshoppers. *Annual Review of Entomology*, *46*(1), 667. https://doi.org/10.1146/annurev.ento.46.1.667

Lou, Z., Xin, F., Han, X., Lan, Y., Duan, T., & Fu, W. (2018). Effect of Unmanned Aerial Vehicle Flight Height on Droplet Distribution , Drift and Control of Cotton Aphids and Spider Mites. *Agronomy*, *8*(187), 1–13. https://doi.org/10.3390/agronomy8090187

Magor, I., & Pender, J. (1997). Desert Locust Forecasters' GIS. In *New Strategies in Locust control* (pp. 21–26).

Martin, D. E., Woldt, W. E., & Latheef, M. A. (2019). Effect of Application Height and Ground Speed on Spray Pattern and Droplet Spectra from Remotely Piloted Aerial Application Systems. *Sensors*, *3*(83), 1–21. https://doi.org/10.3390/s20051487

Matthews, G. A. (2021). New Technology for Desert Locust Control. *Agronomy*, *11*(1052), 1–9.

Mogili, U. M. R., & Deepak, B. B. V. L. (2018). Review on Application of Drone Systems in Precision Agriculture. *Procedia Computer Science*, *133*, 502–509. https://doi.org/10.1016/j.procs.2018.07.063

Mroczkwoski, D. B. (2018). *Development of a system for detection, control and prevention of locust pests using UAV platforms*. Universitat Politechnica De Catalunya.

OECD. (2021). *Report on the State of the Knowledge – Literature Review on Unmanned Aerial Spray Systems in Agriculture* (Issue 105).

Otsu, K., Pla, M., Vayreda, J., & Lluis, B. (2018). Calibrating the Severity of Forest Defoliation by Pine Processionary Moth with Landsat and UAV Imagery. *Sensors*, *18*(3278), 1–14. https://doi.org/10.3390/s18103278

PFG. (1994). *Evaluation of field trial data on the effectiveness of insecticides against locust and grasshopper*.

Pramod, A., Deekesha, R., Neha, H., & Munavalli, J. R. (2020). AUTOMATED REAL-TIME LOCUST MANAGEMENT USING ARTIFICIAL INTELIGENCE. *International Journal of Engineering Applied Sciences and Technology*, *5*(4), 133–138.

Psirofonia, P., Samaritakis, V., Eliopoulos, P., & Potamitis, I. (2017). Use of Unmanned Aerial Vehicles for Agricultural Applications with Emphasis on Crop Protection : Three Novel Case-studies. *International Journal of Agricultural Science and Technology*, *5*(1), 30–39. https://doi.org/10.12783/ijast.2017.0501.03

Retkute, R., Hinton, R. G. K., Cressman, K., & Gilligan, C. A. (2021). *Regional Differences in Control Operations during the 2019 – 2021 Desert Locust Upsurge*. 1–11.

Seifert, E., Seifert, S., Vogt, H., Drew, D., Aardt, J. Van, Kunneke, A., & Seifert, T. (2019). Influence of Drone Altitude , Image Overlap , and Optical Sensor Resolution on Multi-View Reconstruction of Forest Images. *Remote Sensing*, *11*(1252), 1–19. https://doi.org/10.3390/rs11101252

Severtson, D., Callow, N., Flower, K., Andreas, N., Oleknik, M., & Christian, N. (2016). Unmanned aerial vehicle canopy reflectance data detects potassium deficiency and green peach aphid susceptibility in canola. *Precision Agriculture*, *17*(6), 659–677. https://doi.org/10.1007/s11119-016-9442-0

Sharma, A. (2014). Locust Control Management: Moving from Traditional to New Technologies – An Empirical Analysis. *Entomology, Ornithology & Herpetology*, *4*(1), 1–7. https://doi.org/10.4172/2161-0983.1000141

Shrestha, S., Thakur, G., Gautam, J., Acharya, N., & Pandey, M. (2021). *Desert locust and its management in Nepal : a review*. *4*, 1–28.

Shuvo, S. B., Tusher, M. A., & Ghosh, M. (2020). A Technical Approach to Prevent Locust Swarm. *Team TETRAHEDRON*, 1–4.

Song, X. P., Liang, Y. J., Qui, Z. X., Qiang, Q. Z., Ju, W. J., Rui, L. Y., & Wu, J. M. (2020). Intrusion of Fall Armyworm (Spodoptera frugiperda) in Sugarcane and Its Control by Drone in China. *Sugar Tech*, 1–4. https://doi.org/10.1007/s12355-020-00799-x

Stanton, C., Starek, M. J., Starek, M. J., Elliott, N., Brewer, M., Maeda, M. M., & Chu, T. (2022). Unmanned aircraft system-derived crop height and normalized difference vegetation index metrics for sorghum yield and aphid stress assessment sorghum yield and aphid stress assessment. *Journal of Applied Remote Sensing*, *11*(2), 1–20. https://doi.org/10.1117/1.JRS.11.026035

Stumph, B., Virto, M. H., Medeiros, H., Tabb, A., Wolford, S., Rice, K., Leskey, T., & Aug, R. O. (2019). Detecting Invasive Insects with Unmanned Aerial Vehicles. *International Conference on Robotics and Automation (ICRA)*, 648–654. https://doi.org/10.1109/ICRA.2019.8794116.Research

Subramanian, K. S., Pazhanivelan, S., Srinivasan, G., Santhi, R., & Sathiah, N. (2021). Drones in Insect Pest Management. *Frontiers in Agronomy*, *3*, 1–12. https://doi.org/10.3389/fagro.2021.640885

Symmons, P. M., & Cressman, K. (2001). Desert Locust Guidelines, Biology and behaviour. In *Food and Agriculture Organization of the United Nations*.

Vanegas, F., Bratanov, D., Gonzalez, F., Powell, K., & Weiss, J. (2018). A Novel Methodology for Improving Plant Pest UAV-Based Hyperspectral and Spatial Data. *Sensors*, *18*(260), 1–21. https://doi.org/10.3390/s18010260

Wang, C., Zeng, A., He, X., Song, J., Herbst, A., & Gao, W. (2020). Spray drift characteristics test of unmanned aerial vehicle spray unit under wind tunnel conditions. *Int J Agric & Biol*

Eng, *13*(3), 13–21. https://doi.org/10.25165/j.ijabe.20201303.5716

Wang, G., Lan, Y., Yuan, H., Qi, H., Chen, P., Ouyang, F., & Han, Y. (2019). Comparison of Spray Deposition , Control Efficacy on Wheat Aphids and Working Efficiency in the Wheat Field of the Unmanned Aerial Vehicle with Boom Sprayer and Two Conventional Knapsack Sprayers. *Applied Sciences*, *9*(218), 1–16. https://doi.org/10.3390/app9020218

Wang, J., Lan, Y., Zhang, H., Zhang, Y., Wen, S., & Yao, W. (2018). Drift and deposition of pesticide applied by UAV on pineapple plants under different meteorological conditions. *Int J Agric & Biol Eng*, *11*(6), 5–12. https://doi.org/10.25165/j.ijabe.20181106.4038

Yan, X., Zhou, Y., Liu, X., Yang, D., & Yuan, H. (2021). Minimizing Occupational Exposure to Pesticide and Increasing Control Efficacy of Pests by Unmanned Aerial Vehicle Application on Cowpea. *Applied Sciences*, *11*(9579), 1–11. https://doi.org/doi.org/10.3390/app11209579

Youssef, N. A. (2014). Effect of certain entomopathogenic fungi and nematode on the desert locust Schistocerca gregaria (Forskal). *Annals of Agricultural Sciences*, *59*(1), 125–131. https://doi.org/10.1016/j.aoas.2014.06.017

Zhang, H., Wang, L., Tian, T., & Yin, J. (2021). *A Review of Unmanned Aerial Vehicle Low-Altitude Remote Sensing (UAV-LARS) Use in Agricultural Monitoring in China*. 1–17.