Norwegian University of Life Sciences
Faculty of Environmental Sciences
and Natural Resource Management

Philosophiae Doctor (PhD)
Thesis 2019:101

Crop pollination by insects in small-scale agroforestry farming in Tanzania

Insektpollinering av landbruksvekster i småskala jordbruk i Tanzania

Thomas Corodius Sawe

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Ås (2019)

Thesis number 2019:101
ISSN 1894-6402
ISBN 978-82-575-1666-6

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Acknowledgement

I would like to say thanks to my former supervisor Prof. Ørjan Totland for accepting me as your PhD student. I must admit that, you saved my life when I arrived at Gardermoen in January 2016 (-13^0 C) wearing sandals and tropical costumes. Thank you so much for helping to settle in Norway and for introducing me to the exciting field of pollination ecology.

To my current supervisors, Associate Prof. Katrine Eldegard, Dr. Anders Nielsen and Dr. Samora, I really appreciate your intellectual and moral support. Katrine you have been very supportive in every aspect of my PhD. You helped make really important decision when I didn't know what to do. You made this journey smooth despite many difficulties including lacking field budget. It has been tough journey for me, especially learning new skills but with your help I have been able to make important progress in my academic career.

I would like to say thanks to Norwegian government through Lånekassen for sponsoring my living expenses during the pursuit of this study. Furthermore, I would like to extend my sincere gratitude to MINA administration staffs including Grethe, Kari, Ole-Wiggo and Mette for making this journey successful.

To my friends at MINA, you have been wonderful all the time since I arrived at Ås in 2016. The chats we had at blue room during lunch, at the corridor, by the coffee machine energized me as I noticed it's impossible to impress reviewers. Many thanks to Yennie, Miguel, Denis, Solrun, Meley and Pablo for dragging me out of the office, though you were unsuccessful most of the times, I really enjoyed each moment we spent together outside our offices. Yennie thank you so much for being super generous and friendly person, I have learnt so much from you and I enjoyed your company watching "stranger things". To my office mate Denis, your loud chatter to your own computer was helpful indeed as I learnt we were pursuing road to madness together. Professor Samuel I really appreciate the short occasional chats we had, though for few minutes, but your words filled with wisdom were motivating. Ruben, Mengstab, Dawit and Lennart thank you for jogging routines, I really enjoyed jogging randomly in the forest except when we had to go through mud.

My sincere appreciation goes to field assistants and all farmers who agreed their agriculture fields to be part of this study and agreed to share relevant information about farming system in Tanzania.

To my beloved wife Loveness and my son Lincoln, you are simply amazing, thank you for your tireless encouragement and understanding my academic excuses even when they didn't make sense to you. To my brother Hendry Sawe and your wife, thank you so much for your generosity and courage during my field trips in Tanzania. To my mom (Jane Sawe), aunt (Dorothy Sawe) thank you for phone calls and texts which you didn't get tired sending or calling.

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Summary

Context. The decline of pollinating insects worldwide threatens pollination services for wild angiosperms and important food crops. The importance of insect pollination services for food production has been documented for crops that are available on the global markets, and which stem from large-scale farming systems. Little effort has been directed towards understanding the role of insect pollinators in small-scale farming systems in developing countries, even though these systems feed a substantial part of the World's population.

Objective. I studied crop pollination by insects in a small-scale agroforestry farming system in the Kilimanjaro and Arusha regions in northern Tanzania. I assessed to which degree crop yield was limited by insect pollination; how environmental context and agricultural practices influenced pollinators, and consequently pollination and crop yield; to which degree local farmers were aware of pollinators; and local farmers' potential vulnerability to changes in pollination services, in terms of declines in household income and food availability.

Methods. I carried out a combination of observational and experimental ecological studies in a total of 24 local small-scale agroforestry type farms, and interviewed 147 local farmers, to assess the importance of insect pollination for production of watermelons (*Citrullus lanatus* Thunb., Cucurbitaceae). Insect pollination is essential for fruit development in watermelons, and watermelon is an important cash crop to local farmers in my study area.

Main results. Results from hand-pollination experiments and observational studies of relationships between flower visits by insects and fruit quantity and quality, showed that watermelon crop yield was limited by pollination services. My findings indicate that local farmers can double the number of marketable fruits and increase sugar content of the watermelons by approximately 10%, if the watermelon flowers are sufficiently pollinated throughout the blossom period. The main groups of visitors to watermelon flowers were wild honeybees (*Apis mellifera*; 87.8%), followed by hoverflies (Syrphidae; 8.5%) and other Hymenoptera (3.7%). Environmental context influenced pollinators, and consequently pollination and crop yield; visitation rates by insects to watermelon flowers increased with abundance of co-occurring flowers of other plants, especially at high tree cover in the field surroundings. Visitation rates by non-honeybee visitors were higher at the edge compared to centre of crop fields. Pesticide spraying reduced visitation rates by 50% from the lowest to the highest observed frequencies of pesticide application. Increasing inputs of fertilizer and watering had little effect on crop yield, compared to enhanced pollination. Only 7% of the local farmers were aware of pollinators and their importance for crop pollination, although 67% of

crops grown by local farmers for household food and income depended on insect pollination to a moderate to essential degree. Watermelon crops contributed nearly 25% of household income and were grown by 63% of the interviewed farmers.

Management Implications. It is critically important that small-scale farmers understand the role of pollinators and their importance for agricultural production. Agricultural policies to improve yields in developing countries should include measures to improve pollination services, such as education and advisory services to local farmers on how to develop pollinator friendly habitats in agricultural landscapes. The seemingly alarming negative impact of pesticide use on flower visits by insects need to be addressed by the responsible management authorities, who should develop a sustainable strategy for managing pests and ensuring increased agriculture yield.

Synopsis

Introduction

Human land use change – impacts on ecosystem services and human well-being

Human well-being is highly dependent on functioning ecosystems, and linkages between ecosystem services like provisioning of food and fresh water, have been well documented (Millennium Assessment 2005). In light of an increasing global human population and global climate change, the demand for food is increasing and is becoming more challenging to supply in sustainable quantities (Hanjra & Qureshi 2010). Over the past 50 years, humans have converted natural ecosystems into agricultural land more rapidly and extensively than ever before (Tilman et al. 2001, Ecosystem 2005, Tanentzap et al. 2015). According to Schultz & De Wrachien (2002), about 12% of the terrestrial area or 15 billion ha globally is currently under cultivation. However, in order to prevent the wide spread of food insecurity arising from the expected human population increase, it is reported that the agricultural land will have to increase production by 60% or more (Alexandratos and Bruinsma 2012).

Agricultural landscape homogenization caused by decrease of semi-natural cover, crop specialization, and field enlargement threatens biodiversity and the delivery of key ecosystem services to people (Batáry et al. 2011, Aguilar et al. 2015, Newbold et al. 2015). No doubt agriculture intensification has increased the agriculture output of different crops in many places globally in the past decades (Perkins and Jamison 2008). However, its sustainability is in question because ecosystem functioning that support agriculture production is being degraded (Millennium Assessment 2005). One of the crucial ecosystem services threatened by agriculture intensification is crop pollination supported by insects (Deguines et al. 2014), which benefits about 75% of all agriculture crops for seed or fruit production (Klein et al. 2007). Insect pollinators visit crop habitats for foraging but might need to return to natural habitats to complete their reproductive cycle because of the frequent disturbance regime in agricultural fields (Greenleaf, Williams, Winfree &Kremen, 2007; Holzschuh, Steffan- Dewenter, Kleijn, & Tscharntke, 2007). Agriculture intensification by increasing the amount of cultivated land and providing more agricultural inputs such as fertilizer, pesticides, or watering, will not necessarily improve crop yield of certain crops if pollination services are limited. For instance, studies comparing crop yields across agriculture intensification gradients have demonstrated low yields in highly intensified landscapes due to low insect pollination services (Bartomeus et al. 2014). Indeed, habitat loss and agriculture intensification are well documented as important drivers of declining entomofauna (Díaz et al. 2019).

In agricultural landscapes, agri-environmental schemes that improve the habitat quality of marginal areas, such as field margins, have been suggested to promote wild bee diversity (Batáry et al. 2015). Agricultural landscapes that embrace nature through ecological intensification rather than agricultural intensification has received more attention in recent decades due to their sustainable food production through biodiversity conservation, which enhances insect pollination and pest resilience (Biddinger and Rajotte 2015). To compensate for the loss of insect pollinators resulting from agricultural intensification, habitat loss and other causes of decline in pollination services, some farmers keep and manage domesticated pollinators, i.e. honeybees (*Apis mellifera*) to complement pollination by wild insects (Biddinger and Rajotte 2015). This is however, occurring mostly in developed countries, whereas small-scale farmers in developing countries still rely mainly on natural occurring pollinators (Kasina et al. 2009, CBD 2016). Unfortunately, these same areas lack documentation on the importance of crop insect pollination despite their probable high reliance on insect pollination for food production (CBD 2016, Millard et al. 2019, Timberlake and Morgan 2018).

Food production and ecosystem services in small-scale farming systems

Our understanding of the linkage between agriculture intensification and loss of ecosystem services, such as crop pollination by insects, is mainly based on studies of large-scale systems in developed countries. There is a lack of studies from small-scale systems, although small-scale farming is a major source of food production and income in many countries (Lowder et al. 2016) and employs about 2.1 - 2.5 billion people globally, of which the majority live in developing countries (Tscharntke et al. 2012). In these farming systems, people typically work on land plots smaller than 2 hectares, and the majority are poor, food insecure and have limited access to markets and services (Steward et al. 2014). Their choices are constrained, but they farm their land and produce food for a substantial proportion of the World’s and region’s population (De Romemont et al. 2018). For instance, in Tanzania and Kenya small-scale farmers produce 63 and 69 percent of the food in their countries, respectively (FAO 2015).

In addition to the importance of small-scale farming in maintaining food security, the environmental benefits of this farming system have been recognized and advocated by different scholars (Bianchi et al. 2006). One of the environmental benefits of small-scale farming systems is that they constitute highly diverse semi-natural ecosystems through a combination of wild and domesticated species (Boyce 2006). This farming practice can therefore both conserve biodiversity and sustain agriculture production over long periods of time (Kok et al. 2017). Yet, balancing biodiversity conservation and agriculture production is becoming increasingly difficult due to the urge for agriculture intensification to meet food requirements and increase household incomes (Emmerson et al. 2016, Simons and Weisser 2017, Quintana et al. 2019). This has raised concerns about the sustainability of small-scale farmer's livelihoods that depend on ecosystem services for agriculture production (Malmborg et al. 2018, Wisely et al. 2018). Poor technology and low financial resources in developing world limit agriculture investment in arable lands (Enete and Onyekuru 2011) and this can exacerbate degradation of natural habitat because local farmers target fertile and moist natural habitats such as wetlands and forests. For instance, in Tanzania where agriculture is mainly rain fed (Mkonda and He 2017a) only 23% of the arable land (set for agriculture purposes) has been used for agriculture, and yet agriculture encroachment is a major cause of forest degradation (Kimaro et al. 2014, URT 2014).

Economic and food security values of crop pollination

As flower visitors move from one flower to another or different parts of the flower searching for nectar and or pollen, they transfer pollen from the anther to the stigma and become pollinators as they enhance fertilization (Willmer 2011). This process is accountable for 35% volume of total global agriculture production (Klein et al. 2007) and thus contributes significantly to global food security and socio-economic status of the small-scale household farmers (IPBES 2016). Animal-pollinated food plants are typically of high nutritional value because they − in addition to providing energy − are richer in micro-nutrients, such as vitamin A, iron and folate (Eilers et al. 2011; Archer et al. 2014; Chaplin-Kramer et al. 2014; Smith et al. 2015) than wind-pollinated crops (Aizen et al. 2009).

Insects are the major crop pollinators because the large number of insect individuals enable them to effectively pollinate mass-flowering agriculture crops (Abou-Shaara 2014), and insects are often able to adapt to varying landscape perturbations (Patrício-Roberto and Campos 2014). These desired attributes are however generalized from the managed pollinators such as honeybees and bumblebees. Insect pollination plays a significant role in global economy and food security. For example, the total economic value of insect pollination was estimated to be 235-557 billion USD worldwide representing 9.5% of the value of the agricultural production used for human food (IPBES 2016). Insect-pollinated crops have a higher market value (Gallai et al. 2009), which makes them economically important in intensive cropping systems, such as in the USA, Europe and China, where industrial-scale agriculture is crucial for national economies. However, the degree to which insect-pollinated crops are important to household economy and consumption (food security) in small-scale farming systems in developing countries is largely undocumented.

Threats to insect pollination

In recent years, there has been major concern about declining insect pollinations (Garibaldi et al. 2009, Kjøhl et al. 2011, CBD 2016), both because of the role of the insect pollinators in the reproduction of many wild angiosperms (Ollerton 2011), and because of the presumed negative consequences of decline in pollination services for food production (IPBES 2016). Much of this concern about reduced food production comes from well-documented declines in managed pollinators populations in North America (Kulhanek et al. 2017) and Europe (Brodschneider et al. 2018) but there have also been recent reports of declines and even local or global extinctions of some wild bees, such as bumblebees (*Bombus* species) (Bommarco et al., 2012; Bartomeus et al., 2013; Williams et al., 2009). Agriculture expansion and intensification in large-scale farming systems is a major driver for land use dynamics with significant negative effects on population of insect pollinators at global (Ollerton et al. 2017) and regional scales (Biesmeijer et al. 2006, Ollerton et al. 2014). However, little is known about how changes in agricultural practices in small-scale farming systems − caused by rapidly growing demands for food in developing countries − potentially affect pollinators and pollination services, and to what extent food production and household income is linked to insect pollination in such systems.

Objectives

The main objective of this thesis has been to increase understanding of crop pollination in a small-scale farming system in Northern Tanzania. I achieved this by combining observational and experimental approaches to study the importance of insect pollination for production of watermelons (*Citrullus lanatus* Thunb., Cucurbitaceae), a crop which is highly dependent on insect pollination, and also an important cash crop to many local farmers. Specifically, I aimed to answer the following main questions;

1. Is watermelon production limited by pollination services in small-scale farming systems Northern Tanzania? (paper I, II, and III)
2. How does environmental context influence pollinators, and consequently pollination and crop yield of watermelon, in small-scale farming systems in Tanzania? (paper III)
3. How do conventional agricultural inputs influence pollinators and/or crop yield of watermelon, in small-scale farming systems in Tanzania? (paper II and III)
4. Are small-scale farming systems in Tanzania vulnerable to changes in pollination services, and how may this influence household income and food availability? (paper IV)

Study System and Methods

Small-scale farming systems in Tanzania

Small-scale farming employs about >75% of people living in the rural areas of Tanzania (Lokina et al. 2011). The style, type of crops and size of the land owned varies among the farmers in different regions of the country (Mkonda and He 2017b). As many of the other sub Saharan African countries, agriculture in Tanzania is constrained by many factors leading to low crop yields, including low agriculture investment (Adjognon et al. 2017), unreliable markets (Dillon and Barrett 2017), post-harvest loss (Affognon et al. 2015), pests and lack of technology to deal with emerging climate effects (Thornton et al. 2014). Most of the farmers are poor and live in rural areas, pursuing different economic activities for subsistence livelihoods. Yet, despite the limitations and low contribution to the total country GDP, agriculture is the backbone of the Tanzanian economy (URT 2017).

Efforts to improve agricultural productivity in Tanzania has mainly focused on increasing agriculture inputs i.e. irrigation, fertilizers, and pesticides, in addition to increasing the amount of cropland. Furthermore, the main focus has been on increasing yields of bulk food producing crops such as cereals, which are mainly self or wind-pollinated. Consequently, pollinator conservation and management has received little attention in the region. The increasing population growth − and the associated need for more and healthier food − are important drivers for increasing agriculture production and agricultural intensification among small-scale farmers in Tanzania, similar to what has been observed in other regions (Mkonda and He 2018). Low productivity, due to low agriculture inputs, may lead to a demand for more land to increase agriculture production (Jayne et al. 2014). In addition, similar to the situation in many other developing countries, insect pollinators are unmanaged in Tanzania, thus crops depend on naturally occurring species (Kasina et al. 2009). Therefore, any agriculture activities focusing on increasing agriculture productivity at the expense of natural habitats may have significant impacts on natural pollinator communities.

Study area

Data were collected in two regions in Northern Tanzania; Kilimanjaro and Arusha. The mean annual temperature and precipitation for the two regions are 28.4ºC and 873 mm, and 24.7 ºC and 906 mm for Kilimanjaro and Arusha, respectively (Tanzania Meteorological Agency, 2013). Agroforestry farming whereby crops such as ornamental flowers, vegetables, fruits and or animals are integrated with trees in different arrangements and practices (Figure 1) is common in these two regions. Local farmers in this area obtain most of the daily food from their farming activities. In addition to farming, they practice other income-generating activities, including livestock keeping and small business. The amount of land owned by local farmers is often small, and thus most of the farmers also borrow or rent land, which is usually situated a few miles from their home.

Figure 1. Different agroforestry farmig systems in Tanzania; (A) Watermelon field sorrounded by tree patches (B) Intecropping of Tomatoes, Banana and Trees

The study units for the data collection in this PhD thesis were fields of small-scale farms, referred to as ‘gardens’ (Paper I & III), which is the local term used to describe these fields. Field sizes ranged from 0.5 - 2 ha, which are typical sizes of these local gardens (Classen et al. 2014). These gardens usually vary in shape, crop composition and arrangement, for example a garden can be used for growing a single crop (Figure 1A) or several integrated crops (Figure 1B), which can also vary between seasons. The levels of agriculture inputs applied in these gardens, for instance fertilizer, irrigation, pesticides and weeding intensity vary among the farmers, crops and seasons. In addition, the attributes of the field margins, hereafter called “field edges” (paper III) vary in composition and structure (Figure 1 & 2).

In this thesis, I focused my research on watermelon gardens (paper I, II and III). Selected watermelon gardens were distributed among five different sites within the Arusha and Kilimanjaro regions and surrounded by varying amounts of natural vegetation (Figure 2). Distance from one garden to another ranged from 0.8 - 4.2 km, whereas distance between sites was 11 - 83 km with the elevation gradients ranging from 800-1200 meter above sea level. We selected gardens based on the availability of watermelons during the study period and accessibility (i.e. distance to road).

Figure 2: Google earth image showing variation in structure of agriculture garden and surrounding natural vegetation in study sites

Study crop

For paper I, II & III, I used watermelon as the focal crop to study flower visits, crop pollination and crop yield. Watermelon is vital cash crop in Tanzania and its market value has recently increased due to growing demands (Van Ittersum et al., 2016; Makuya et al., 2017) and thus watermelom production supports livelihoods of numerous local farmers. The main criteria for choosing watermelon as the focal crop for this study, were 1) approval by a majority of local farmers in the study area to collect data on their watermelon cropland, 2) the high dependency of pollinators for fruit set in watermelon, and 3) the short life span (75-90 days). Fruit setting in watermelon relies 100% on insect pollination for optimal yield because of sticky and big pollen grains (Brewer, 1974; Sanford and Ellis, 2016; Bomfim et al., 2015). In addition, the pollinators are crucial because the plant is monoecious with low ratio of female to male flowers (Delaplane et al. 2000)

Data collection and analysis

To understand to which degree watermelon yield is limited by pollination services, I conducted a pollination supplemental experimental in 13 watermelon gardens. I also took soil samples from 13 gardens to account for effects of local soil conditions as detailed in paper I.

I analysed the effects of hand pollination on (i) fruit initiation, (ii) fruit abortion, (iii) fruit maturation and (iv) weight of the fruits, at the individual flower level − treating individual flower as the study unit − to match the resolution of the data collection using GLMMs (paper

I, Table 1). To account for variation among gardens, sites and regions variations, I included them in the model as nested random variables.

Table 1: Statistical models applied for different response variables in paper I. The final model was obtained by backward elimination. Explanatory variables were retained in the final model if their influence on the response variable was statistically significant ($p < 0.05$)

Response variable	**Model**	**Response variable description**
Probability of a flower to initiate a fruit	Binomial GLMM	A binary variable (success/failure) created using cbind function whereby Success = Fruit initiated, Failure = No fruit initiation
Probability of initiated fruit to abort	Binomial GLMM	A binary variable (success/failure) created using cbind function whereby Success = Initiated fruit developed to maturity, Failure = Initiated fruit aborted
Probability of a flower developing a mature fruit	Binomial GLMM	A binary variable (success/failure) created using cbind function whereby Success = Flower developed to mature fruit, Failure = Flower did not form a mature fruit
Fruit weight	LMER	

Furthermore, I carried out a hand-pollination experiment at one location, where I could control all other agriculture inputs i.e. fertilizer and watering. I assessed the same response variables as in paper I, except this time I also analysed fruit quality (shape, sugar concentration, and colour). I carried out statistical analyses to assess the effect of enhanced pollination and increased levels of fertilizer and water on watermelon yield (paper II, Table 2).

Table 2: Statistical models applied for different yield response variables in paper II.

Response variable	Model	Response variable description
Probability of a plant to initiate a fruit (2^{nd} week after blossom)	Binomial GLMM	Binary variable (success/failure) created using cbind function whereby Success = Plant initiated fruit, Failure = No initiated fruit
Number of initiated fruits per plant (4^{th} week after blossom)	Poisson GLMM	
Probability of a treatment plant having a second sellable fruit (≥1.5 kg) at harvest time	Binomial GLMM	Binary variable (success/failure) created using cbind function whereby Success = Initiated fruit developed to maturity, Failure = Initiated fruit aborted
Fruit weight	LMER	Kg
Sugar concentration	LMER	Brix
Fruit colour	Multinomial regression	Three-level categorical response variable (deep red/red/pale yellow)
Fruit shape	Multinomial regression	Three-level categorical response variable (normal shape/ mildly misshaped/ misshaped)

To understand how environmental context influenced pollinators and in turn affected yield, I observed watermelon flower visitors and visitation frequencies to watermelon flowers in 23 watermelon gardens, which included the 13 gardens included in paper I. I observed flower visitors in observation plots at the edge and in the centre of each garden simultaneously (paper III), in the morning, midday and in the evening. Distance from edge to the centre of the garden varied among gardens depending on the field size. I also quantified abundance of co-occurring plants in the observation plots. In addition, I collected information on the frequency of pesticide application per week, as practiced by every farmer in the 23 gardens. Approximately one week before harvesting, I quantified number of fruits and fruit weight in each watermelon garden. I estimated tree cover surrounding each garden from Sentinel satellite photos using the Google Earth engine (paper III). I analysed factors influencing flower visits, and the relationship between flower visits and yield (paper III, Table 3).

Table 3: Statistical models applied for different response variables in paper III. The final model was obtained by backward elimination. Explanatory variables were retained in the final model if their influence on the response variable was statistically significant ($p < 0.05$). For Model 1, explanatory variables in the final model were; number of pesticide sprayings, number of co-occurring flowers in the observation plot, time of day (morning/noon/evening), position-in-field, type of flower visitor (honeybee/other Hymenoptera/hoverflies), and tree cover in a 250 m radius surrounding the field. In paper III, we carried out the same analysis for honeybees only. The final model included the same explanatory variables, except type-of-visitor, and position-in-field. For the Model 2, only visitation rate and fruit weight were explanatory variables; variables influencing visitation rate in Model 1 were not included.

Model No	Response variable	Model	Response variable description
1	Number of flower visits per observation session	Zero-inflated negative binomial	All groups of flower visitors in Synopsis. Only visits by honeybees in Paper III.
2	Number of mature fruits per plant at harvest time	Poisson GLMM	

To understand how conventional agricultural inputs influenced pollinators and/or crop yield of watermelon, we conducted an experiment to enhance pollination, water and fertilizer and assess their separate and combined contributions to watermelon yield as detailed in paper II and Table 2. In addition, in paper III, I collected information about pesticide use, i.e. type of pesticides (insecticide, herbicide and fungicide) and frequencies of application, and I used this information to analyse the relationship between flower visits by insects and frequency of pesticide spraying (paper III, Table 2).

To understand how small-scale farming in Tanzania is vulnerable to changes in pollination services, and how this may influence household income and food availability, I obtained information related to local small-scale farming by interviewing 147 local farmers in the same sites as where observational ecological studies were conducted. The interview focused on type of crops grown, contribution of agriculture activities to their income and food, their farming practices and awareness of insect pollination services. Different statistics tools were used to summarize and analysed data from the questionnaire forms (paper IV).

Results and Discussions

1. Is watermelon production limited by pollination services in small-scale farming systems Northern Tanzania?

Insufficient insect pollination limits watermelon yield

I have shown that watermelon yields are limited by pollination services, both through experimental studies (hand-pollination; paper I and II) and observational studies of relationships between insect visits to watermelon flowers and yield (paper III). Results in paper I were based on 13 watermelon gardens under varying management and agricultural regimes, and all assessed response variables i.e. fruit initiation, fruit abortion, mature fruit setting and fruit weight were limited by pollination services. Results from both paper I and II demonstrate that, local farmers can double number of fruits if the flowers are sufficiently pollinated.

In contrast to findings in paper I, I did not find fruit weight to be limited by pollination services in paper II. Since data used in paper II are based on an experiment carried out in only one location and under similar environmental conditions and levels of agricultural inputs, I speculate that, the differences in observed results are a consequence of spatial variations and differences in farm management practices and environmental conditions. Also, results in paper II show that, relying on ambient level of available natural pollination, farmers are likely to miss the second marketable fruit as the grown variety has a potential of producing two fruits of 3-5 kg.

Results from this study concur with previous studies, which have found insect pollination to improve yield quantity in various crops (Sajjad et al. 2009). The main mechanism behind increased yield quantity in sufficiently pollinated flowers − as observed in Paper I and II − is related to increased pollination success as nectar/pollen foraging insects visit crop flowers and move the pollen from male to female flower/part. This movement is not only crucial to self-sterile or monoecious plants like watermelon, but to a majority of flowering plants, because insect pollination contributes to out-crossing, which increases plant yield (Abrol 2011).

Besides improved yield quantity as a result of insect pollination, previous studies have shown that insect pollination can increase yield quality even in self-pollinating crops, for example seed quality in canola (Chambó et al. 2018), shelf life and shape of strawberry (Klatt et al. 2014) and tomato fruit colour (Vergara and Fonseca-Buendía 2012). Results in paper II support these previous results as I found that hand-pollinated flowers produced fruits with significantly higher sugar concentrations.

Results in paper II suggest that, low yield in watermelon in my study area is a result of delayed pollination. During first fruit initiation assessment I found that, hand-pollinated treatment plants had initiated higher number of fruits, as compared to the other treatments, whereas at the second assessment, number of initiated fruits were the same across all treatments (Paper II). I suspected that, the observed increase in number of initiated fruits in control plants was function of increased number of insect flower visits which was low during early blooming (Figure 3 A & B not in the paper II). I also observed that, the chance of getting a second sellable fruit in hand-pollinated plants was high. Based on these facts and local farmer harvesting schedules I speculated that, late pollinated flowers in plants that did not receive hand-pollination did not get enough time to attain market value at the time of harvesting and hence considered as rejects. Similar study in cucumber (cucurbit) by (Connor and Martin 1970) recommended pollination by honeybees to be delayed after blossom as he found late produced fruits to be heavier and produced more seeds. These findings were however explained to be a function of mature vines in cucumber, which produced bigger and vigour flowers compared to early produced flowers.

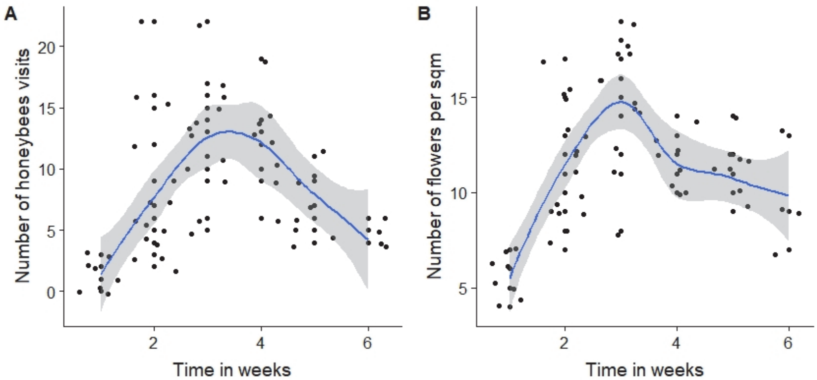

Figure 3: A: Honeybee visits pattern throughout the flowering period of the observed watermelon plants and B: Flowering pattern during six weeks of blossom

Relationship between flower visits and yield

I found that number of mature fruits per plant increased with number of flower visits per observation seesion (paper III). This finding is consistent with findings from other studies of watermelon (Bomfim et al. 2015) and other crops (Winfree et al. 2008, Garibaldi 2014). I did not find fruit weight to correlate directly with flower visitation rates, however fruit weight was negatively related to the number of fruits per plant, suggesting a trade-off between number and weight of fruits. In contrast, Brewer (1974) found that flower visitation increased fruit weight in watermelon, but not the number of fruits.

2. How does environmental context influence pollinators, and consequently pollination and crop yield of watermelon, in small-scale farming systems in Tanzania?

Insect visitors to watermelon flowers - abundance and diversity

Transect walks and flower visits counts data from 23 gardens included in paper III revealed that watermelon fields were highly dominated by honeybees, whereas the proportions of other groups of flower visitors were quite low; honeybees 87.8%, hoverflies 8.5% and other Hymenoptera (i.e., wild bees from the *Eucera* genus and wasps) 3.7% (Table 1, Figure 4A).

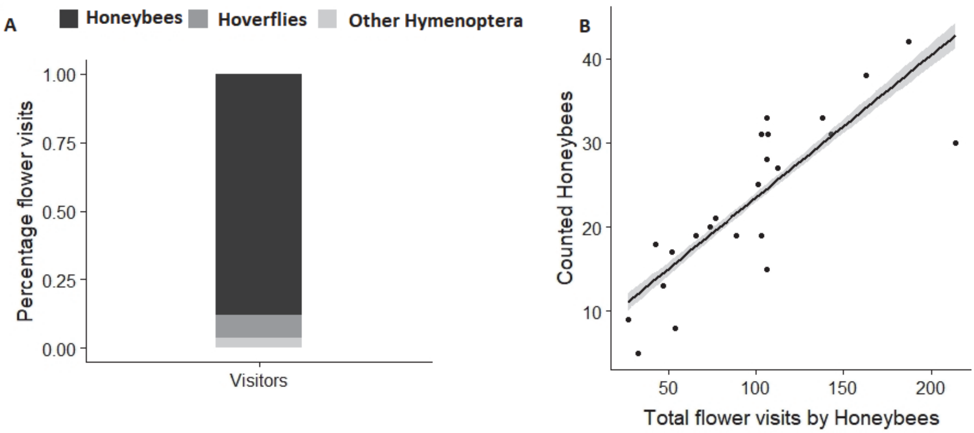

Figure 4: (A) Proportion of observed flower visits by different groups of insect visitors. (B) Relationship between numbers of counted honeybees during transect walks and observed honeybees visiting flowers within 1-m^2 observation plots in 10 minutes). Lines are estimated relationships and associated 95% confidence polygons.

The number of honeybees observed visiting watermelon flowers in 1-m^2 observation plots and the number of honeybees counted during transect walks within each garden were highly correlated ($r = 0.83$, $df=21$, $p <0.01$; Figure 4B).

Factors influencing flower visits

I analysed factors influencing watermelon flower visits, both for a subset of the data, which included only honeybees (87% of the observed visits; presented in Paper III), and for the whole dataset including all types of flower visitors (honeybees, hoverflies, and other Hymenoptera; Table 4).

Irrespective of whether I included all insect visitors or only honeybees, number of flower visits increased with number of co-occurring flowers of other plant species in the observation plots, but this positive influence of co-occurring flowers was relatively more important at high values of tree cover in the garden surroundings. Or put it another way, watermelon flower visits decreased with tree cover in the surrounding landscape, but the negative impact of tree cover was weak at high abundances of co-occurring (wild) flowers. This concurs with other studies which have found that presence of co-occuring flowering plants in agriculture sytems can both enhance pollination services by attracting more flower visitors towards target crop plants (Sidhu and Joshi 2016), or distract flower visitors away from target crops (Nicholson et al. 2019). Indeed both inter and intraspecific interactions for flower visitors can be scale dependent, as too few flowers attract few pollinators, while too many flowers cause a dilution effect resulting in fewer visits on a per flower basis (Hegland 2014). Flowering trees may compete with watermelon flowers for insect visitors. Indeed, both positive, negative, and no relationships between tree cover and flower visits have been reported in the literature (see Discussion in paper III for a detailed account). Even though flowering trees may potantially compete with crop plants for insects visitors, the trees may also provide crucial food and nesting resources for a diversity of insects, and thereby sustain stable insect populations in the landscape.

I found that flower visits depended on position-in-field for hoverflies and other Hymenoptera, but not for honeybees (Table 1, paper III); flower visits was higher at the edge than in the centre for hoverflies, and higher and more variable at the edge than in the centre for other Hymenoptera (Table 1, Figure 5A). Previous studies that found increased abundance of non-honeybees at the edge of the fields, pressumed that this could be explained by flight limitations (Herrera 1989, Inouye et al. 2015) and thus most individuals forage at the field margins where they also reside (Rands and Whitney 2011). Pasquet et al. (2008) suggested that, increased tree cover proximal to agriculture fields might benefit crops at the edge compared to the interior of agricultural fields, due to food and nesting resources available at the edge that support more flower visitors.

Table 4. Factors influencing visitation by insects to watermelon flowers in 1-m^2 observation plots in 23 watermelon fields in northeast Tanzania; the response variable is the number of visitors (given that ≥1 visitor was observed). Explanatory variables: number of pesticide sprayings, number of co-occurring flowers in the observation plot, time of day (morning/noon/evening), position-in-field (center/edge of garden), type of flower visitor (honeybee/other Hymenoptera/hoverflies), and proportion of tree cover in a 250 m radius surrounding the field.

	β	SE	z	P
Conditional model				
Intercept	-6.66	0.41	-16.06	<0.01
Type of visitor: Honeybees (vs hoverflies)	5.59	0.34	16.57	<0.01
Type of visitor: Hymenoptera (vs hoverflies)	-2.09	0.58	-3.57	<0.01
Position in field: Edge (*vs* centre)	0.25	0.10	6.43	<0.01
Pesticide application frequency	-0.25	0.10	2.44	0.01
Tree cover within 250m	-0.05	0.01	-3.66	<0.01
Number of co-occurring flowers	-0.01	0.04	0.23	0.81
Time of day: Morning (*vs* evening)	1.58	0.21	7.49	<0.01
Time of day: Noon (*vs* evening)	0.92	0.21	4.30	<0.01
Honeybee×Position in field: Edge (*vs* centre)	-1.54	0.26	-6.04	<0.01
Other Hymenoptera × Position in field: Edge (*vs* centre)	-0.21	0.39	-0.56	0.58
Honeybee × Pesticide application frequency	-0.57	0.10	-5.50	<0.01
Other Hymenoptera × Pesticide application frequency	0.52	0.16	3.16	<0.01
Tree cover within 250m×Number of co-occurring flowers	0.02	0.01	2.66	<0.01
Random effects		**Groups**	**σ**	**SD**
Observation day		5	0.15	0.39
Field ID		23	0.01	0.12
Site ID		5	0.01	0.09
Region ID		2	0.02	0.12

Concurrently, size of the fields have been reported to have similar effects, as most of the flying insects can only fly a short distance in searching for food (Inouye et al. 2015). In this study, position-in-field did not influence flower visits by honeybees. Perhaps this could be a due to the limited size of the watermelon fields; honeybees can fly more than 10 kilometers to forage (Hagler et al. 2011). This implies that the size of the fields in our study system (i.e. maxmum size 2.5 ha) were not a problem for honeybees to navigate.

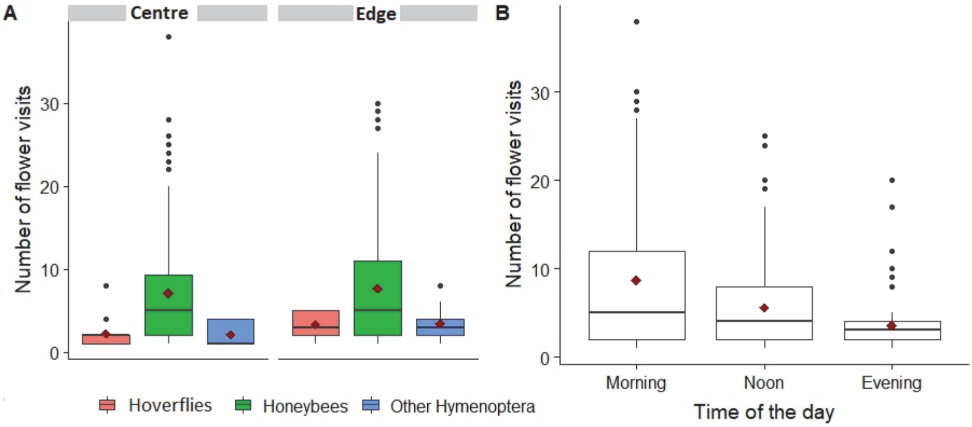

Figure 5: (A) Number of visits by different types of flower visitors at the at the edge of the vs centre of the observed gardens. (B) Average number of flower visitors at different times of the day. Boxplots showing observed medians (midline), observed means (red diamonds), and the 75th and 25th percentiles (upper and lower limits of the box).

Number of flower visits was highest in the morning, intermediate mid-day, and lowest in the evening, for all types of visitors (Figure 5B). Similar flower visitation patterns have been observed in other studies (Bheemanahalli et al. 2017) and described as a function of flower morphology; most of the flowers open in the morning and close around mid-day to prevent desiccation due to high temperatures (Li et al. 2016). This also suggest that, most of the flower visits in the evening present low chances of pollination success in watermelon. Following this pattern of flower visits, I recommended local famers to spray pesticide in the evening (see also discussion of the influence of pesticides below).

In paper III, I argue that observed dominance of the honeybees on watermelon flowers could perhaps be a result of flower unattractiveness to other flower visitors (Sanford 2016). Previous studies have documented significant contribution of non-honeybees to agriculture yield (Hoehn et al. 2008). However, this is not to say non-honeybee insect visitors are not important, because despite their low abundance in the crop fields, they can improve yield in other crops which depend less on pollinators (Jauker et al. 2012), or complement pollination provided by honeybees as observed by Brittain et al. (2013) in almond production and Rader et al. (2016) in 37 different crops including watermelon.

In addition, my results (paper III) show that, despite average number of honeybee visits being around the proximal required for optimal pollination of watermelon flowers, i.e. 8 visits (Delaplane et al. 2000), I still found the study crop to be limited by pollination. One explanation for this observed phenomenon could be related to observations in paper II; i.e. increased flower visits influenced fruit initiation, but as this happens at the late stages of blooming, most of the initiated fruits did not attain maturity by the time of harvest. Another explanation could be that observed visitors spend less time per visit (Adlerz 1966).

Influence of soil conditions on yield

My results indicate that pollination, not soil moisture, was the limiting factor on watermelon yields in my study system. However, if the plants are sufficiently pollinated, it is worth to optimize the soil conditions towards drier soils (paper I). I also found that fruit initiation and fruit weight were positively related to soil carbon, irrespective of pollination treatment (paper I).

Random variables output shows that, response variables varied substantially at the between regions, among sites and gardens implying that local environmental conditions or management practices might play a significant role in crop yield. These variations were confirmed by post hoc analyses which showed how the, between-regions and among-sites and gardens variation influenced treatment effects (see Appendices1-6).

3. How do conventional agricultural inputs influence pollinators and/or crop yield of watermelon, in small-scale farming systems in Tanzania?

Pesticides

Number of flower visits by honeybees depended on the number of pesticide applications per week; there was little difference between none and one application per week but increasing to 3-4 applications per week reduced flower visits by about 50%.

Increased pesticide application frequency significantly reduced number of hoveflies and honeybees (Table 1; Figure 6, paper III), whereas no clear trend was found for other Hymeoptera (Table1, Figure 3C). Previous studies have documented multiple effects of different classes of pesticides, both to wild and managed bees, such as memory loss (Siviter et al. 2018), reduction in reproductive ability (Sandrock et al. 2014) and death (Oldroyd 2007). I suspect similar effects can apply to other insects such as hoverflies. I do not have clear explanation as to why other Hymenoptera showed a different pattern (Table 1, Figure 5C). Perhaps this was a consequence of reduced honeybees density, and thus reduced competition (Valido et al. 2019).

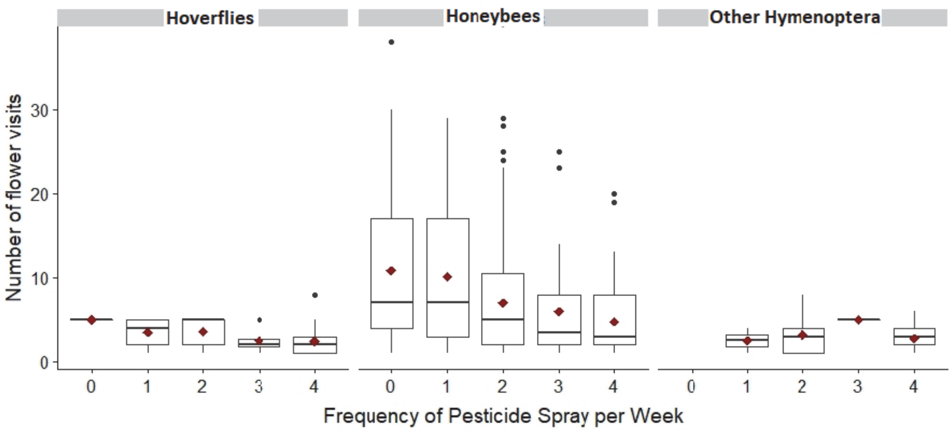

Figure number 6: Average number of flower visits by different types of flower visitors in relation to frequency of pesticide spraying. Boxplots showing observed medians (midline), observed means (red diamonds), and the 75th and 25th percentiles (upper and lower limits of the box).

I found that pesticide application frequencies in watermelon gardens were high (Figure 6), which perhaps applies to other crops in the study area as well. Results in paper IV also confirm the farmers' perceived need for pesticide use as pests were mentioned among the top three problems resulting into low yield. The quest for pesticide use is however not reflected in (FAO 2019), which shows that average amount of pesticide use in Tanzania is 1 tonne per year and this has not changed for nearly two decades. Perhaps absence/inefficiencies in controlling imported pestices and lack of inventories of both locally made and imported pesticides, as reported by Tanzania Controller and Auditing General (CAG) report (URT 2018), can explain the apparent descrepancy.

Enhancing pollination versus conventional agriculture inputs

In paper II, I found that, increasing the amounts of fertilizer and water beyond the levels used by most of the local farmers was not important for watermelon yield. Lack of soil nutrients and water can limit agriculture production, and even though soils are often poor in nutrients, the average level of fertilizer application in Tanzania is far behind many places around the globe (Chianu et al. 2012, Senkoro et al. 2017) with great variation within the country/regions. Even so, this study reveals that, local farmers could benefit from improving pollination services in their agriculture lands rather than only focusing on fertilizer and watering. Using watermelon as focal plant, results in paper II reveal that, current levels of fertilization used by most of the farmers in studied area are sufficient for optimal watermelon yield, and that higher yields can be achieved through increasing the level of pollination.

4. Are small-scale farming systems in Tanzania vulnerable to changes in pollination services, and how may this influence household income and food availability?

Local household dependency on insect pollination

In paper IV I found that, local farmers derive their food from all grown crops and that not all crops grown were meant for selling purposes. The majority of the farmers who grow "modest" pollinator dependant crops aimed only for home consumptions, these included crops such as *Solanum melongena* (egg-plants), *Solanum aethiopicum* (bitter tomatoes) and *Abelmoschus esculentus* (okra). The reason why the majority did not depend on such crops for market purposes was poor yields resulting from poor seeds. Most of the local farmers mentioned that, they usually plant seeds from the previous harvest, which suggest that, improving cross pollination in their fields could also improve sawing seeds for the following season.

I also found that despite local farmers' dependence on maize for income generation, they have potential of benefiting from increased watermelon yields; watermelon was the most important cash crop (25% of household income) and was cultivated by 63% of the farmers. This is because, in paper II, I found that watermelon yield can be increased up to 58 % by improving pollination conditions, while using the same amounts traditional agriculture inputs i.e. watering and fertilization.

Pollinators conservation and awareness

Results showed that a large majority of the local farmers were not aware of pollination and pollinating insects. The few farmers who reported to be aware of pollinating insects (7%), did not know how the insects can improve yields and only one of these farmers deliberately sprayed pesticides in the evening to avoid killing pollinating insects. When the farmers were asked about the beneficial insects visiting their crops, they mentioned honeybees and butterflies, though butterflies were mentioned as pests as well. Honeybee visits were considered beneficial because they collect raw materials for honey production. I confirmed lack of pollination awareness among farmers as they all agree to have experienced yield decline, but none of them thought pollination deficit could contribute to yield decline. The main perceived and reported pressing problems were pests, lack of fertilizers and lack of good seeds. The level of education or type of crops grown did not seem to play a role in pollination awareness, in contrast to findings in other studies (Bhattacharyya et al. 2017, Schönfelder and Bogner 2017, Sieg et al. 2018). The few farmers aware of the role of insects as pollinators seemed to acquire this information from agriculture officers through extension services or from other farmers. These results concur with observations made by (Kasina et al. 2009) in Kenya and by (Munyuli 2011) in Uganda who found local farmers to have low awareness about pollinators and their role in agriculture productions. In contrast (Hordzi 2014) found that most of the local pigeon pea (*Cajanus cajan*) farmers in Ghana understood the roles of insect pollination.

Conserving ecosystem services versus agricultural intensification

Agricultural landscapes that embrace nature through ecological intensification rather than agricultural intensification has received more attention in recent decades due to their sustainable food production through biodiversity conservation, which enhances insect pollination and pest resilience (Biddinger and Rajotte 2015). To compensate for the loss of insect pollinators resulting from agricultural intensification, habitat loss and other causes of decline in pollination services, some farmers keep and manage domesticated pollinators, i.e. honeybees (*A. Mellifera*) to complement pollination by wild insects (Biddinger and Rajotte 2015). This is however, occurring mostly in developed countries, whereas small-scale farmers in developing countries still rely mainly on natural occurring pollinators (Kasina et al. 2009, CBD 2016). Unfortunately, these same areas lack documentation on the importance of crop insect pollination despite their probable high reliance on insect pollination for food production (CBD 2016, Timberlake and Morgan 2018).

The conflict between conserving ecosystem services − such as animal pollination − and agriculture intensification has often been considered a function of the extent of intensification (Aguirre-Gutiérrez et al. 2015), i.e. highly intensified agriculture lands are more deprived of pollination services compared to less intensified land. I argue that in addition, the pros and cons depend on crop type, and the type of flower visitors involved. The levels of agriculture intensification in Tanzania and most sub Saharan Africa countries are considered low because of field size is typically small, with low levels of agriculture inputs (Binswanger-Mkhize and Savastano 2017). This thesis reveals that crop yields in Northern Tanzania are limited by naturally available pollination services (paper I, II, and III) and that there is a negative relationship between number of pollinators and the frequency of pesticide spraying. Perceived western concepts of agricultural practices entailing intensification might not apply in Tanzania because of social-economic status of the local farmers, which prevent them from owning and managing large areas of agriculture land. However, some of the agricultural practices used, irrespective of the magnitude or spatial scale involved, can be detrimental to pollinators. For instance, the commonly use of mixing several pesticides can increase the level of toxicity even in small doses (Laetz et al. 2009).

Moreover, in this study I have demonstrated that, local farmers are unaware of insect pollination, and that most of them focus on other agriculture inputs to increase production. I assume that this is related to the low levels of education among the local farmers and thus leaving a high demand for agriculture capacity building. Findings from my study could be utilized to develop farming practices to enhance flower visitation by insect pollinators. In addition to maintaining natural habitats for wild pollinators, results indicate that it may be beneficial to maintain some wildflower resources in the agricultural fields, to help attract pollinators. Deploying beehives (i.e., nesting sites for honeybees) around the field could attract more honeybees around the fields, since these colonies are unmanaged, they can inhabit a hive and leave when food resources are insufficient. Also, ensuring continuity of flower resources in the area would prevent periods of food shortage for wild pollinators. These measures could both enhance insect pollination and generate honeybee products at the end of the seasons.

Based on findings from paper I, II and III, I recommend agriculture authorities to inform local farmers to keep good agricultural practices to improve conditions for pollinators in, and around, their crop fields. These practices include limited use of insecticides, increased availability of floral resources at times where the crops are not flowering and establishment of nesting sites for e.g. honeybees. Better agricultural and land management practices will ensure better crop yields and ultimately farm economy and livelihood of people in these rural communities.

Low awareness on roles of insect pollinators and presence of unsustainable agriculture practices such doubling the concentration of pesticides as described in paper III, reveals vulnerability of ecosystem services offered by small agroforestry farming systems in the study area. Apparently, equipping local farmers with the right knowledge about the link between ecosystem services and agriculture production through training could make these practices intentional for enhanced ecosystem services and improved agriculture production.

Conclusions

In this PhD thesis, I have shown that watermelon yield was limited by pollination services, and that the environmental context influenced pollinators, and consequently pollination and crop yield; flower visits by insects (mainly wild honeybees) to watermelon flowers increased with abundance of co-occurring wildflowers, especially at high tree cover in the field surroundings. Flower visits by non-honeybee visitors were higher at the edge compared to centre of crop fields. I found that pesticide spraying had a strong negative effect on flower visits. Compared to enhanced pollination, increasing inputs of fertilizer and watering had little effect on crop yield. I found that very few of the local farmers were aware of pollinators and their importance for crop pollination. This probably prevents the farmers from exploiting the potential to increase yields – and thus to increase household food availability and income – through pollinator friendly agricultural practices. It also makes them vulnerable to changes in agricultural practices, which may have negative impacts on the pollinator community.

My findings add to the scientific evidence of the importance of ecosystem functioning and ecosystem services for human well-being (Ecosystem 2005, Summers et al. 2018). My results also imply that ecosystem change – in terms of habitat destruction – or extensive use of pesticides that reduce local insect abundance and abundance wildflowers – may have negative impacts on biodiversity and ultimately affect human wellbeing.

Management Implications

I urge agriculture authorities in Tanzania to act to ensure that local farmers become aware of insect pollinators and their important role in agriculture production, and to establish education and advisory services for farmers on how develop pollinator friendly agricultural practices.

Local farmers should focus their attention on improving quality of the landscape to sustain and enhance healthy pollinator communities. This will both conserve local biodiversity and ecosystem services, and ultimately improve household food availability and income.

I suggest that farmers should continue with current practices with respect to fertilize and focus their irrigation schemes to the later phase of fruit development to ensure that they do not impair the positive effects of pollination services. Also, my findings indicate that there is no need for increasing the effort to remove flowering weeds; on the contrary, some co-occurring wild flowers in the watermelon fields may aid in attracting pollinators to the watermelon flowers.

Importantly, the alarming negative impact of pesticide use on flower visits by bees needs to be addressed by the responsible management authorities, who should explore the drivers of observed pesticide practices, and aim to develop a sustainable strategy for managing pests and ensuring increased agriculture yield.

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List of Appendices

Appendix 1

Table S1: Interaction Effects between Treatments and Garden on Probability of Fruit set. Results from a generalized linear mixed model with binomial response (fruit set vs no fruit set) and logit link function

	β	SE	z	P
(Intercept)	-0.280	0.421	-0.663	0.507
Hand-pollinated	2.349	0.742	3.166	0.002
Garden B	-1.366	0.640	-2.133	0.033
Garden C	-0.428	0.621	-0.689	0.491
Garden D	-1.423	0.684	-2.079	0.038
Garden E	-0.887	0.624	-1.421	0.155
Garden F	-1.167	0.647	-1.805	0.071
Garden G	-2.306	0.840	-2.745	0.006
Garden H	-0.535	0.576	-0.930	0.352
Garden I	-0.221	0.591	-0.373	0.709
Garden J	-0.843	0.662	-1.274	0.202
Garden K	-2.746	1.101	-2.495	0.013
Garden L	-0.611	0.611	-1.001	0.317
Garden M	-1.316	0.641	-2.052	0.040
Hand-pollinated: Garden B	-0.454	0.979	-0.464	0.643
Hand-pollinated: Garden C	-4.077	1.149	-3.548	<0.001
Hand-pollinated: Garden D	-0.546	1.023	-0.534	0.594
Hand-pollinated: Garden E	-0.379	0.968	-0.392	0.695
Hand-pollinated: Garden F	0.679	1.053	0.645	0.519
Hand-pollinated: Garden G	-0.941	1.165	-0.808	0.419
Hand-pollinated: Garden H	-1.952	0.941	-2.074	0.038
Hand-pollinated: Garden I	-0.504	0.995	-0.506	0.613
Hand-pollinated: Garden J	-0.868	1.007	-0.862	0.388
Hand-pollinated: Garden K	0.866	1.335	0.648	0.517
Hand-pollinated: Garden L	-2.067	0.980	-2.110	0.035
Hand-pollinated: Garden M	-1.780	0.997	-1.785	0.074

Table S2: Interaction Effects between Treatments and Site on Probability of Fruit set. Results from a generalized linear mixed model with binomial response (fruit set vs no fruit) and logit link function

	β	SE	z	P
(Intercept)	-0.901	0.599	-1.504	0.133
Hand-pollinated	0.288	0.641	0.449	0.653
Mbuguni	-0.680	0.741	-0.917	0.359
Mijongweni	0.142	0.646	0.220	0.826
Mwanga	-1.193	0.784	-1.521	0.128
Nduruma	-0.706	0.703	-1.004	0.315
Hand-pollinated: Mbuguni	1.408	0.796	1.768	0.077
Hand-pollinated: Mijongweni	1.238	0.700	1.770	0.077
Hand-pollinated: Mwanga	2.024	0.834	2.426	0.015
Hand-pollinated: Nduruma	0.301	0.766	0.393	0.694

Table S3: Interaction Effects between Treatments and Regions on Probability of initiated fruit to abort. Results from generalized linear mixed models with binomial response (fruit aborted vs no fruit abortion) and logit link function

	β	SE	z	P
(Intercept)	-0.245	0.572	-0.428	0.669
Hand-pollinated	-0.308	0.586	-0.525	0.599
Kilimanjaro Region	1.531	0.719	2.130	0.033
Hand pollinated*Kilimanjaro Region	0.064	0.707	0.090	0.928

Table S4: Interaction Effects between Treatments and Garden on Probability of a flower developing mature fruit. Results from generalized linear mixed models with binomial response (fruit vs no fruit) and logit link function

	β	SE	z	P
(Intercept)	-1.386	0.500	-2.773	0.006
Hand-pollinated	2.022	0.648	3.121	0.002
Garden B	-0.223	0.700	-0.319	0.750
Garden C	-1.609	1.140	-1.412	0.158
Garden D	-1.056	0.891	-1.186	0.236
Garden E	0.234	0.685	0.341	0.733
Garden F	-0.049	0.705	-0.069	0.945
Garden G	-1.910	1.134	-1.683	0.092
Garden H	0.043	0.678	0.063	0.950
Garden I	0.875	0.654	1.339	0.181
Garden J	0.288	0.719	0.400	0.689
Garden K	-16.135	1391.942	-0.012	0.991
Garden L	-0.223	0.742	-0.301	0.764
Garden M	-1.946	1.134	-1.716	0.086
Hand-pollinated: Garden B	-0.333	0.906	-0.367	0.713

Hand-pollinated: Garden C	-1.424	1.420	-1.003	0.316
Hand-pollinated: Garden D	-1.027	1.128	-0.910	0.363
Hand-pollinated: Garden E	-0.801	0.882	-0.908	0.364
Hand-pollinated: Garden F	-0.850	0.919	-0.924	0.355
Hand-pollinated: Garden G	-0.978	1.418	-0.690	0.490
Hand-pollinated: Garden H	-1.432	0.902	-1.588	0.112
Hand-pollinated: Garden I	-1.848	0.877	-2.107	0.035
Hand-pollinated: Garden J	-0.556	0.935	-0.594	0.552
Hand-pollinated: Garden K	14.275	1391.942	0.010	0.992
Hand-pollinated: Garden L	-1.917	1.013	-1.893	0.058
Hand-pollinated: Garden M	-1.909	1.580	-1.208	0.227

Table S5: Interaction Effects between Treatments and Garden on Fruit Weight. Results from a linear mixed model with identity link function

	β	SE	z	P
(Intercept)	0.582	1.020	0.570	0.568
Hand-pollinated	-0.258	0.525	-0.493	0.622
Garden B	2.688	1.579	1.702	0.089
Garden C	-0.082	1.832	-0.045	0.964
Garden D	0.618	1.681	0.368	0.713
Garden E	1.443	0.625	2.310	0.021
Garden F	2.218	1.113	1.993	0.046
Garden G	1.318	1.832	0.719	0.472
Garden H	0.076	0.625	0.122	0.903
Garden I	0.388	0.565	0.687	0.492
Garden J	0.368	0.652	0.564	0.573
Garden K	4.118	1.829	2.251	0.024
Garden L	0.968	1.596	0.606	0.544
Garden M	2.618	1.445	1.811	0.070
Hand-pollinated: Garden B	0.938	0.755	1.243	0.214
Hand-pollinated: Garden C	3.108	1.368	2.272	0.023
Hand-pollinated: Garden D	2.833	1.036	2.735	0.006
Hand-pollinated: Garden E	1.283	0.724	1.774	0.076
Hand-pollinated: Garden F	1.253	0.776	1.615	0.106
Hand-pollinated: Garden G	1.058	1.368	0.774	0.439
Hand-pollinated: Garden H	0.275	0.765	0.359	0.719
Hand-pollinated: Garden I	1.163	0.699	1.665	0.096
Hand-pollinated: Garden J	-0.318	0.755	-0.422	0.673
Hand-pollinated: Garden K	-2.008	1.232	-1.631	0.103
Hand-pollinated: Garden L	1.083	0.899	1.206	0.228
Hand-pollinated: Garden M	1.508	1.550	0.973	0.331

Table S6: Interaction Effects between Treatments and Regions on Fruit Weight. Results from a linear mixed model with identity link function

	β	SE	z	P
(Intercept)	1.769	0.519	3.408	0.001
Hand-pollinated	1.561	0.415	3.765	0.000
Kilimanjaro Region	0.206	0.622	0.331	0.741
Hand-pollinated * Kilimanjaro Region	-1.250	0.462	-2.704	0.007

Paper I

Inadequate pollination services limit watermelon yields in northern Tanzania

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Abstract

Insect pollination plays a vital role for the yield of many important crops, such as apples, strawberries and coffee, which are economically significant commodities on the global market. Yet, knowledge about the role of insect pollination is lacking for many cash crops produced by and supporting the livelihoods of small-scale farmers in developing countries.

To assess if pollination services limit the yield of watermelon *Citrullus lanatus*, an important cash crop in tropical agriculture worldwide, we conducted a supplemental hand-pollination experiment in 13 small-scale farms in an agricultural landscape in the Kilimanjaro and Arusha regions in northern Tanzania. We assessed fruit set, fruit abortion and the weight of the mature fruits stemming from hand pollinated and control flowers. In the analyses of the effects of the hand pollination, we also accounted for local soil conditions.

We found that hand pollination i) increased the probability of fruit initiation by 30%, ii) reduced the probability of fruit abortion by 13%, iii) increased the probability of flowers developing into mature fruits by 42% and iv) increased average fruit weight by 1.3kg (± 0.15 SE). Our results suggest that sufficient pollination is important for watermelon yields and that our focal system is pollinator limited.

Our results indicate that pollination was the limiting factor in our study system, not soil moisture, but if the plants are sufficiently pollinated, it is worth to optimize the soil conditions towards drier soil. Fruit initiation and fruit weight were positively related to soil carbon, irrespective of treatment.

We suggest that the farmers in our focal area should focus their attention on improving the quality of the landscape to sustain and enhance healthy pollinator communities ultimately improving yields. We also suggest that farmers should continue current practices with respect to fertilization and focus their irrigation schemes to the later phase of fruit development to ensure that they do not impair the positive effects of pollination services.

Keywords: crop yield; fruit abortion; fruit initiation; food security; fruit weight; pollinator limitation;

1. Introduction

Pollination is crucial for food production since, about one third of the food produced for human consumption derives from animal-pollinated plants and most of these are bee-pollinated crops (Aizen et al. 2014). Animal-pollinated food plants are typically of high nutritional value because they – in addition to providing energy – are richer in micro-nutrients, such as vitamin A, iron and folate (Eilers et al. 2011; Archer et al. 2014; Chaplin-Kramer et al. 2014; Smith et al. 2015), than wind-pollinated crops (Aizen et al. 2009). In general, insect-pollinated crops also have a higher market value (Potts et al. 2016), which makes them economically important in intensive cropping systems, such as in the USA, Europe and China, where industrial-scale agriculture is crucial for national economies. Growing evidence shows that there is a particularly high demand for animal pollination in the tropics, due to the human population increase and the increasing number of pollinator dependant crops (Giannini et al. 2015, Ollerton et al. 2011). However, more than half of all the studies of pollinators and pollination comes from North America (36 %) and Europe (27%) whereas tropical Africa (4%), Latin America (7%) and Asia (18%) are highly underrepresented in the scientific literature (Timberlake and Morgan, 2018). This highlights an unfortunate bias in information and lack of data on pollination services from regions where small-scale farming systems are of crucial importance for the economy of rural communities and the livelihood of millions of people (Steward et al. 2014).

There is a high and growing demand for increasing agriculture production to sustain the rapidly growing human population (ca 2.7% per year; OECD, 2016) and to meet dietary nutritional demands (Lachat et al. 2015). In most of the sub Saharan Africa countries, the main approaches to increase crop yields have been to improve soil conditions (fertility and moisture) and to increase the amount of farmland (Perrings and Halkos, 2015). Indeed gradual increase in agriculture production in some Sub Saharan Africa has been achieved through efficient utilization of massive available arable lands and through steadily improving policies on agriculture inputs and markets (Badiane and Makombe, 2014). Yet, if the number of pollinators are limited in landscape, the potential production of insect-pollinated crops will never be achieved by only improving soil conditions or turning more areas into cropland. This also suggest that, the quest to meet daily dietary nutrition requirements might not attainable, as insect-pollinated crops are the main sources of vitamins and other important nutrients. According to the Convention for Biological Diversity report (CBD), (2016) and Gemmill-

Herren et al. (2014), the African continent has large numer of insect pollinated crops which are highly important for food and nutrition security and for the income of small-scale farmers (Steward et al. 2014). However, lack of knowledge about which animal pollinators visit these crops, to what extent crop yields are limited by pollinator availability, and whether the effect of pollination status on crop yield depends on soil conditions, can jeopardize the ambitious goal of meeting necessary food and dietary requirements. Thus, it is imperative for researchers, farmers and decision makers to be aware of how pollinators may influence yields of various agricultural crops.

Crop pollination in Tanzania depends on naturally occurring flower visitors; pollinators are largely un-managed, although some people practice honeybee keeping for honey production. Studies documenting pollination limitation in agriculture crops in Tanzania are rare. Classen et al. (2014 and 2015) observed no pollination limitation in mixed coffee fields under different anthropogenic disturbance levels in Mount Kilimanjaro in Tanzania, but it is not known if this is the case for crops under the same or different agriculture systems in the region. According to Samnegård et al. (2016), low anthropogenic disturbance might not guarantee sufficient pollination services. Moreover, factors believed to be causing alarming declines in pollination services in different parts of the globe, such as pesticide use, habitat degradation and fragmentation (Potts et al. 2010, Rafferty, 2017), also apply to Sub Saharan Africa (Eardley et al. 2006; Initiative, 2007; Timberlake and Morgan, 2018) including Tanzania. Furthermore, pollinator conservation and management has received little attention in the region, due to focus on bulk food producing crops such as cereals (which are mainly self/wind pollinated), which has resulted in their negligence.

Watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai) is a pollinator dependent (Delaplane et al. 2000), widely planted crop in northern Tanzania and throughout Africa (Makuya et al. 2017). Honeybees (*A.mellifera*) – which occur naturally in Tanzania and most of Africa – are the main pollinators of watermelon (Sanford M 2016, Walters, 2005), however non-honeybees insects have also been reported to visit and pollinate watermelon flowers (Winfree et al. 2008, Campbell et al. 2019). In this study, we examined how pollinators influence the production of watermelons, while we also accounting for local soil conditions, i.e. soil moisture and soil organic carbon. Soil organic carbon is assumed to be the best predictor of soil fertility as it improves both the chemical and physical properties of soil

(Oldfield et al. 2019, Liu et al. 2015), whereas soil moisture provides water for plant metabolism (Hong and Jin, 2007).

We carried out a hand pollination experiment in 13 watermelon gardens in a small-scale agricultural system in Northern Tanzania. We aimed to understand how naturally available biotic pollination services – in interaction with soil moisture and organic carbon – affected: (i) fruit initiation, (ii) early fruit abortion, (iii) late fruit set and (iv) fruit weight in watermelon plants.

2. Methods

2.1. Study area

We conducted the study in the Kilimanjaro and Arusha regions in northern Tanzania (Fig. 1), from August to December 2016. The mean annual temperature and precipitation are 28.4ºC and 873 mm, and 24.7 ºC and 906 mm for the Kilimanjaro and Arusha regions, respectively (Tanzania Meteorological Agency, 2013). Agroforestry farming of vegetables, fruits, ornamental flowers and coffee is common in both regions, with different farming practices i.e. varying use of fertilizers, watering and pesticides among farmers. We focused our research on typical small-scale farms with watermelon gardens of areas ranging from 0.5 - 2 ha. Distance from one garden to another ranged from 0.8 - 4.2 km, whereas distance between sites was 11 - 83 km, and the elevation gradient ranged from 800-1200 meters above sea level. To assess whether pollination was a limiting factor throughout the two regions, we included 13 gardens (situated in five study sites); eight in the Kilimanjaro region (three study sites) and five in the Arusha region (two study sites) (Fig. 1). We selected gardens based on the availability of watermelons during the study period and accessibility (i.e. distance to road).

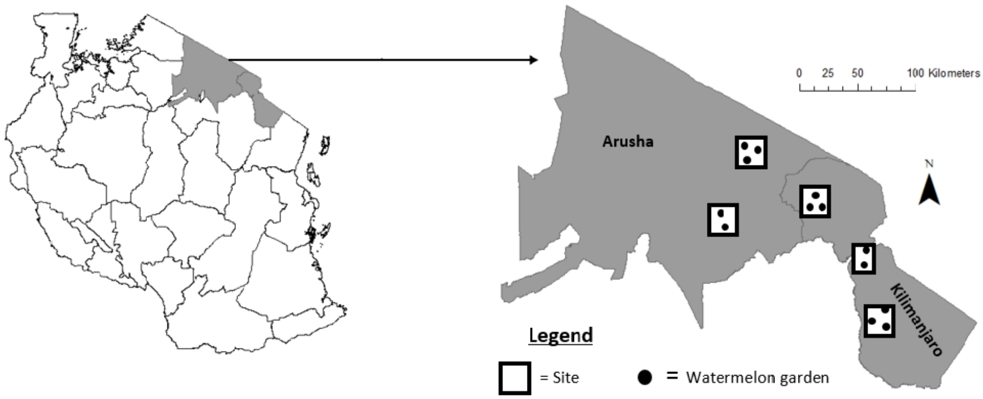


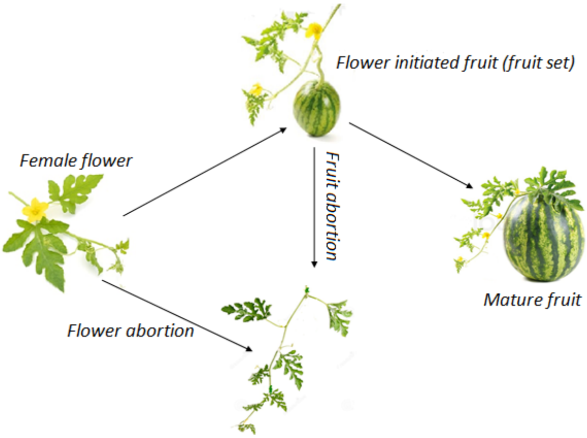
Figure 1. Left: Map of Tanzania showing the Kilimanjaro and Arusha regions in grey color. Right: Map showing the distribution of 13 watermelon gardens clustered in five study sites; three in the Kilimanjaro and two in the Arusha regions.

2.2. Study design

We randomly selected 20 focal plants throughout the centre of each of the gardens to minimize edge effects. We randomly assigned 10 of the plants to receive the hand-pollination treatment and the other 10 to receive only natural pollination (control). On each hand-pollinated plant, we selected three young female flowers and added pollen to their stigmas. We saturated the stigmas of the selected flowers with mixed pollen from the same plant and different plants within the garden. We conducted hand pollination between 6:00 and 10:30 AM, which corresponds to the period of maximum stigma receptivity (Bomfim et al. 2015). For the control plants, we also selected and marked three focal flowers that only received natural levels of pollination.

2.3. Fruit set and yield

Two weeks after we conducted the hand pollination treatment, we assessed the status of the marked flowers as either undeveloped (flower abortion) or developing into fruit (fruit initiation). Eleven weeks after the hand pollination treatment (approximately one week before harvesting), we re-assessed the marked flowers that had initiated fruit set and assigned each as either developed into mature fruit or aborted (fruit abortion) (Fig. 2). For the mature fruits, we measured their weight (kg) as an additional estimate of yield.



2.4. Measurements of soil conditions

To account for the effect of soil conditions to watermelon yield, we collected 10 soil samples at a depth of 0-20 cm from each of the surveyed gardens. We mixed the ten samples thoroughly to obtain a single composite soil sample per garden for analyses. The composite soil sample from each garden was analysed for moisture content (percent water) and soil organic carbon content (average weigh 54.1g ± (0.7 SE), including the plastic vial). We quantified moisture content by taking the ratio of the difference between weight of wet soil and oven-dried soil, and we assessed organic carbon content by the wet oxidation method (Nelson and Sommers, 1982) at Seliani Agriculture Research Institute (SaRI) in Arusha, Tanzania.

2.5. Data analysis

We conducted initial exploratory analyses on the dataset following Zuur et al. (2010) to check for outliers and collinearity between candidate explanatory variables, and to explore relationships between response variables and explanatory variables. We used the statistical software R version 3.3.3 for windows for all exploratory and statistical analyses (R Core Team 2017). Effects of hand pollination was analysed on the individual flower level − treating individual flower as the study unit − to match the resolution of the data collection.

To analyse the effect of hand pollination on fruit set, we termed a flower that developed into fruit a success (Y=1) and a flower that did not develop into a fruit a failure (Y=0). We conducted three separate analyses on; 1) fruit initiation, i.e. the probability of having a flower initiating fruit set two weeks after treatment, 2) fruit abortion (i.e. the probability of not setting a mature fruit although fruit set was initiated), and 3) formation of mature fruit (probability of a flower developing to a mature fruit). To analyse probability of each of the above mentioned responses, we created a two-vector (success/failure) response variable using the “cbind” function in R (Zuur et al. 2013). We assumed a binomial distribution of errors and used the logit link function to fit generalized linear mixed models (GLMMs) in the lme4 library in R (Bates et al. 2015). We first included treatment (hand pollination or control), soil organic carbon, soil moisture content, and the interactions between treatment and each of the other explanatory variables as fixed effects in the full (most complex) model. To account for the hierarchical study design and the random, spatial variation among regions, sites, gardens and individual plants, we included them in the model as nested random variables. (See Supplementary information Table S1 for list of all fixed and random variables).

To analyse the effect of hand pollination on fruit weight, we fitted a linear mixed model with fruit weight as response variable. We included the same set of explanatory variables and random effects in the full model as for the GLMMs for fruit set.

We carried out model selection by backward elimination (Crawley, 2012), using the “drop1” function (Bates et al. 2015). Explanatory variables were retained in the final model if their influence on the response variable was statistically significant ($P< 0.05$) or trending towards significance ($P< 0.10$). Model adequacy was checked by use of graphical validation techniques recommended by Zuur et al. (2013), including residuals versus fitted values to verify homoscedasticity, QQ-plots of the residuals to assess normality, and residuals versus each explanatory variable to check independence. For the generalized linear models, we also checked for model over and under-dispersion. To assess the robustness of our results, we also carried out model selection based on AIC values; for each response variable, the models with lowest AIC value was the same as the final models selected by backward elimination.

To test for independence of measured parameters between neighbouring gardens/replicates, we used average fruit weight and centre coordinates of each garden to run Moran’s I test using the morans I.v function in the “lctools” library in R (Kalogirou, 2019).

3. Results

3.1. Probability of fruit initiation

We observed that 53% (n=164) of the hand-pollinated flowers initiated fruits compared to 23% (n=76) of the control flowers (Fig. 3, Table 1). Fruit initiation in control flowers was stable (around 29 %) across the moisture gradient (Fig. 3A). There was a significant interaction between treatment and soil moisture, where fruit initiation was negatively related to soil moisture in flowers receiving the supplemental pollination treatment (Fig. 3A). In addition, fruit initiation was positively related to soil organic carbon in both treatment groups (Fig. 3B). Fruit set varied more among-plants than among regions, sites or gardens (Table 1).

Table 1. Factors influencing the probability of initial fruit set in hand-pollinated flowers compared to control watermelon flowers. Parameter estimates, test statistics and p-values from the final (reduced) generalized linear mixed model with binomial response (1 = fruit vs 0 = no fruit) and logit link function.

Explanatory variables	**β**	**SE**	**z**	**P**
Fixed effects				
Intercept	-3.33	1.40	-2.38	0.01
Hand pollination	2.50	0.44	5.70	<0.01
Soil moisture (%)	0.01	0.02	0.46	0.65
Soil organic carbon	2.78	0.92	2.80	<0.01
Hand pollination*Soil moisture	-0.07	0.03	-2.70	<0.01
Random effects	**Groups**		**σ**	**SD**
Regions	2		0.03	0.18
Site	5		<0.01	<0.01
Garden	13		0.03	0.16
Plant individual	130		0.08	0.29

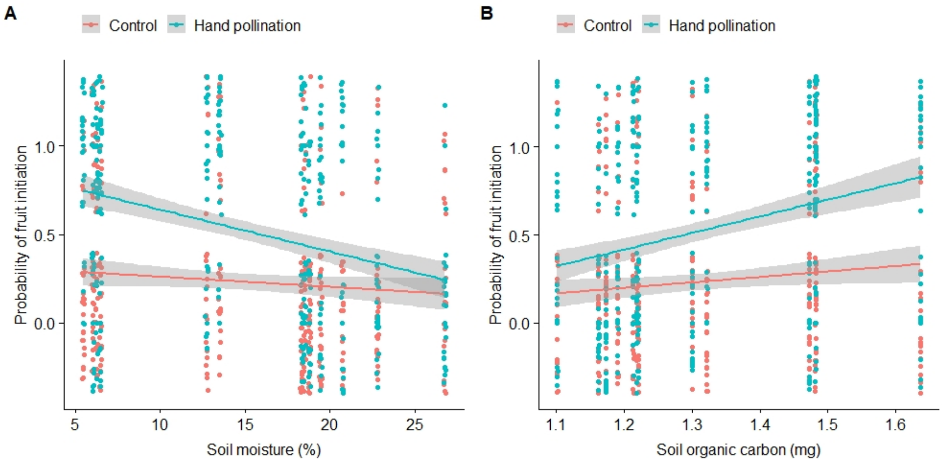


Figure 3: Effects of treatment (hand-pollination and control), soil moisture and organic carbon on probability of fruit initiation. Lines are estimated relationships and associated 95% confidence polygons for the reduced model shown in Table 1. The points show how the original data were distributed along the soil parameter gradients. Note that all response observations were either 1 = 'success' (fruit initiation) or 0 = 'failure' (no fruit initiation), but we have introduced a slight jitter to separate the observations, which were completely overlapping.

3.2. Probability of fruit abortion

Hand-pollination reduced the probability of fruit abortions (i.e. probability of initiated fruit not developing into a mature fruit), such that only 34% (n= 59) of the initiated fruits aborted whereas in the control group 47% (n=36) aborted. We observed a significant interaction between treatment and soil moisture, i.e. the negative relationship between soil moisture and fruit abortion was stronger in the control plants (Fig. 4A, Table 2). The level of fruit abortion varied substantially among the gardens (Table 2).

Table 2: Factors influencing the probability that an initiated fruit would abort in Hand-pollinated flower compared to control (reference level) in watermelon. Parameter estimates, test statistics and p-values from the final (reduced) generalized linear mixed model with binary response (1 = abortion vs 0 = no abortion) and logit link function.

Explanatory variables	β	SE	z	P
Fixed effects				
Intercept	3.2	1.1	2.9	<0.01
Hand pollination	-2.3	0.87	-2.60	<0.01
Soil moisture	-0.17	0.06	-2.8	<0.01
Hand pollination*Soil moisture	0.14	0.06	2.6	<0.01
Random effects		**Groups**	**σ**	**SD**
Region		2	0.12	0.34
Site		5	<0.01	<0.01
Garden		13	0.62	0.79
Plant individual		130	0.05	0.22

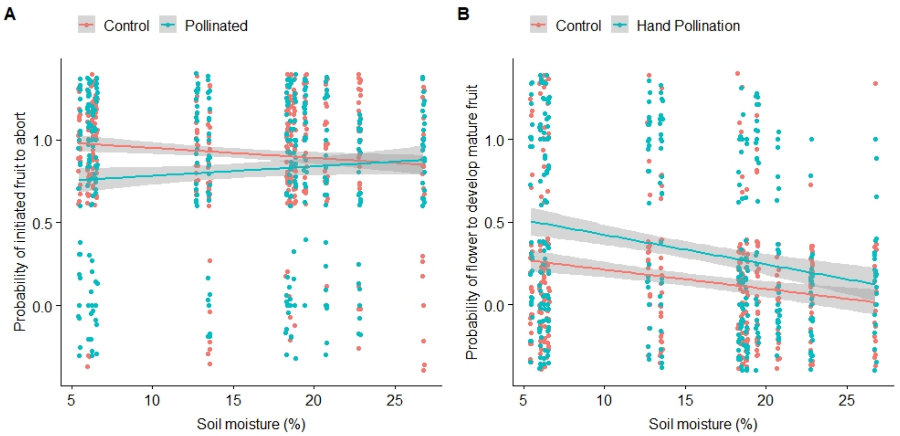


Figure 4: (A). Effects of treatment (hand-pollinated or control) and soil moisture on the probability that an initiated flower would abort. Lines are estimated relationships and associated 95% confidence polygons for the reduced model shown in Table 2.

(B) Effects of treatment (hand-pollinated or control) and soil moisture on the probability that a flower would develop a mature fruit. Estimated relationships and 95% confidence polygons for the reduced model in Table 3.

3.3. *Probability of a flower developing a mature fruit*

Hand-pollination increased the probability of a flower developing into a mature fruit (Fig. 4B, Table 3) such that, 34% (n= 104) of hand pollinated flowers developed to mature fruits whereas only 13% (n=40) of the control flowers developed to mature fruits. Furthermore, the probability of a flower developing into a mature fruit was negatively related to soil moisture (Table 3 and Fig. 4B). The probability of developing a mature fruit varied more between the regions and among gardens than among sites and individual plants (Table 3).

Table 3: Factors influencing the probability of a flower developing mature fruit in hand-pollinated flowers compared to control (reference level) watermelon flowers. Parameter estimates, test statistics and p-values from the final (reduced) generalized linear mixed model with binary response (1 = mature fruit vs 0 = no mature fruit) and logit link function.

Explanatory variables	**β**	**SE**	**z**	**P**
Fixed effects				
Intercept	-0.77	0.52	-1.5	0.14
Hand pollination	1.1	0.21	5.38	<0.01
Soil moisture	-0.09	0.03	-3.34	<0.01
Random effects		**Groups**	**σ**	**SD**
Regions		2	0.17	0.40
Site		5	<0.01	<0.01
Garden		13	0.17	0.40
Plant individual		130	<0.01	<0.01

3.4. *Fruit weight*

Hand pollination resulted in heavier fruits (average weight 2.5 kg ± 0.14 SE) compared to flowers receiving only natural levels of pollination (1.9 kg ± 0.18 SE) (Table 4, Fig. 5). Fruit weight was positively related to soil organic carbon (Table 4, Fig. 5). We found higher variation in fruit weight between regions as compared to among sites and gardens (Table 4).

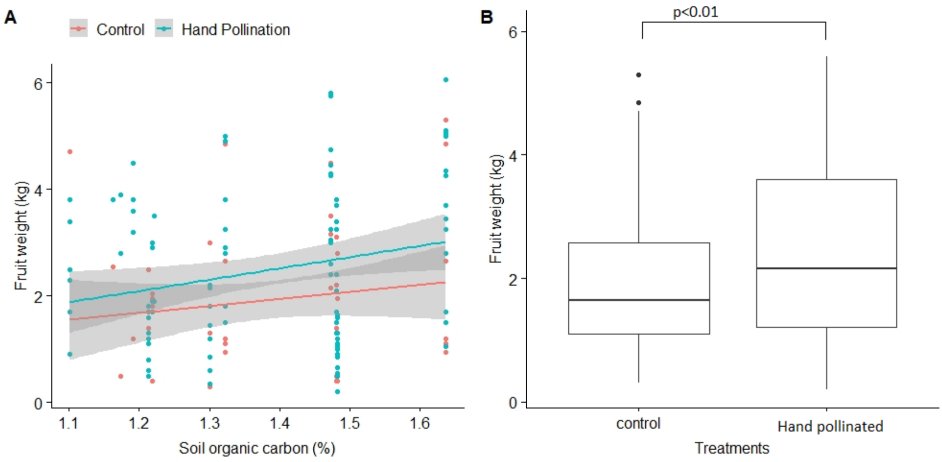


Figure 5: Estimated effects of treatment (hand-pollinated and control), and soil organic carbon on fruit weight. (A) Estimated relationships and 95% confidence intervals for the reduced model presented in Table 4. (B) Box-and-whisker plots for observed fruit weights of watermelons from hand-pollinated and control plants. P-value for the difference between the treatments group from the model in Table 4.

The morans I.v test showed a weak positive correlation at two (Moran`s I= 0.43, p= 0.03) and three (Moran`s I = 0.31, p = 0.02) neighbouring gardens, but the effect became insignificant as number neighbouring gardens increases.

Table 4: Factors influencing fruit weight in hand-pollinated flowers compared to control (reference level) watermelon flowers. Parameter estimates, test statistics and p-values from the final (reduced) linear mixed model with identity link function.

Explanatory variables	**β**	**SE**	**z**	**P**
Fixed effects				
Intercept	-1.20	1.50	-0.79	0.42
Hand pollination	0.57	0.19	3.01	<0.01
Soil carbon	2.76	1.45	1.91	<0.01
Random effects		**Groups**	**σ**	**SD**
Region		2	0.60	0.77
Site		5	0.34	0.58
Garden		13	0.36	0.60
Plant individual		87	<0.01	<0.01
Residual			1.20	1.10

4. Discussion

Hand-pollination increased fruit initiation and the production of mature fruits, as well as average fruit weight in our focal watermelon gardens in Tanzania. Based on these findings, we infer that our focal plants and gardens suffered from pollen limitation due to insufficient pollination service. Other studies have shown that wind cannot move pollen grains among watermelon flowers because of their large size and sticky nature (Delaplane et al. 2000). This means that insects foraging for pollen and nectar in watermelon flowers are the only potential pollen carriers. We conclude that there is insufficient pollen transfer in our study system, seen as lower fruit set from flowers receiving natural pollination as compared to hand-pollinated flowers. Past studies in other crop species have demonstrated that increased flower visitation frequency results in higher fruit set. For example, Klein et al. (2003) found that fruit set increased substantially in coffee with increase in flower visitors abundance and diversity.

Fruit set at maturity varied substantially among the gardens and with the same magnitude as between regions. This finding is intriguing because we would expect less variation among gardens compared to larger spatial scales, i.e. sites and regions. This suggests that agricultural practices on the particular farm (Fan et al. 2011) and/or small-scale local variation in pollination service (Ricketts et al. 2008; Ferreira et al. 2013) influence the probability of a flower developing into a mature fruit.

According to Stephenson, (1981), flower predation, diseases, plant vigour, resources availability and pollination services are the proximate causes of flower abortions in plants. In our study, 34% of the hand-pollinated flowers developed into mature fruit, whereas only 13% of flowers developed into mature fruits in the control group, suggesting positive effect of hand-pollination on fruit maturation. These findings are similar to Bommarco et al. (2012) and Schüepp et al. (2014) who observed increased fruit set in oils seed rape and cherry fruits with increasing pollinators visitation rates. However, Garantonakis et al. (2016) compared two bee pollinators (*Lasioglossum* sp. and *Apis mellifera*) varying in pollination efficiency and found that efficient pollinators only increased seed set per fruit in watermelon and neither fruit set nor fruit size. Furthermore, Hoehn et al. (2008) found a positive effect of pollinator abundance and richness on seed set – but not on fruit size – in pumpkins, and suggested size might be related other environmental factors. Our results suggest that pollination service limits fruit development, i.e. the proportion of flowers developing into mature fruits, in our study area.

We also predicted that abortions of initiated fruit would not differ between the hand-pollinated and control flowers. However, this was not the case, as a larger proportion of the initiated fruits in the hand-pollinated treatment group developed to mature fruits compared to the control flowers. Other studies in cucurbits have shown that the chances of well-pollinated flowers to develop a mature fruits are higher (Taha and Bayoumi, 2009; Hoehn et al. 2008; Garantonakis et al. 2016). We are however, not aware of any study investigating whether a transition from initiated fruit to mature fruit also depends on how well the flower is pollinated. According Delaplane et al. (2000) and Stephens (1994) a female watermelon flower requires about 800-1000 pollen grains to develop to a mature fruit. Our results suggest that many of our control flowers did not receive enough pollen to enable the initiated fruits to develop to mature stage, and that they therefore were aborted. According to Willmer, (2011) a flower need sufficient pollen for fertilization of all ovules within the ovary. Fruit development to maturity is highly linked to seed set because plants will allocate resources to the fruits that that has the potential to contribute the most to parent fitness (Díaz *et* al. 2003). We therefore infer that the observed frequency of fruit abortion in our study is attributed to insufficient pollination resulting in reduced seed set and hence abortion of the whole fruit. Pereira et al. (2017) and Stephenson (1981) showed that pests and diseases can result in fruit abortions in watermelon. During our fieldwork, we observed larvae of the melon fly (*Bactrocera cucurbitae*) destroying some of the initiated fruits, confirming this process. However, this was not very frequent and appeared to occur randomly in both hand-pollinated and control plants, and thus cannot explain the high abortion rate in the control flowers only.

Hand-pollination significantly increased fruit weight. This is in accordance with our prediction that weight of watermelon fruits are pollen limited. According to Klatt et al. (2014), the mechanism behind increased fruit weight for a well pollinated flower is that the stigma needs to be saturated with pollen to maximise the number of ovules that are fertilized. Fertilized ovules produce auxins, which also stimulate the production of gibberellic acid. Both these hormones induce fruit growth by improving cell division and cell size, thereby enhancing fruit weight (Li et al. 2011; Rastogi et al. 2013; Kumari et al. 2018). Our findings concur with several pollinator exclusion experiments, in both wild plants and insect pollinated crops, showing that fruit weight is related to the amount of pollen received on the stigma (Klein et al. 2003; Stein et al. 2017; Stout et al. 2018).

Fruit weight varied significantly between regions and among gardens in an interaction with treatment, suggesting that pollinator limitation is highly variable in space. This suggest that the ambient pollinator availability and agricultural practices found in our system vary both at local and regional scales. These findings are also supported by Moran's I test, which indicated a positive spatial auto-correlation in nearby gardens compared to the more spatially distant ones.

Unmanaged honeybees were the main flower visitors in our focal gardens with average flower visits of 0.61 (± 0.3 SD) per ten minutes (Sawe et al., unpublished data). Similarly, Classen et al. (2014) found that honeybees were the most common flower visitors in coffee open gardens in the same region, although they did not find coffee yield to be limited by pollination services. Other studies (e.g. Winfree et al. 2008), have shown that wild pollinators can be very efficient in crop pollination. In our study areas, documentation of beekeeping or detailed assessment of species diversity of wild pollinators available for pollination of crops is lacking. According to Kasina et al. (2009), the main reason for not managing pollination in developing countries is the lack of understanding of the economic value of pollination services. At the same time, the combinations of wild bees and managed bees has been shown to improve yields in watermelon and other crops (Garibaldi et al. 2013). A study by Sanford and Ellis (1992) showed that watermelon flowers are not always attractive to honeybees especially when other, more attractive plants are flowering nearby. In contrast, other studies have showed that deploying honeybee hives around watermelon gardens during flowering significantly increase yield (Garibaldi et al. 2011). According to Sanford and Ellis (1992) and Delaplane et al. (2000), 4.5 hives are sufficient for pollination of 1-ha watermelon garden. Local farmers could therefore benefit from improved yield by establishing beehives on their farms. However, beekeeping can be costly and laborious (Rucker et al. 2012), and farmers may therefore benefit from facilitating wild pollinators by creating pollinator friendly habitats (Carvalheiro et al. 2012; Bartomeus et al. 2014).

The observed positive relationship between soil organic carbon and fruit initiation and fruit weight can be explained by the role of carbon in improving the fertility as well as the physical and chemical properties of the soil (Fageria, 2012, Adiaha, 2017, Musinguzi et al. 2013). The overall positive influence of soil organic matter on fruit set did not appear to depend on the level of pollination. In contrast, the influence of soil moisture differed among the measured responses, and between the hand-pollinated and the control group. Increased soil moisture was positively related to the probability of an initiated fruit forming a mature fruit, but negatively related to the probability of a flower developing a mature fruit. This suggests that watermelon plants require higher soil moisture to ensure that the initiated fruit develop into a mature fruit, whereas soil moisture is less critical during fruit initiation. The significant interaction effects of pollination status and soil moisture; for example as indicated in Figure 3A, shows little effect of controlling soil moisture without enhancing pollination service in a garden. Optimizing soil conditions is much easier to apply and might be the farmers' first attempt, but our results indicate that both parameters (pollination and soil moisture) need to be optimized in parallel to increase the probability of fruit set. In fact, pollination appears to be the limiting factor in this system, not soil moisture (indicated by the control line in figure 3A, which is stable across the moisture gradient). However, if the plants are sufficiently pollinated, it is worth to optimize the soil conditions towards drier soil.

These findings also suggest that, in presence of sufficient pollination services, rainfall might also lower yields due to increased soil moisture. Therefore, farmers need to select carefully where to grow watermelon during rain seasons, for example by avoiding areas with high water holding capacities.

5. **Conclusions**

We have demonstrated the importance of sufficient pollination for optimal watermelon yields in small-scale farms in northern Tanzania. This is crucial information to agricultural authorities to inform local farmers in our focal area and elsewhere in the world with similar ecological and agricultural settings. Small-scale farmers in the study regions tend to focus on fertilizer application, pesticides and soil moisture improvement to increase yields. This study therefore highlights the importance of incorporating ecosystem services, i.e. pollination, as important input to agricultural productivity. We therefore recommend agriculture authorities to inform local farmers to keep good agricultural practices to improve conditions for pollinators in, and around, their gardens. These practices include limited use of insecticides, increased availability of floral resources at times where the watermelons are not flowering and establishment of nesting sites for e.g. honeybees. Adopting beekeeping might also potentially improve yields, in addition to the honey the managed hives will produce. Better agricultural and land management practices will ensure better crop yields and ultimately farm economy and livelihood of people in these rural communities. Moreover, we observed that soil moisture might have a negative effect during flowering, as it decreases the probability of a flower setting fruit. After the fruit set, on the other hand, water limitation seems to increase fruit abortion. This suggests that farmers should reduce watering during flowering at least in areas with high soil moisture and focus the watering during the fruiting stage. In the presence of sufficient pollination services, soil moisture needs to be optimized to maximize fruit initiation and reduce fruit abortions. This will also have economic implications, as there are normally costs associated with irrigation in the form of fuel for powered generators or charges billed for acquiring water share from village streams. Local farmers should use different means to maintain and improve soil organic carbon/matter for heavier fruits.

Acknowledgement

The Norwegian Government through the Norwegian State Education Loan Fund supported this research. The contribution of A.N. was financed by the Research Council of Norway (project 268415 − NEOPOLL). We thankfully acknowledge the field assistance of Erica Mmuru, Vicent Elisante, Jumanne Kway, Nassoro Kimaro and Msaki David for soil analysis. We thank all farmers who allowed us to use their garden for this study and Professor Douglas Sheil for his valuable comments on earlier drafts of the manuscript.

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Paper II

Enhancing pollination is more effective than increased conventional agriculture inputs for improving watermelon yields

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Abstract

Agricultural practices to improve yields in small-scale farms in Africa usually focus on improving growing conditions for the crops by applying fertilizers, irrigation and/or pesticides. This may however, have limited effect on yield if the availability of effective pollinators is too low.

In this study, we established an experiment to test whether soil fertility, soil moisture and/or pollination was limiting watermelon (*Citrullus lanatus*) yields in Northern Tanzania. We subjected the experimental field to common farming practices while we treated selected plants with extra fertilizer applications, increased irrigation and/or extra pollination in a three-way factorial experiment. One week before harvest, we assessed yield from each plant, quantified as the number of mature fruits and their weights. We also assessed fruit shape since this may affect the market price. For the first fruit ripening on each plant, we also assessed sugar content (brix) and flesh color as measures of fruit quality for human consumption.

Extra pollination significantly increased the probability of a plant producing a second fruit of a size the farmer could sell at the market, and also the fruit sugar content, whereas additional fertilizer applications or increased irrigation did not improve yields. In addition, we did not find significant effects of increased fertilizer or watering on fruit sugar, weight or color.

We concluded that, insufficient pollination is limiting watermelon yields in our experiment and we suggest that this may be a common situation in sub-Saharan Africa. It is therefore critically important that small-scale farmers understand the role of pollinators and understand their importance for agricultural production. Agricultural policies to improve yields in developing countries should therefore also include measures to improve pollination services by giving education and advisory services to farmers on how to develop pollinator friendly habitats in agricultural landscapes.

Key words: fertilizer, irrigation, agriculture, fruit-quality, brix, pollinator-limitation

Introduction

The role played by animal pollinators in agricultural production is largely unknown by the majority of local farmers in Sub Saharan Africa (Eardley et al., 2006; Gollin, 2014), while at the same time it attracts enormous attention in the northern hemisphere (Timberlake and Morgan, 2018). Governments and agricultural stakeholders in Sub Saharan Africa have emphasized the significance of improving soil conditions through fertilization and artificial irrigation to maximize yields in this region (Gollin, 2014; Lema et al., 2014; Güneralp et al., 2017), whereas the potential contribution of pollination for optimizing crop yield has been largely overlooked. According to Klein et al. (2007), 35% of global food production comes from animal pollinated crops, and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have estimated the direct economic contribution of animal pollinators to global agricultural production to be in the range of 5-8% (IPBES 2016). This might seem low, but it constitutes a crucial part of the human diet, because most animal pollinated food plants – such as vegetables and fruits – have high nutritional value, whereas cereals, such as wheat, rice and maize, are wind or self-pollinated (Sulewska et al., 2014). Moreover, insect-pollinated crops have higher economic value and might thus contribute more to farmers' income and countries' Gross Domestic Product (Gallai et al., 2009). Insect-pollination can also significantly improve fruit quality such as fruit shape, sugar content and shelf life (Klatt et al., 2014).

According to Hopwood et al., (2016), most research on crop pollination over the last 20 years have been conducted in developed countries and have mainly focused on how insect-pollination alone can improve yield. There is a general lack of studies addressing multiple yield-limiting factors, such as insufficient pollination, fertilization and/or water availability. Consequently, the degree to which pollination regulates yield in cropping systems is still debated (Ghazoul 2007, Kremen et al. 2008), and the role of pollination relative to water and nutrient limitation, seed quality, pests and diseases is poorly understood (Klein et al. 2015), especially in tropical agro-ecosystems.

In Sub-Saharan Africa, most researchers emphasize low levels of soil nutrients and insufficient rainfall as the main factors responsible for low agriculture production (Sheahan and Barrett, 2017). For these reasons, improving soil conditions, and investing in irrigation schemes, are the focuses for agricultural development to improve yields. This focus on fertilizers and water to increase yield in staple crops such as rice, wheat, maize and potatoes has underpinned the lack of research on pollination deficits in insect-pollinated cash-crops. In Tanzania for example, the use of fertilizer has increased from an average of 5.5 kg/ha in 2004/2005 to 9 kg/ha in 2009/2010 (Mather et al., 2016). This is, however, far below levels reported in Southern Asia (129.4 kg/ha), South East Asia (109.6 kg/ha) and Latin America (104.8 kg/ha) (Senkoro et al., 2017). Efforts to improve irrigation schemes have also been implemented in Tanzania. According to (Mdee et al., 2014) the agricultural area under irrigation in Tanzania has expanded from 150,000 ha in 2003 to 460,000 ha in 2013 and is expected to reach 1 million ha in 2020.

In addition to abiotic factors, insufficient animal-pollination can also put limitations on yields in animal-pollinated crops, since pollen availability can affect fruit and seed set (Delaplane et al., 2000; Willmer, 2011) and fruit quality (Gajc-Wolska et al., 2011; Klatt et al., 2014). However, in most cases, the effects of biotic and abiotic agricultural inputs have been studied independently. Manipulating fertilization and water availability in combination with pollination experiments is rarely done (but see Klein et al. 2015), although this is crucial for understanding the potential of these factors, separately, or in combination, for improving yields.

It is common practice among watermelon growers in North East Tanzania to fertilize their plants at least once during the growing season and irrigate at least once per week (Sawe et al., personal communication). This is in addition to other common farm practices such as pesticide spraying and weeding. Generally, different type varieties of pesticides are used at different rates, depending on type of pests, affordability and knowledge (Sawe et al., personal communication). Watermelon (*Citrullus lanatus* Thunb., Cucurbitaceae) is self-compatible and monoecious, and thus highly dependent on insect pollination for optimal yield (Brewer, 1974; Sanford and Ellis, 2016; Bomfim et al., 2015). Watermelon has become a vital cash crop in Sub-Saharan Africa as its market value has recently increased due to growing demands (Van Ittersum et al., 2016; Makuya et al., 2017), providing households with an extra source of income (Makuya et al., 2017). The main watermelon cultivars (Sukari F1 hybrid and Pato F1) used in the area has the potential of producing two (3-5kg) fruits per plant. We did however, observe that most of the second ripening fruits were too small to achieve a good market price (<1.5 kg) and none of the plants produced more than two fruits reaching this size (Sawe et al., in preparation). Most of the local watermelon growers suggest that low levels of fertilizer and irrigation limit their yields (Sawe et al., in preparation).

In this study, we aimed to assess the relative contribution of enhancing pollination to watermelon yield, – compared to increasing fertilization and irrigation beyond current levels of agricultural inputs by local farmers. We established an experiment and tested the effects of the following three treatments; (i) extra pollination, (ii) extra fertilization and (iii) extra watering, as well as all possible treatment combinations. We compared the plants subjected to the treatments to control plants receiving standard agricultural practice and natural levels of pollination from the local pollinator community. We hypothesized that the combination of extra pollination, extra irrigation and extra fertilization would have positive effects on the quantity and quality of watermelon yields. We tested the effects of our three treatments on fruit initiation, fruit weight, fruit set, fruit sugar content, fruit shape and fruit flesh colour.

Materials and methods

Study area

In August 2017 we established an experiment at Mererani in the Simanjiro-Manyara region in Northern Tanzania (3°36'9.98"S" S, 36°54'37.83"E" E). We selected this particular area because it houses many watermelon growers with well-established irrigation systems. Maize is however the main agriculture crop in this area. Vegetables and fruits are usually grown after the maize harvest or in relatively small agricultural gardens. The area is semi-arid with a mean annual temperature of 24.7ºC and an annual rainfall of 906 mm (Tanzania Meteorological Agency, 2013). The landscape is generally flat and dominated by naturally occurring *Acacia* trees in non-agriculture and residential areas.

Experimental design

To test the effect of our three treatments (extra-pollination, extra fertilization, and extra-watering) on watermelon yields, we prepared a garden of about 0.2 ha by dividing it into 21 square blocks of 25 m^2 each. In each block, we planted 16 seeds of watermelon (F1 Sukari hybrid) at a distance of 1 m from each other (Fig.1) as proposed by seed manufacture and as a practice commonly adopted by most local farmers. Upon germination, we randomly selected two plants as control; similarly, we randomly assigned each treatment and all possible treatment combinations to two plants in each block.

Control: We adopted the practice used by the majority of the watermelon growers around our study area as the control to mimic the regular local farming practices. This includes two rounds of fertilizer applications (10 g/plant of UREA-YaraMila after germination; and 20 g/plant Nitrogen, Phosphorus and Potassium (NPK-YaraMila) during blossom), spraying of pesticides, irrigation and weeding. It is common for farmers to use different types of pesticides for the same or different pest and at different stage of crop development. We subjected all plants in our experiment to the common local field practice. We subjected all plants in our experiment to this common local field practice. The two control plants received no further treatment, whereas each of the other plants selected for the experiment received one of the – or a combination of the – following treatments;

Extra pollination: From the onset of flowering, we conducted daily observations and registered each time a new female flower emerged on the plants. As soon as the flower opened, we hand-pollinated it by rubbing it with anthers loaded with pollen. We collected anthers from male flowers from the same and different plants, ensuring a mixed pollen load that more realistically mimic the natural pollination conditions in this plant. We extra-pollinated all emerging female flowers for three weeks, resulting in a minimum of three and maximum of six female flowers being extra-pollinated per plant.

Extra watering: After onset of germination, each plant subjected to the extra watering treatment received an extra liter of water between the two weekly regular irrigating events.

Extra fertilization: For all plants subjected to the extra fertilization treatment, we added 10 g of Urea one week after the first regular application of fertilizer, and 20 g of NPK one week after the second regular application. This extra fertilization corresponds to a doubling of the regular amount of fertilizers applied by local farmers. Fertilizer addition was preceded by watering to dissolve the fertilizer. Urea and NPK are the major type of fertilizer used by local farmers, moreover soils in this region are known for Nitrogen and Phosphorous deficiency (Okalebo et al. 2007).

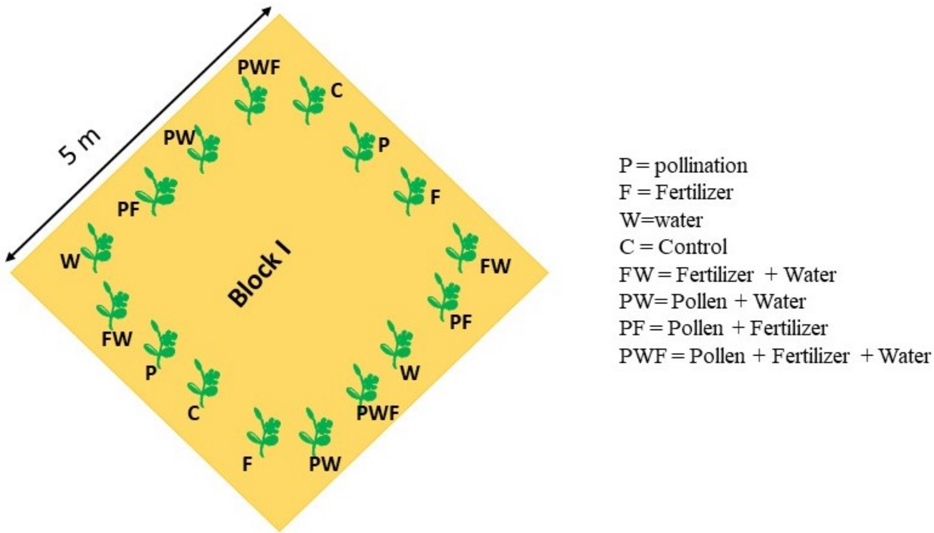

Figure 1: Illustration of the experiment layout with all the treatment combinations, which were the same for all the 21 replicate blocks.

Fruit initiation set and yield quantification

To assess the effect of our treatments on fruit initiation, we counted initiated fruits on all plants twice. We conducted the first assessment towards the end of the second week of flowering and the second at the end of the fourth week of flowering.

One week before harvesting fruits, we counted the number of mature fruits per plant. We also measured the weight of each fruit – using an electronic balance (model: Gourd shaped portable electronic scale, precision=0.0005kg) – and categorized them as the first, second or third, based on the order of appearance of the flower they developed from. We only recorded fruits with weights above 1.5 kg because the farmers consider smaller fruits as unsellable at the market.

Fruit quality assessment

We assessed sugar content of aqueous solution (brix), flesh colour and fruit shape as indicators of fruit quality. We assessed the fruit flesh color and brix from 48 fruits by randomly selecting six fruits from each treatment combination and control (we only selected among the first fruits appearing since not all plants produced more than one fruit). We juiced each fruit and determined brix using a refractometer (model: Grinding Mix Cutting Fluids) at Nelson Mandela Institute of Science and Technology in Arusha, Tanzania. Before juicing the fruit, we bisected the fruit and categorized the color of the flesh as either, “deep red” (high quality), “red” or “pale yellow” (low quality). In addition, we categorized the shape of each fruit as either “normal shape”, “mild misshaped” or “misshaped”, since fruit shape affects the market price.

Data analysis

We conducted initial exploratory analyses of the dataset following (Zuur et al., 2010) to check for outliers and to explore relationships between response variables (i.e. number, weights, fruit shape and sugar content of fruits) and explanatory variables (i.e. fertilizer, irrigation and pollination). We used the statistical software R version 3.3.3 for windows (R Core Team 2017) for all statistical analyses. To build generalized linear mixed models (GLMMs) we used the lme4 library version 1.1-19 (Bates et al., 2015). We used GLMMs with Poisson error distribution and log link function to assess the effect of our treatments on the number of initiated fruits. We included block as a random factor in the models to account for any among-blocks variability.

We analyzed how fruit weight and brix varied in response to our treatments using separate linear mixed models (LMMs), including block as a random factor in the models. Fruit order (first or second fruit) was included as a fixed effect covariate. Using the multinomial function in the nnet library (Ripley et al., 2016) and function in the car library (Fox et al., 2012) we also analyzed likelihood of each treatment predicting fruit shape and fruit color (both being categorical response variables with three levels).

Since our plants had at least one marketable fruit and since most of the subsequent ripening fruits did not attain market quality, we estimated the probability of our plants producing a second fruit that could be sold at the market. We assigned plants with two sellable fruits as “success” and plants with only one or no fruits as “failure”. We used a GLMM with binomial error distribution and log link function to fit a model including all treatments and their combinations as explanatory variables, and included block as a random factor.

We report parameter estimates and associated standard errors and test statistics for Wald Z tests for full models; i.e. we did not carry out any model selection, because we wanted to assess the estimated effect of each main treatment and all treatment combinations, compared to the control reference level. Treatments with associated p-values <0.05 were assessed as statistically different from the control treatment.

Results

Fruit initiation

Average number of initiated fruits two weeks after blossom − across all the treatments − was 0.5 ± 0.9 (SE) (Fig. 2A). Extra-pollination significantly increased the probability of initiating fruit (Table 1); average number of initiated fruits in plants receiving extra pollinated treatment was more than twice as high as for plants receiving only natural pollination (Fig. 2A). In contrast, neither extra fertilizer nor extra water significantly affected initial fruit set two weeks after onset of flowering. None of the combined treatments affected fruit set at this stage. On the other hand, a similar analysis of number of initiated fruits four weeks after onset of flowering revealed that the average number of initiated fruits was higher than at the first fruit set assessment (two weeks after onset of flowering) across all treatments 3.4 (SE ± 0.4) (Fig. 2B). Moreover, the combination of water and fertilizer addition had a negative effect on number of initiated fruits four weeks after onset of flowering, although the effect was only marginally significant (Table 1). The rest of the treatments did not influence fruit initiation at this stage (Table 1).

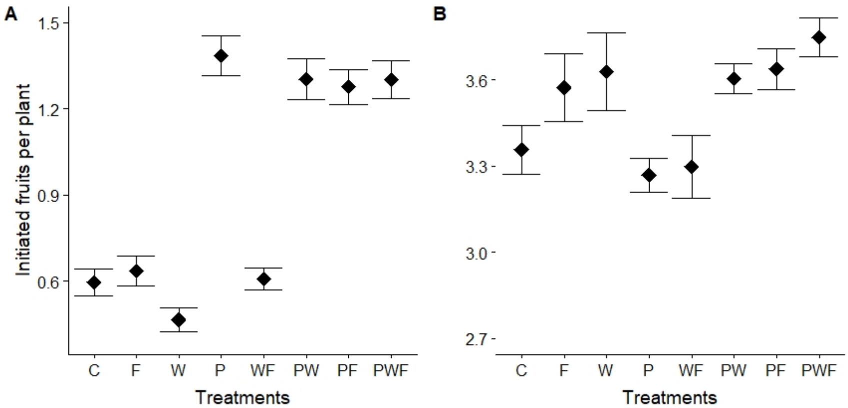

Figure 2: Number of initiated fruits per plant in the (A) 2nd week and the (B) 4th week after blossom. C= control; F = extra fertilizer; P = extra pollination; W = extra water. Other letter combinations correspond to different combined treatments of the three basic treatments. Points and associated error bars are observed means and standard errors.

Table 1: Main and combined effects of applied treatments on number of initiated fruits per plant during first and second initial fruits assessment in a watermelon field in Northern Tanzania. Estimated means and standard errors, and results from Wald Z tests, from a full Generalized Linear Mixed Model with Poisson error distribution and log link function. Response variable was number of initiated fruits. F = extra fertilizer; P = extra pollination; W = extra water.

Explanatory variables	β	SE	z	P
First fruit set assessment (2nd week post-blossom)				
Intercept	-0.69	0.18	-3.90	<0.01
F	0.06	0.14	0.44	0.66
P	0.84	0.11	7.42	<0.01
W	-0.26	0.15	-1.75	0.08
FP	-0.15	0.16	-0.97	0.33
FW	0.22	0.20	1.08	0.28
PW	0.20	0.17	1.21	0.23
FPW	-0.15	0.23	-0.66	0.51
Random effects	***Groups***		***σ***	***SD***
Block	21		0.45	0.67
Second fruit set assessment (4thweek post-blossom)				
Intercept	1.21	0.05	25.01	0.00
F	0.06	0.06	1.08	0.28
P	-0.03	0.05	-0.47	0.64
W	0.08	0.06	1.35	0.18
FP	0.05	0.08	0.62	0.53
FW	-0.16	0.08	-1.93	0.05
PW	0.02	0.08	0.22	0.83
FPW	0.09	0.11	0.85	0.40
Random effects	***Groups***		***σ***	***SD***
Block	21		<0.01	<0.01

Fruit weight

Average fruit weight across all treatment was 3.7 kg (Fig. 3A). Neither of the treatments affected fruit weight, but the second fruit was 42% lighter than the first (Table 2, Fig. 3B).

Table 2: Main and combined effects of applied treatments on fruit weight in a watermelon field in Northern Tanzania. Estimated means and standard errors, and results from Wald Z tests, from a full Linear Mixed Model with Gaussian error distribution and identity link function. Response variable was fruit weight (kg). F = extra fertilizer; P = extra pollination; W = extra water.

Explanatory variables	**β**	**SE**	**z**	**P**
Intercept	3.67	0.21	17.24	<0.01
F	0.13	0.28	0.48	0.63
P	0.10	0.26	0.39	0.70
W	0.41	0.28	1.50	0.13
FP	-0.31	0.37	-0.84	0.40
FW	-0.48	0.39	-1.24	0.21
PW	-0.41	0.37	-1.11	0.27
FPW	0.47	0.52	0.90	0.37
2^{nd} Fruit	-1.53	0.18	-8.61	<0.001
Random effects	***Groups***		***σ***	***SD***
Block	21		0.12	0.35

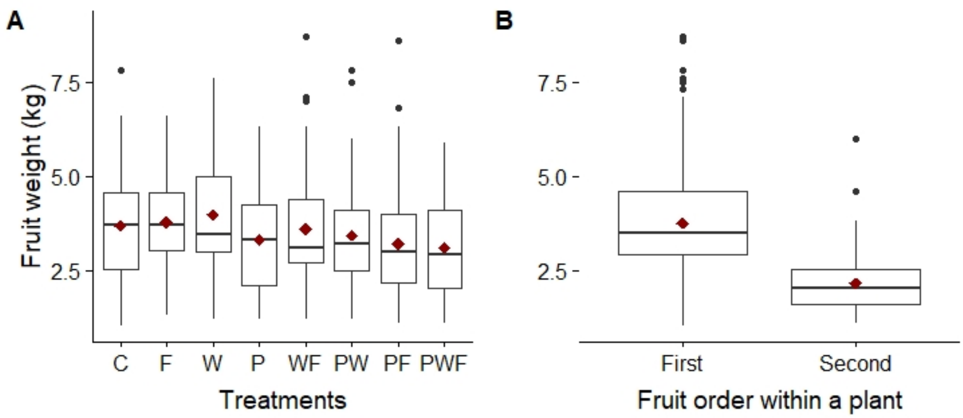

Figure 3: Fruit weight (A) in different treatments and (B) of first and second fruit on the same watermelon plant. C = Control; F = extra fertilizer; P = extra pollination; W = extra water. Other letter combinations correspond to different combined treatments of the three basic treatments. Boxplots showing observed medians (midline), observed means (red diamonds), and the 75th and 25th percentiles (upper and lower limits of the box). The whiskers extend *up to* 1.5 times the interquartile range from the top (bottom) of the box to the furthest weight

within that distance; if there are any data beyond that distance, they are represented individually as points.

Probability of producing a second marketable fruit

Irrespective of the treatments, all plants produced at least one marketable fruit. In our analyses, we therefore focused on the probability of producing a second marketable fruit, as none of the plants had more than two marketable fruits at the time of harvest. Overall 43% of the plants produced two fruits. The average number of marketable fruits per plant across the treatments was 1.1 (SE±0.6); but there was a substantial difference among treatments, whereby plants receiving extra pollination treatment had 20% higher probability of producing a second marketable fruit (Table 3, Fig.4). In contrast, we observed no significant effects of either extra water, extra fertilizer, or any combination of treatment effects.

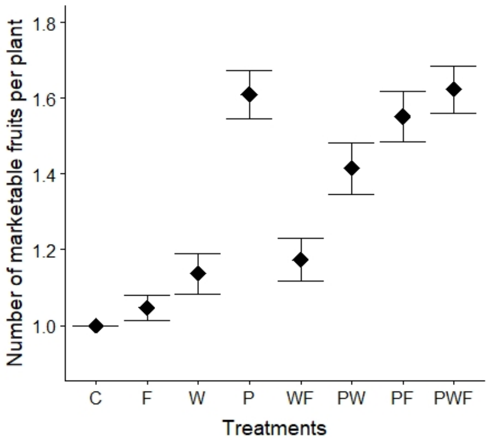

Figure 4: Average number of marketable watermelon fruits per plant. C = Control; F = extra fertilizer; P = extra pollination; W = extra water. Other letter combinations correspond to different combined treatments of the three basic treatments. Points and associated error bars are observed means and standard errors.

Table 3: Main and combined effects of applied treatments on the probability of a plant individual developing a second marketable fruit in a watermelon field in Northern Tanzania. Estimated means and standard errors, and results from Wald Z tests, from a full Generalized Linear Mixed Model with binomial error distribution and logit link function, with binary response (fruit vs no fruit). F = extra fertilizer; P = extra pollination; W = extra water.

Explanatory variables	**β**	**SE**	**z**	**P**
Intercept	0.69	0.19	3.67	<0.01
F	0.05	0.27	0.18	0.86
P	0.92	0.29	3.13	<0.01
W	0.14	0.27	0.52	0.60
FP	-0.16	0.41	-0.40	0.69
FW	0.00	0.38	0.01	0.99
PW	-0.49	0.41	-1.21	0.23
FPW	0.52	0.58	0.90	0.37
Random effects	**Groups**		**σ**	**SD**
Block	21		<0.01	<0.01

Fruit quality

Average amount of fruit sugar content was 13.6 °Bx (SE ±0.68) (Table 4, Fig. 5). Extra-pollination significantly increased the sugar content by approximately 10%, compared to the control treatment, while neither extra water. Extra fertilizer, nor any of the treatment combinations had any effect. None of the treatments affected fruit shape nor flesh colour.

Table 4: Main and combined effects of the applied treatments on the amount of sugar (brix) in the fruits in a watermelon field in Northern Tanzania. Estimated means and standard errors, and results from Wald Z tests, from a full Linear Mixed Model with Gaussian error distribution and identity link function. Response variable was sugar content (brix). F = extra fertilizer; P = extra pollination; W = extra water.

Explanatory variables	**β**	**SE**	**z**	**P**
Intercept	13.56	0.68	20.03	<0.01
F	-0.47	0.77	-0.61	0.54
P	1.70	0.79	2.15	0.03
W	1.12	0.79	1.42	0.16
FP	0.08	1.09	0.08	0.94
FW	0.16	1.09	0.15	0.88
PW	-1.36	1.10	-1.24	0.22
FPW	1.30	1.54	0.84	0.40
Random effects	**Groups**		**σ**	**SD**
Block	21		1.15	1.07
Residual			1.78	1.33

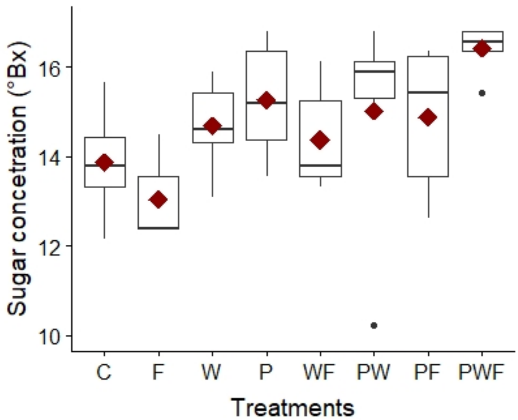

Figure 5: Sugar concentration in fruits. C = Control; F = extra fertilizer; P = extra pollination; W = extra water. Other letter combinations correspond to different combined treatments of the three basic treatments. Boxplots showing observed medians (midline) and observed means (red diamonds).

Discussion

Our results suggest that under current fertilizer application and irrigation schemes, insufficient pollination is limiting watermelon yield, in particular the probability of a plant producing a second sellable fruit. In contrast, we found that increased fertilization and irrigation levels, i.e. increased beyond the levels applied by local farmers, did not improve watermelon yields in our experimental garden in northern Tanzania, neither in terms of quantity nor quality.

Most farmers in Sub-Saharan Africa are small-holders with limited access to fertilizers and irrigation due to limited monetary and technological resources. Indeed, when asked about the causes of decline in agriculture production (not specified to type of crop), soil nutrients were the most frequently mentioned factor by local farmers in our study area (60% of 147 interviewed farmers, Sawe et al. in preparation). No one of the interviewed farmers mentioned insufficient pollination as a potential cause (Sawe et al. in preparation).

We observed higher initial fruit set in extra-pollinated plants at the first assessment, and this indicates insufficient pollination early in the flowering season. This might be a result of a low flower density that fails to attract sufficient pollinators during the early stages of flowering (Essenberg, 2012). Experimentally increased nutrient and water availability did not affect fruit initiation, suggesting that current levels of watering and fertilization are sufficient for initial fruit set. During the second fruit initiation assessment, we observed a general increase in fruit set, and at this stage extra-pollination did not enhance fruit initiation. This indicates that natural levels of insect pollination increased later in the flowering season. We suggest that increased flower density within the watermelon field later in the flowering season attracted more flower visitors to the field from surrounding areas (Nielsen et al., 2012; Russo et al., 2013; Hegland, 2014). We also observed a negative effect of the combined treatment of water and fertilizer addition on fruit initiation during the second assessment. In a previous study, we found separate negative relationships between − respectively − increased soil moisture and soil potassium concentrations and the probability of watermelon plants initiating fruits (Sawe et al., under revision). Findings from the current experiment suggest that the water and fertilizer levels normally applied by farmers (i.e. those received by the control plants) are above the plant threshold requirements for fruit initiation.

Neither extra pollination, fertilization nor watering affected fruit weight in our experiment. This does not necessarily indicate that fertilizer, water and pollination is unimportant for watermelon fruit development. However, our results suggest that current levels of fertilizer addition, irrigation and insect pollination are not limiting fruit weight. This contradicts the findings of Sabo et al. (2013), who observed that fertilizer addition caused heavier watermelons in Nigeria, and those of Erdem & Yuksel (2003) and Fuentes et al, (2018) who found that fruit weight of watermelon increased with irrigation. Brewer (1974) found an increase in fruit weight in watermelon in response to increased flower visitation rates, suggesting that pollination might play a role also for fruit size. Studies on other crops, such as tomatoes, kiwi, apples and strawberries have also found that fruit weight increases with enhanced pollination (Miñarro and Twizell, 2015; Abrol et al., 2017; Çolak et al., 2017).

The first fruits to emerge were heavier than the second fruit at the time of harvest, irrespective of treatment. Most of the second fruits were not mature, and they might have grown to a larger size if given more time to develop. However, in our study area, farmers harvest the watermelon fields only once, due to the limited yield after the main harvest and the high labor costs related to harvesting.

Extra-pollination significantly increased the probability of a plant producing a second marketable fruit, while additional water or fertilizer had no effect. Several other studies have shown that fruit set increases with insect pollination in other insect-pollinated crops (Klein et al., 2003; Klein et al., 2007; Garibaldi et al., 2013). The role of pollination on physiological mechanisms driving resource allocation during fruit development within a plant is well understood (Roussos et al., 2009; Klatt et al., 2014; Wietzke et al., 2018). Watermelon plants can inhibit the development of additional flowers and fruits and allocate their resources to the first initiated fruits (Sanford and Ellis, 2016; Mussen and Thorp, 1997; Delaplane et al., 2000). This suggests that increasing pollinator availability may not necessarily increase fruit initiation and development since plants allocate their resource to early initiated fruits. Therefore, since farmers harvest only once, early fruit initiation is crucial since fruits initiating later will not reach marketable size by the time of harvest. In our first assessment of fruit initiation, we found increased fruit set in extra-pollinated plants, whereas in the second assessment, fruit initiation did not differ among treatments. This suggests that the probability of developing a second marketable fruit is constrained by pollinator availability early in the flowering season. We suggest that in our study system, this is not related to the effective pollination period. We suggest that such early-season pollen limitation may be due to density-dependent processes affecting our focal plants' attractiveness as a forage resource for the local pollinator community. Presence of other plants such as *Acacia* trees and other flowering agricultural crops around our study site could be an explanation for limited pollinator visitation in watermelon flowers. This hypothesized relationship between pollinator attractiveness at particular times during flowering, and number of fruits produced, might also be relevant for other insect-pollinated crops, but we are not aware of other studies addressing this issue.

Previous studies of pollination of watermelon plants have proposed deploying honey bee hives on commencement and throughout the blossom period to increase the chance of all flowers being pollinated (Taha and Bayoumi 2009). In addition, Adlerz (1966) suggested that, increasing number of honeybees increase resource competition and hence time spent per flower. Sawe et al. (in preparation) found that unmanaged honeybees were the main (87%) visitors of watermelon flowers in this region; on average 0.46 (± 0.02 SE) flower visits by honeybees per ten minutes were observed (N = 23 gardens).

Extra pollination increased fruit sugar concentration, while increased watering and fertilizer application did not. This is in line with other studies documenting positive effects of pollination on fruit sugar content in oilseed rape (Bommarco et al., 2012), cucumber (Gajc-Wolska et al., 2011), strawberries (Klatt et al., 2014) and muskmelon (Al-Mefleh et al., 2012). In contrast, Cabello et al., (2009) suggested moderate use of water and nitrogen fertilizer on watermelon since they did not find any positive effects on fruit quality, including sugar concentration. On the other hand, for tomatoes, no (Arbex de Castro Vilas Boas et al., 2017) and even negative effects (Delazari et al., 2016) of increased watering on sugar concentration have been reported. These contrasting results imply that optimal watering and fertilization regimes for improving fruit sugar content in watermelon and other fruits depend on local environmental conditions.

None of our treatments affected fruit flesh color or fruit shape. Both color and shape are important qualities that influence the market price of watermelons and other fruits. Positive effects of pollination services on fruit shape have been reported in e.g. apples and raspberries (Matsumoto et al., 2012; Garratt et al., 2014; Sáez et al., 2014; Pashte and Kulkarni, 2015; Çolak et al., 2017). Sufficient pollination can therefore increase farmer’s revenue through increased fruit quality. We found misshaped fruits on some of our experimental plants, but since the treatments did not affect the probability of misshape, we suggest that other factors, such as frugivorous insects, might play a more important role for fruit shape than pollination, soil nutrients and water availability.

Conclusion

We have shown that increase in conventional agricultural inputs (increased fertilization and water) beyond the levels typically applied by local farmers had no effect on the numbers weight or quality of watermelon fruits produced in Northern Tanzania. In contrast, enhanced pollination early in the flowering season increased the number of fruits that attained market size, and fruits from extra-pollinated flowers had higher sugar content. Thus, insufficient insect pollination is probably the main limiting factor for optimal yield in our study area. Our results suggest that there is a substantial need of a higher awareness of insect pollination as a crucial factor to increase agricultural production in Northern Tanzania, both among local farmers and agricultural authorities, and most likely also in other parts of Sub-Saharan Africa. We therefore suggest that agricultural authorities encourage a mind shift among local farmers from focusing mainly on nutrients and water addition to considering insect-pollination as an important factor for improving yield. Moreover, agriculture authorities should help local farmers to develop management strategies, which will enhance pollinator availability from the early flowering stage. This can be achieved through; improvement of local pollinator habitats (Aslan et al., 2016), deployment of honeybees hives (Hoover and Ovinge, 2018), and increasing flowering resources such as flower strips to attract pollinators (Rundlöf et al., 2018) and at the same time ensuring low or no competition for flower resources (Holzschuh et al., 2011).

Authors` contribution

ØT conceived the ideas and AN, ØT, KE and SM designed the study and data collection protocols together with TS; TS collected the data; TS and AN analyzed the data; TS led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Acknowledgement

The Norwegian Government through the Norwegian State Education Loan Fund supported this research. The contribution of A.N. was financed by the Research Council of Norway (project 268415 − NEOPOLL). We thankfully acknowledge the field assistance of Stella Swai, James Mollel, Charles Laizer and Dr Athanasia Matemu for fruit quality analysis.

Conflict of Interest

None

Data Accessibility Statement

Data for this study will be archived in the Dryad Digital Repository

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Paper III

Tree cover, wild floral resources and pesticides affect crop pollination and yield in small-scale agroforestry systems in Tanzania

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Abstract

Entomophilous crops depend on pollination services for optimal yield. To determine which groups of insects visited watermelon flowers and to understand the relationships between flower visitation, agricultural practices and field-specific environmental context, we studied insects visiting watermelon flowers in 23 small-scale agroforestry fields in north-east Tanzania, from July to November 2016. In addition, we measured the yield; i.e. number of fruits and fruit weight in each field. We found that honeybees were the main visitors (87.8 %) of watermelon flowers, followed by hoverflies (8.5%) and other hymenoptera (i.e, wild bees from the *Eucera* genus and wasps) (3.7%). The frequency of visits by honeybees to watermelon decreased with tree cover in the surrounding landscape, but the negative impact of tree cover was weaker at high abundances of co-occurring (wild)flowers in the observation plots. The probability of receiving zero honeybee visits followed a bimodal pattern, with the highest chance of observing no honeybee visits in plots with no or few co-occurring flowers, and in plots with the highest observed abundances of co-occurring flowers. Flower visitation frequency was highest in the morning, intermediate mid-day, and lowest in the evening. Flower visitation frequency by honeybees also depended on the number of pesticide applications per week; there was little difference between none and one application per week but increasing to 3-4 applications per week reduced visitation by about 50%. Number of fruits per plant increased with the number of honeybee visits, but was negatively related to average fruit weight, suggesting a trade-off between fruit size and number. The seemingly alarming negative impact of pesticide use on flower visits by bees needs to be addressed by the responsible management authorities, who should explore the drivers of observed pesticide practices, and aim to develop a sustainable strategy for managing pests and ensuring increased agriculture yield.

Keywords: Pesticides, pollination, flower-visitors, agriculture, tree cover and agroforestry

Introduction

Globally, the yields from 70% of the most important crops, accounting for 35% of all agriculture production, benefit to some extent from animal pollination (Klein et al. 2007). According to the IPBES (2016), animal pollination is an ecosystem service in decline, a conclusion based on numerous studies (e.g. Potts et al. 2010, Lautenbach et al. 2012, Vanbergen and Initiative 2013, Smith et al. 2015). Managed honeybees have been widely used to compensate declining pollination services from wild pollinators (Garibaldi et al. 2009, Garibaldi et al. 2011). However, recent studies have shown that both wild bees and non-bee insects provide substantial pollination services to many crops and complement each other through varying spatio-temporal foraging behaviours (Winfree et al. 2008, Garibaldi 2014, Pisanty et al. 2016, Hodgkiss et al. 2018). In addition, managed honeybees are susceptible to attack by parasitic *Varroa* mites (Abbo et al. 2017), deformed wing virus (Roberts et al. 2017) and occasional extreme mortality rates, such as colony collapse disorder (Vanengelsdorp et al. 2009). Still, pollination is a non-managed ecosystem service in many parts of the world. In areas where crop pollination entirely depends on the wild pollinator community, measures for safeguarding pollination services is required.

Measures to promote pollination services from wild insects include maintaining or re-establishing natural habitats surrounding agriculture land. Studies have shown pollination services to increase with the proportion of tree cover, and other semi-natural elements, in the surrounding landscape (Black 2008, Carvalheiro et al. 2010, Carvalheiro et al. 2012). This is due to the ability of natural habitats to provide floral and nesting resources for abundant and diverse pollinator communities (Hoehn et al. 2008). Managed pollinators might also benefit from access to wild floral resources despite their lower dependence on natural habitats and landscape configuration (Bartomeus et al. 2014). Carvalheiro et al. (2014) demonstrated that plants sharing flower visitors can influence each other's pollination. Increased co-flowering resources in or proximate to agriculture fields can results in facilitative or competitive interactions among wild and crop plants, for pollinator services. Competition for flower visitors among co-flowering plants is largely driven by the quality and quantity of floral resources resulting in one plant attracting visitors from the other (Mitchell et al. 2009, Morales and Traveset 2009). Studies have also documented facilitative effects, showing that increased amounts and diversity of floral resources may attract flower visitors towards crop plants (Campbell et al. 2017, Sutter et al. 2017, Rundlöf et al. 2018). The strength and direction (facilitative or competitive) of these interactions are, however, complex and both context and scale dependent (Hegland 2014).

Pesticide use in agricultural fields can have negative effects on both target and non-target species, including pollinators (Sponsler et al. 2019). For example, pesticides are reported to not only kill pollinators directly (Marion-Poll et al. 2010), but also to have sub-lethal effects such as reduced reproductive ability (Williams et al. 2015), impaired learning and memory loss (Stanley et al. 2015, Lamsa et al. 2018, Siviter et al. 2018). In many high and middle-income countries, pesticides that pose high risk to both human and environmental health, such as organochlorine, organophosphate and carbamate, have been banned (CBD 2016). However, old-fashion pesticides are still used in many parts of the developing world, including sub-Saharan Africa (Tomlin 2009), where their effects on pollinators and other non-targeted organisms have not been documented. The general perception of low-input agriculture, assuming limited pesticide application, has − most likely − caused this potential problem to receive little attention in the developing world. For example, Williamson et al. (2008) reported low levels of pesticide use in agriculture in sub-Saharan Africa countries compared to Latin America and Asia. However, Adjognon (et al. 2017) argue that this is a mere speculation, due to lack of sufficient data.

Crop pollination is context dependent and is likely to be affected by agricultural practices and local environmental conditions (IPBES 2016). For example, pesticides can have negative effects on non-target organisms such as pollinators (Sponsler et al. 2019), while at the same time playing a major role in protecting crops against pests (Oerke 2006). Maintaining both the agricultural production and important ecosystem functions in a landscape requires understanding how the different ecological components interact and how any human intervention, such as pesticide use, may influence ecosystem functions and services.

In Tanzania, the majority of local people depend on small-scale agriculture (Anderson et al. 2016). Farmers use different practices, which vary among regions, planted crops and available resources. In Northern Tanzania, the majority of local farmers practice hedgerow agroforestry (i.e. growing trees at the farm margins) and the use of pesticides is common. In 23 watermelon fields, we explored potential relationships between number of insect visits to watermelon flowers and pesticide application frequency, amount of surrounding tree cover, field size, position in field, and abundance of co-occurring flowers. In addition, we assessed the potential relationship between watermelon yield in each field and observed flower visitations. We aimed to answer the following questions: (i) What are the main groups of insects visiting watermelon flowers in this system? (ii) Does the number of flowers of co- occurring plants affect watermelon flower visitation? (iii) Does the proportion of tree cover surrounding the field affect watermelon flower visitation? (iv) Does the number of pesticide applications per week affect flower visitation? and (v) Are watermelon yields related to observed flower visitation frequency?

Methods

Study area

This study was conducted in the Arusha and Kilimanjaro regions in northeast Tanzania from July to November 2016. Agroforestry (i.e. trees integrated in agriculture) type of farming is common in these regions, and the main crops grown by farmers include vegetables, fruits (e.g. watermelon and banana), ornamental flowers and coffee. We collected our data from 23 watermelon fields with approximately rectangular shape, distributed among five sites throughout the study area. The fields ranged from 0.5 - 2 ha in size, with distances from one field to another within site ranging from 0.8 - 4.2 km, whereas the distances from one site to another ranged from 11- 83 km. The number of fields within a site was 4 or 5, depending on availability during the study period.

In each watermelon field, we did all observations both at the edge and in the centre of the field to account for any edge effects (i.e. effects of distance to more natural habitats). In each watermelon field, we collected the following data;

Flower visitation observations

To estimate flower visitation frequency (i.e. the number of visits per flower per 10 minutes) we observed flower visits by insects to watermelon flowers in each field three times per day: morning (8:30-11:30), mid-day (11:30-14:30), and evening (14:30-17:30). Two observers conducted simultaneous observation sessions in the same field; one observer at the edge and one observer at the centre of the field. To avoid observer bias, the observers switched between recording flower visits at the edge and in the centre of the field. We observed each field for 5 days, giving 30 observation sessions per field and 690 observation sessions for the 23 fields altogether. Every time we visited a field, we randomly established one 1-m^2 observation plot in the centre and one at the edge. In each plot, we counted the number of watermelon flowers and the number of non-watermelon flowers.

In each observation session, we observed the watermelon flowers in the 1-m^2 plot for ten minutes, and recorded the type of insect visitor (honeybee, other hymenoptera, or diptera), and whether the visits were to male or female flowers.

To determine the diversity of watermelon flower visitors in each field, we walked in straight lines (transects) across the field for ten minutes (after the flower visitation recordings had been made) to record flower visitors throughout the entire field. Along these transects, honeybees were recorded, but not collected, whereas other insects that were detected visiting watermelon flowers were collected with sweep nets and stored in 90% ethanol for species identification in the laboratory. We brought the collected flower-visiting insects to the entomology lab at the Norwegian University of Life Sciences, where they were identified to genera by M. A. K. Sydenham.

Watermelon yield

During blossom, we selected and marked 20 plants in each watermelon field, i.e. 10 at the edge and 10 in the centre, for yield quantification. Approximately one week before harvest, we counted the number of fruits on each focal plant and measured the weight of each fruit.

Pesticide application practices

We visited the fields on days of pesticide application to record the type of pesticides (insecticide, herbicide and fungicide) used, amount applied and to get information from the farmers about the frequency of spraying. We also interviewed the farmers to obtain similar information for the pre-blossom periods.

Remote sensing data

To estimate amount of tree cover in the surroundings of each field, we performed a land cover classification over the extent of the study sites using satellite remote sensing. Using Google Earth Engine (GEE) (Gorelick et al. 2017) we obtained Sentinel 2 top of atmosphere satellite imagery acquired during the period of study (June-November 2016). Sentinel scenes have been orthorectified and radiometrically corrected by GEE and were masked for cloud cover using the ‘pixel_qa’ band. We performed a supervised classification by manually digitizing points over tree, agricultural and urban land cover classes and training a Random Forest machine learning classifier. Points were digitized within the GEE JavaScript console with very visual interpretation of very high-resolution Digital Globe satellite imagery as a base layer. With the resulting land cover map, we extracted the proportion of tree cover pixels at six different radii (250m, 500m, 750m, 1000m, 1500m and 2000m) around each watermelon field.

Data analysis

We conducted initial exploratory analyses of the dataset following Zuur et al. (2010) to check for outliers and collinearity between candidate explanatory variables, and to explore potential relationships between response variables and explanatory variables. We did not detect outliers (i.e. extreme observations that could influence estimation) in our data, and highly correlated candidate explanatory variables ($r \geq 0.7$) were not included in the same model. We used the statistical software R version 3.6.0 for Windows for all exploratory and statistical analyses (R Core Team 2017).

We carried out a pre-selection of explanatory variables by fitting single-variable models for individual relationships between our response variables and each candidate explanatory variable. Only variables that were significantly related ($p < 0.05$) to the response in the single-variable models were included in the full (most complex) models. The main rationale for this pre-selection of variables was to identify which one of the six tree cover radii, had the strongest signal on the response, since the tree cover variables were strongly correlated. Another rationale for the pre-selection was to avoid overly complex models.

Model selection was carried out by backward elimination whereby only explanatory variables that statically influenced the response variable at ($P< 0.05$) or trending towards significance ($P< 0.10$) were retained in the final models. To assess the robustness of our results, we also carried out model selection based on AIC values; for each response variable, the model with lowest AIC (Burnham and Anderson 2002) value was identical to the final model selected by backward elimination.

Number of flower visits

The response variable ‘number of flower visits by insects per 10 minutes’ was heavily zero-inflated. To assess the potential relationship between number of visits and candidate explanatory variables we fitted zero inflated mixed models with negative binomial distribution using glmmTMB package (Brooks et al. 2017). Zero inflated models consisted of two parts, which are fitted simultaneously; 1) a zero-inflated model (with logit link function, assuming binomial distribution of errors), to determine what explanatory variables influenced the probability of observing zero visits, and 2) a conditional model (with log link function, assuming a negative binomial distribution of errors), to determine what explanatory variables influenced the number of visitors, given that there were ≥ 1 visits. We used the following explanatory variables to build the most complex models; type of flower visitor (Honeybee, other Hymeotera, or Diptera), position in field (edge or centre), number of pesticides sprayings (per week), proportion of tree cover, field size and the number of flowers of co-occurring plants within the observation plot. In addition, we also included the following interactions; (i) Proportion of tree cover x Number of flowers of co-occurring plants (ii) Proportion of tree cover x Position in field (iii) Pesticides sprayings x Position in field (iv) Number of flowers of co-occurring plants x Position in field and (v) Field size x Position within field as explanatory terms. We included number of watermelon flowers per observation session (plot) as an offset variable in all models (Reitan and Nielsen 2016). To account for the hierarchical study design and the spatial variation among regions, sites and fields, as well as the temporal variation (i.e., observation days), we included region, site, field and observation day, as nested random variables in the model.

Number of fruits per plant

We analysed number of fruits per plant by assuming a Poisson distribution of errors and log link function to fit generalized linear mixed model (GLMMs) in the lme4 library in R (Bates et al., 2015). We included the maximum number of female flowers – i.e. the potential number of mature fruits – as an offset variable. We included position in field (edge or centre), number of flower visits by insects, field size and all possible two and three-way interactions as fixed explanatory variables in the full (most complex) model. Explanatory variables, which were found to influence the probability and number of flower visits by insects (see Table 1), were not included as explanatory variables in the full model. Region, site, field and plant identity, were included as nested random variables.

Results

Flower visitors in field transects

From the 10 minutes transect walks conducted to assess the diversity of flower visitors we counted 3657 (87.8%) honeybees, 132 (8.5%) hoverflies (Diptera: Syrphidae) and other Hymenoptera (3.7%) which includes; 17 individuals from the *Eucera* genus (family Apidae), and 15 wasps.

Flower visitors in observation plots

Honeybees also carried out 87% of the total observed visits to watermelon flowers. Therefore, we decided to exclude the other observed groups of flower visiting insects from the analyses. The best model explaining flower visits by honeybees to watermelon flowers showed a negative influence of number of pesticide applications per week and a peak in flower visits in the morning (Table 1).

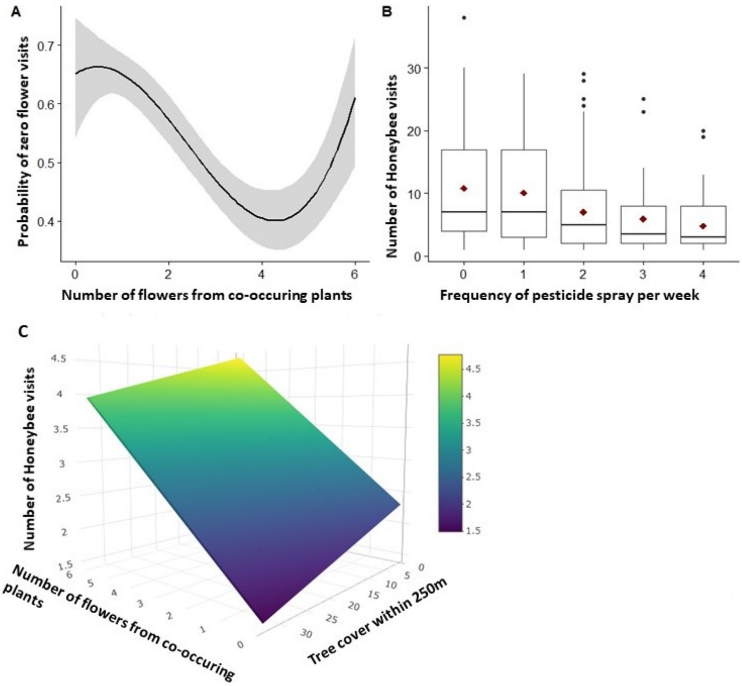

Figure 1. *(A) Probability of observing zero honeybee visits (per 10-min observation sessions) in relation to abundance of flowers of co-occurring plants in the 1-m*^{2} *observation plot. The solid line is the predicted relationship and shaded areas show 95% confidence limits. (B) Number of honeybee visits (per 10-min observation sessions) in relation to frequency of pesticide spraying. Boxplots showing observed medians (midline), observed means (red diamonds), and the 75th and 25th percentiles (upper and lower limits of the box). (C) Interacting influences of Number of flowers of co-occurring plants and Tree cover within 250m on honeybee visits. The colour gradients correspond to Honeybee visits values, ranging from low values (deep blue) to high values (green).*

Flower visits by honeybees to watermelon flowers was also influenced by tree cover and the number of flowers of co-occurring plants in the observation plots, but not by field size nor position within the field (centre or edge) (Table 1). The probability of zero flower visits (by honeybees) was highest at very low abundance of flowers of co-occurring plants, and decreased with increasing abundance, but at abundances of >5 co-occurring flowers per 1-m^2 observation plot, the probability of zero visits increased again (Table 1, Figure 1A). In other words, the chances that the watermelon flowers would receive flower visits from honeybees was at the highest when there were intermediate numbers of flowers of co-occurring plants.

Table 1. Agricultural practice and environmental context variables influencing visitation by honeybees to watermelon flowers in 1-m^2 observation plots in 23 watermelon fields in northeast Tanzania; the response in the zero-inflated model is the predicted probability of observing zero visits by honeybees (per 10-min observation sessions), whereas the response in the conditional model is the number of visits (given that ≥1 visit was observed). Parameter estimates, test statistics and associated p-values for the final model. Explanatory variables in the final model: frequency of pesticide sprayings (0,1,2,3,4), number of flowers of co-occurring plants in the 1-m^2 observation plot, time-of-day (morning/mid-day/evening), and proportion of tree cover in a 250 m radius surrounding the field.

	β	**SE**	**z**	**P**
Zero-inflated model				
Intercept	-2.66	1.14	-2.34	0.02
Number of co-occurring flowers	-0.38	0.09	-4.11	<0.01
Conditional model				
Intercept	-1.68	0.45	-3.76	<0.01
Time-of-day: morning (*vs* evening)	2.46	0.24	10.36	<0.01
Time-of-day: mid-day (*vs* evening)	1.98	0.24	8.32	<0.01
Number of co-occurring flowers	-0.05	0.04	-1.10	0.27
Tree cover in 250 m radius (Tree cover)	-0.03	0.02	-2.12	0.03
Pesticide sprayings (1) (*vs* 0)	-0.27	0.36	-0.76	0.45
Pesticide sprayings (2) (*vs* 0)	-0.60	0.33	-1.80	0.07
Pesticide sprayings (3) (*vs* 0)	-0.74	0.36	-2.04	0.04
Pesticide sprayings (4) (*vs* 0)	-1.23	0.37	-3.34	<0.01
Number of co-occurring flowers × Tree cover	0.01	0.01	1.91	0.01
Random effects		**Groups**	**σ**	**SD**
Observation day		5	0.04	0.19
Field ID		23	0.03	0.18
Site ID		5	0.01	0.09
Region ID		2	0.02	0.12

The number of visits by honeybees depended on the number of pesticide sprayings per week; there was little difference between zero and one spraying per week but increasing to 3 or 4 sprayings per week reduced visitation significantly (Table 1, Figure 1B). The number of visits was highest in the morning, intermediate mid-day, and reduced to less than 50% in the evening (compared to the number of morning visits) (Table 1). Number of honeybee visits increased with number of flowers of co-occurring plants (given that ≥1 was observed) and decreased with tree cover within 250m radius (Figure 1C). However, the influence of co-occurring flowers depended on tree cover, and *vice versa*; for example, the difference in number of visits to watermelon flowers between plots with high *vs.* low tree cover in its surroundings was smaller when there was a high number of co-occurring flowers (Table 1, Figure 1C).

Relationship between flower visits and watermelon yield

Number of fruits per plant

The best model for explaining number of fruits per plant included the explanatory variables average number of flower visits by honeybees and fruit weight. Number of fruits per plant increased with the frequency of honeybee visits, moreover, plants with few fruits appeared to have heavier fruits (Table 2, Figure 2).

Table 2. Factors influencing number of watermelon fruits per plant. Results from a generalized linear mixed model (GLMMs) with a Poisson distribution of errors and log link function.

	β	**SE**	**z**	**P**
Intercept	-1.38	0.10	-14.41	<0.01
Average flower visitation frequency	0.23	0.09	-6.59	<0.01
Average fruit weight	-0.07	0.02	3.95	<0.01
Random effects		**Groups**	**σ**	**SD**
Region ID		2	<0.01	<0.01
Site ID		5	0.2	0.34
Field ID		21	0.02	0.15
Plant ID		10	0.01	0.1

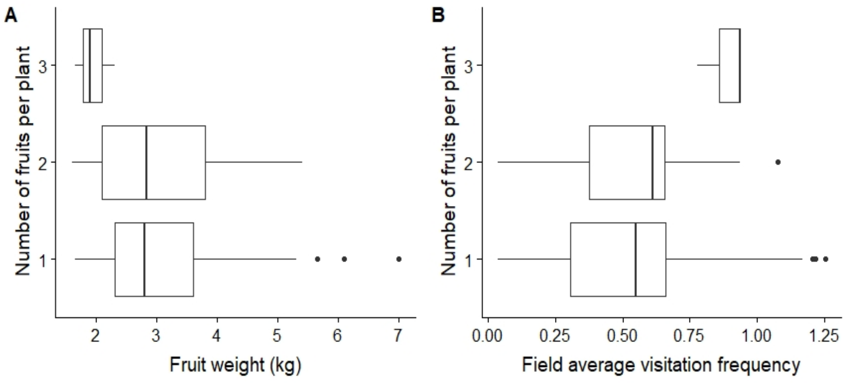

Figure 2. *Relationship between counted number of fruits per plant and (A) observed fruit weight (kg) (B) honeybees visitation frequency. The vertical bars in the box-plots are observed medians.*

Discussion

Revisiting our research questions, we found that (i) honeybees was by far the most common group of visitors to watermelon flowers in our study system. Among watermelon flowers that received honeybee visits, the number (frequency) of visits (ii) increased with number of flowers of co-occurring plants and (iii) decreased with tree cover, but the negative impact of tree cover was weaker at high abundances of co-occurring flowers. The probability of receiving zero honeybee visits followed a bimodal pattern, with the highest chance of observing no honeybee visits in plots with 0–1, or six (maximum number observed), co-occurring flowers. We observed (iv) a decline in the number (frequency) of flower visits by honeybees as levels of pesticide application increased. We also found that (v) number of fruits per plant were positively related to the frequency of honeybee visits, and negatively related to fruit weight. In addition, our results showed that visitation to watermelon flowers decreased throughout the day and that neither field size nor position within the field influenced the frequency of flower visits.

Several studies have documented watermelon flowers to be visited by various insects including bees (Winfree et al. 2008, Njoroge et al. 2010, Campbell et al. 2019). Sanford (2016) recommended deploying honey bee hives arround watermelon fields to improve pollination, because watermelon flowers are not attractive to most other insect species. Pisanty et al. (2016) found a similar pattern, with 85% of flower visits conducted by honeybees, while the remaining 15% visits were conducted by 51 other bee species, suggesting a high diversity of potential flower visitors. Garibaldi (2014) also observed low abundance of non-honeybee flower visitors to water melon flowers, but that they contributed significantly to pollination as they complemented honeybees through temporal variation in flower visits during the day. The non-honeybees also had higher pollination efficiency per flower visit. In concurrence with Garibaldi (2014) study, we also observed low diversity of bees and other insects visiting watermelon flowers in our sites, presumably due to low flower attractiveness. We did not assess polinator effectiveness, on a per visit basis, but still suggest that, despite the low number of visits from non-honeybees in this study, they may still play a role in watermelon pollination.

The observed decline in number flower visits in response to increased pesticide application was not surprising, as insecticides are designed to kill insects, and herbicides most likely have negative impacts on other flowering plant species, which provide floral resources for bees. Different studies have documented possible effects of high dosage of pesticide use on non-target animals. Williamson and Wright (2013) reported induced memory loss to honeybees as a results of high dosage of cholinergic pesticides and Williams et al. (2015) demonstrated effects of pesticides on reproductive ability of honebee queens. The majority of studies reporting on effects of pesticides spray to flower visitors, are small-scale studies testing a specific type of pesticides and concentration within a controlled environment (Tschoeke et al. 2019). In contrast, our study was carried out in a real-life and more complex environment, with many different types of pesticides and applied concentrations. High levels of pesticide use in any system suggest that, either the cropping system is highly vulnerable to pests, the farmers are applying an inefficient or wrong pesticide (due to little knowledege about pesticides, leading to mis-use). The observed pesticide practices in our study systems could be a result of combination of the aforementioned factors. In addition to the direct effects of high dosage of pesticide application, prolonged application are reported to results in pesticide resistance in pest organisms (Biddinger and Rajotte 2015, Sudo et al. 2018). This may in turn require higher levels of pesticides to kill the pest and hence posing more lethal effects to non-target organisms such as pollinators. In addition, synergetic effects (i.e. coctail effects) are likely, due to the use of multiple pesticides (Tosi and Nieh 2019).

The number of visits by honeybees to watermelon flowers increased with number of flowers of co-occurring plants in the observation plots. This positive relationship was relatively stronger in observation plots that were surrounded by a lot of trees (i.e., high percentage tree cover). The probability of having zero honeybee visits followed a bimodal pattern, with the highest chance of receiving no visits in plots with 0–1, or six (maximum number observed), co-occurring flowers. Our results concur with other studies which have found that that presence of co-occuring flowering plants in agriculture sytems can both enhance pollination services by attracting more flower visitors towards target crop plants (Sidhu and Joshi 2016), or distract flower visitors away from target crops (Nicholson et al. 2019). Indeed both inter and intra-specific interactions for flower visitors can be scale dependent, as too few flowers do not attract any pollinators while too many flowers cause a dilution effect resulting in fewer visits on a per flower basis (Hegland 2014).

Generally, increased tree cover within 250m radius reduced honeybee visits, but this decline was less pronounced at high abundances of co-occuring flowers in the observation plots. We suggest that this could be due to that flowering trees compete with watermelon flowers for honeybee visitors. Previous studies have found a postive relationship between flower visitation and tree cover or natural habitat in the surrounding landscape, probably because complex heteregenous agricultural landscapes habour a high diversity of plants and animals, and therefore provide more stable ecosystem services such as pollination (Menalled et al. 2008, Sanderson and Ioris 2017). The fundamental explanation for this relationship lies in the interaction between the inhabitants creating a self-sustaining community, for example, with respect to presence of food, nest sites and natural enemies (Kovács-Hostyánszki et al. 2016). On the other hand, no or even a negative relationship between increased tree cover and bee abundance have been reported by (Samnegård et al. 2016) in Ethiopia and (Saturni et al. 2016) in Brazil. The dynamics of flower visitors in relation to different food resources could explain the observed interaction between tree cover and abundance of co-occuring flowers in the observation plots in our study system. Even though flowering trees may potantially compete with crop plants for honeybee visitors, the trees may also provide crucial food and nesting resources for a diversity of bees, and thereby sustain stable bee populations in the landscape. Pasquet et al. (2008) suggested that, increased tree cover proximal to agriculture fields might benefit crops at the edge compared to the interior of agricultural fields, due to food and nesting resources available at the edge provide more flower visitors at the field margins. Concurrently, size of the fields is reported to have similar effects, as most of the flying insects can only fly a short distance in seraching for food (Inouye et al. 2015). In our study, these variables (i.e. field size and position within field) were neither part of the final model nor showed significant realtionships with number flower visits in single-variable models. Perhaps this could be a due to the limited size of the watermelon fields in our study system and the nature the of dominating flower visitors observed. It is known that, depending on the nature of the landscape, body size and food availability, honeybees can fly more than 10 kilometers for foraging (Hagler et al. 2011). This implies that, the size of our fields (i.e. maxmum size 2.5 ha) were not a problem for honeybees to navigate.

We observed increased fruit set (i.e., number of fruits) per plant with increased flower visitation. This finding is consistent with findings from other studies of watermelon pollination (Bomfim et al. 2015) as well as pollination studies on other crops (Winfree et al. 2008, Garibaldi 2014). According to Delaplane et al. (2000), watermelon plants require about 800 pollen grains to be deposited on a receptive stigma for fruit initiation and development to maturity, equivalent to 6-8 honeybee visits per flower (Stephens 1994). In this study, honeybees visited a watermelon flower 0.46 (± 0.02 SE) times in 10 minutes on average, equating to approximately 8 visits per flower every 3 hours (maximum for fruit set). Adlerz (1966) demonstrated that, time spent per each visit is crucial for fruit set and maturation in watermelon and not only total number visits. This can be achieved by increasing competetion on food resources (pollen and nectar) so that the visitor will spend more time per visit to exhaust the limited available resources (Sanford 2016).

We did not find fruit weight to correlate directly with honeybee visits, however fruit weight was negatively related to the number of fruits per plant, suggesting a trade-off between number and weight of fruits. On the other hand, Brewer (1974) found that flower visitation increased fruit weight in watermelon but not the number of fruits.

Management Implications

Our study has demonstrated that allowing some flowers of co-occurring plants to grow in the watermelon fields can increase the number of honeybee visits to watermelon flowers, possibly because these other flowers help attract bees on a very small scale leading to a spillover effect to the crop flowers. Co-occurring (wild)flowers in the field layer appears to be particularly important for fields surrounded by a well developed tree cover, possibly because flowering trees compete with the watermelon flowers for insect visitors. Our study has also documented a negative impact of frequent pesticide spraying on the frequency visits by honeybees to watermelon flowers. Given the positive relationship between number of bee visits and crop yield, it follows that using pesticides to fight weed and pest insects may decrease crop yield. Thus, based on our findings, we recommend that pesticide spraying should be done in the evening, when bee activity is at the lowest. We encourage the responsible management authorities to explore the drivers for the observed pesticide application practices, and aim for a sustainable strategy of managing pests and ensuring increased agriculture yield. We recommend application of agriculture practices such as integrated pest and pollinator management to avoid the negative effects of increased pesticide use.

Acknowledgments

We are thankful to Norwegian Government through the Norwegian State Education Loan Fund for supporting this study. AN was financially supported by the Research Council of Norway (project 230279/E50 − PolliClim). We are thankful to the following for their assistance during data collection; Erica Mmuru, Vicent Elisante, Jumanne Kway, Nassoro Kimaro and Stella Swai. Finally, we thank all farmers who gave us permission to use their garden.

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Paper IV

Crop pollination in small-scale agriculture in Tanzania: Household dependence, awareness and conservation

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Abstract

Global economic value of agriculture production resulting from pollination services carried out by animal pollinators has been estimated to $235 - $577 billion. This estimate is based on quantification of crops that are available at the global markets and mainly originate from countries with precise information about quantities of agriculture production, exports and imports. In contrast, knowledge about the contribution of pollinators to household food and income in small-scale farming at local and regional scales is still lacking, especially for developing countries where the availability of agricultural statistics is limited. Although the global decline in pollinator diversity and abundance has received much attention, relatively little effort has been directed towards understanding the role of pollinators in small-scale farming systems, which feed a substantial part of the World's population. Here, we have assessed how local farmers in Northern Tanzania depend on insect pollinated crops for household food and income and to what extent farmers are aware of the importance of insect pollinators and how they can conserve them. Our results show that local farmers in northern Tanzania derived their food and income from a wide selection of crop plants and that 67% of these crops depend on animal pollination to a moderate to essential degree. We also found that watermelon − for which pollination by insects is essential for yield − on average contributed nearly 25% of household income, and that watermelons were grown by 63% of the farmers. Our findings indicate that local farmers can increase their yields from animal pollinated crops by adopting more pollinator friendly farming practices. Yet, we found that local farmers' awareness of pollinators, and the ecosystem service they provide, was extremely low and intentional actions to conserve or manage them was generally lacking. We therefore urge

agriculture authorities in Tanzania to act to ensure that local farmers become aware of insect pollinators and their important role in agriculture production.

Keywords: Ecosystem services, Small-scale farming, Insect pollinators, Pollinator conservation, Agricultural intensification

Introduction

Small-scale farming is a major source of food production and income in many countries (Lowder et al. 2016) and employs about 2.1 - 2.5 billion people globally, of which the majority live in developing countries (Tscharntke et al. 2012). The importance of small-scale farming in maintaining food security, as well as the environmental benefits stemming from this farming practice, have been realized and advocated by different scholars (Bianchi et al. 2006). One of the benefits of small-scale farming systems is that they constitute highly diverse semi-natural ecosystems through a combination of wild and domesticated species (Boyce 2006). This practice can therefore conserve biodiversity and sustain agriculture production over long period of time (Kok et al. 2017). Yet, balancing biodiversity conservation and agriculture production is becoming increasingly difficult for a number of reasons, including destruction of natural habitats and agriculture intensification (Emmerson et al. 2016, Simons and Weisser 2017, Quintana et al. 2019). This has raised concerns about the sustainability of small-scale farmer’s livelihoods that depend on ecosystem services for agriculture production (Malmborg et al. 2018, Wisely et al. 2018).

Animal pollination of crops is a threatened ecosystem service known to affect agriculture production in small-scale agro-ecosystems (Steward et al. 2014). As much as 35% of the total global agricultural production depends on animal pollination, and thus this ecosystem service contributes significantly to global food security and the socio-economic status of the small-scale household farmers (IPBES 2016). However, the total effects associated with animal pollination for local livelihoods; i.e. food availability and nutritional value, and farmers income, are poorly understood, as the main emphasis has been on the global monetary economic benefits (Gallai et al. 2009, Eilers et al. 2011). (Chaplin-Kramer et al. 2014) suggest that a more holistic assessment − which also includes the value of insect pollination to human health through a varied diet − would provide better estimates of the total value of pollination services. Considering this, estimates of monetary values, based solely on global food market prices, most likely underestimate the value of pollination services to humans. This is because

– across the globe – there is a great variety of crops that depend on animal pollination, that are not available at global markets, and their monetary value may vary substantially among regions (IPBES 2016). It is therefore important to estimate the economic value of these crops on local or regional scales to understand their direct economic benefits to local farmers. In addition, the nutritional value of a crop can be hard to translate to monetary value, while at the same time nutritional security can be a bigger threat to human livelihoods than food security *per se* (Smith et al. 2015, Hwalla et al. 2016).

The conflict between increased food production and conservation of natural habitats that threaten sustainability of ecosystem services including insect pollination has received a lot of attention by scientists (Marshman et al. 2019). (Díaz et al. 2015, Barbir 2016) show that, small-scale farming by indigenous and local communities are resilient to global declines in pollination services because they have always used agricultural practices that maintain local pollinators on and around their agriculture lands (e.g. agroforestry systems). However, these practices seem to be a bet-hedging strategy for diversifying food and sources of income stemming from limited access agricultural inputs, like fertilizers and pesticides, rather than deliberate actions to protect or conserve pollinators or practice sustainable agriculture (Kassie 2018, Waha et al. 2018). Consequently, local farmers will most likely trade their traditional agricultural systems if they get exposed to different farming system with high return in shorter term. Such changes in practices will most likely lead to changes in land use and potentially pose a threat to local pollinators and ultimately the agricultural production itself.

In Tanzania, about 80% of the population lives in rural areas and depend on small-scale agriculture for their livelihoods (Anderson et al. 2016, FAO 2019), characterized by low inputs and low yields per area (Bergius et al. 2018). Despite a high number of people involved in, and depending on, agriculture, government development strategies have focused more on the communication and infrastructure sectors than on the agricultural sector (Pieterse 2017). Most local farmers strive to increase their production by use of fertilizers and watering. Local experience and knowledge shared among the farmers is the main source of information in pest management, as the farmers receive no or little help or advice from the agriculture authorities. For example, (Laizer et al. 2019) found that local farmers in Arusha use kerosene – a flammable hydrocarbon liquid commonly used as a fuel – mixed with several other pesticides for eliminating pests. Apparently, these practices show that local knowledge in addressing particular problems is usually based on traditions or trial and error procedures, due to lack of proper knowledge. Moreover, the benefits of insect pollination in these regions have received little attention, most likely due to lack of awareness or as it has been considered a common good that is taken for granted (Kasina et al. 2009). We thus hypothesised that knowledge about the importance and economic benefits of animal pollination for food production is low among local farmers in our focal regions (Arusha and Kilimanjaro, northern Tanzania). In this study, we therefore carried out interviews with local farmers to get a better understanding as to what degree their farming system, local household income and food production was depending on insect pollinators. In addition, we acquired information about the farmers' awareness of pollinators and pollination services and their intended actions to protect them.

Methods

Study area and respondents

We interviewed 147 local farmers in the Kilimanjaro and Arusha regions in northeast Tanzania. Most local famers in these regions are small-scale farmers growing different crops through the year, including vegetables, fruits and ornamental flowers. With the help from a local agriculture officer, we purposefully selected candidate farmers for the interviews. The farmers selected for an interview had to be engaged in several economic activities and willing to share their information for research purposes. We conducted the survey with help from three life science graduates well acquainted with Swahili (the local language) to facilitate conversation. The questionnaire had two sets of questions; the first aimed to acquire demographic information such as education, age and household income (Appendix 1). The second aimed at collecting data on farming practices and awareness of pollination services (Appendix 1).

Farming practices, agriculture revenue and operation cost

We interviewed all the farmers about their fields separately to acquire information about farming practices in previous year (2018). For every farmer we obtained information about farming system including; type of crops grown, amount of land used per crop (field size), yield decline experiences and presumed causes, cropping system, costs and revenues associated with growing each type of crop, awareness of pollinating insects and intended activities to conserve them (Appendix 1).

Classification of crop pollination dependency

To estimate to what extent the small-scale farming, i.e. the crops the farmers had grown in the previous year, depended on animal pollination, we used the five categories of crop pollinator dependency developed by (Klein et al. 2007), Appendix 2, Table S1). The category "no increase” refers to crops with no yield reduction following pollinator exclusion, “little” are crops with up to 10% yield reduction, “modest” are crops with >10−40% yield reduction, “great” are crops with >40−90% yield reduction and “essential” are crops with more than 90% reduction.

Data analysis

To summarize the information about local farmers from the questionnaire responses, we used descriptive statistics (means, standard deviations, percentages). To test whether farmers allocated contrasting amounts of their land (field size) to crops of different levels of pollinator dependency, and whether level of pollinator dependency affected the contribution of crops to household income, we used analysis of variance (ANOVA). To test whether the farmers preferred to grow crops with a particular pollinator dependence, we fitted a generalized linear mixed model (GLMM) with Poisson distributed errors and log link. The same type of statistical model was fitted to test if the number of farmers reporting reasons for yield decline, differed between types of perceived reasons for decline. All data analyses were carried out in the statistical software R version 3.6.1.

Results

Farming system

Average age of our respondents was 42 (SD = 7) years, and most of the respondents were male (91.8%) and had basic primary education 77.6% (n=114). Size of the household, i.e. average number of people per household was 8 (SD = 3), however often mentioned to vary at different times of the year. On average, respondents owned small farms (1.4 ha ± 0.89 SD), fragmented into small fields around their residence areas. The majority (89% = 131) did not have enough agricultural land and therefore borrowed or rented land (3.1 ha on average), which was usually located farther away from their home. The borrowed land was mainly used for growing maize, on average the total amount of land used for maize was (3 ha ±1.1 SD) which is almost three times bigger than for other grown crops. Maize was mentioned as the main staple food and as a source of income by most of the farmers. In total we found 32 crops to be grown by the group of respondents, whereby on average every farmer grew a combination of two to four crops per year through intercropping or crop rotation whereby maize was grown by 97% (n=143) of all the farmers (Appendix 2, Table S1). We also found that all main types of crops contributed equally to household income irrespective of their dependence on animal pollination. However, considering individual crops, maize contributed more to household income than the rest of the crops, followed by watermelon and tomatoes. General awareness of the local farmers of pollination and pollinators insect was indeed low.

We found that all farmers practiced monoculture and mixed cropping at different times during the season. Monoculture cropping was most common in maize fields (borrowed/rented land). After harvesting the maize, the field was usually (89%) abandoned until the next season, or replaced with another crop, often beans. There was no statistically significant difference in the average field size used for crops in the different pollination dependency categories ($F_{(4,26)}$, Z=0.42, p=0. 79; Figure 1A).

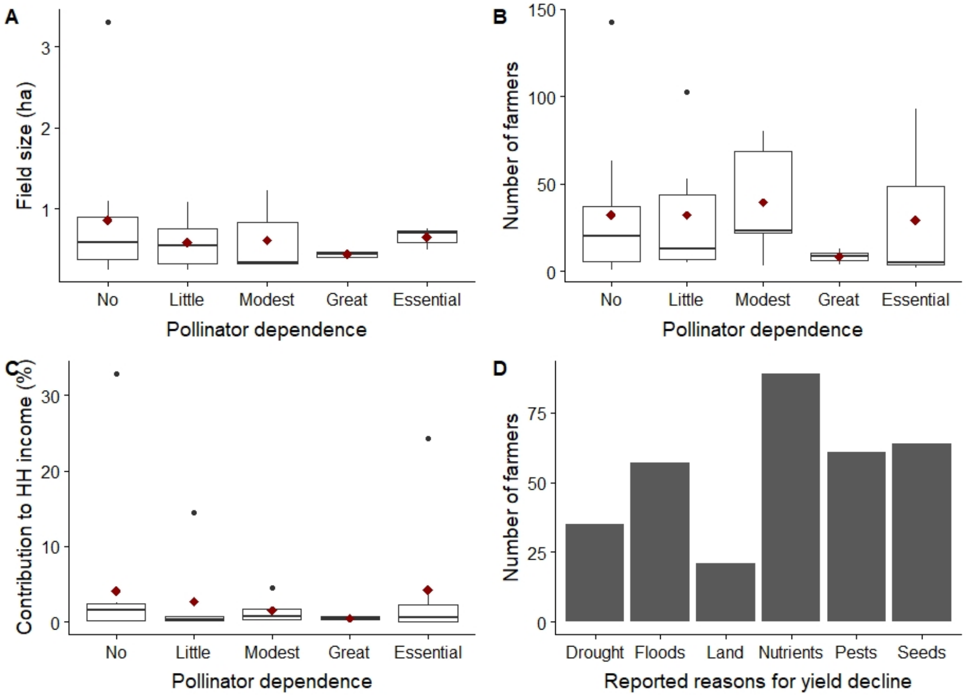

Figure 1. A. Field size used for crops of different levels of dependency on animal pollination. B. Number of farmers growing crops of different dependencies on animal pollination. C. Contribution to household (HH) income from crops of different dependencies on animal pollination. A, B, and C: Boxplots showing observed averages (diamonds), medians (midline) and 75th and 25th percentiles (upper and lower limits of the box). The whiskers extend *up to* 1.5 times the interquartile range; data beyond that distance are represented as points. D. Reported reasons for yield decline, and the number of farmers reporting each type of reason.

Pollinator dependency for food production and household income

We found that 20 out of 32 crops grown by the local farmers in our study areas to some extent benefit from insect pollination (Appendix 2, Table S1). The number of farmers growing crops of different degrees of pollinator dependence was not evenly distributed (χ^2=57.9, df=4, p≤0.01; Figure 1B). A higher number of farmers than expected by chance alone grew crops with “modest” pollinator dependency, such as egg plant, and bitter tomatoes, whereas fewer farmers than expected by chance alone grew crops with “great” dependency on pollinators, such as mangoes and avocado (Appendix 2, Table S1, Figure 1B). Notably, 93 of 147 (63%)

of the farmers reported that they were growing watermelons, which is a crop categorized as "essential" in terms of dependency of insect pollination.

Contribution to the household income did not differ among the crops based on their pollinator dependency ($F_{4,26,}$ Z=0.82, p=0.52; Figure 1C). However, at the individual crop level, three crops grown by the majority of farmers i.e. maize ("no" pollinator dependency), tomatoes ("little" pollinator dependency) and watermelon ("essential" pollinator dependency) contributed more than half of all agriculture revenue respectively i.e. 32%, 14.4% and 24.3% (Appendix 2, Table S1). The farmers reported that they derive their food from all crops belonging to all categories of pollination dependency. Crops grown only for household food production, which did not contribute directly to household income, were distributed across the pollinator dependency categories as follows: 36.7% "no", 20% "little", 20.1% "modest", 2% "great", and 21.2% "essential ". Thus, about three quarters of the crop plants used for producing food for the households were moderately or more strongly dependent on animal pollination.

Knowledge of insect pollinators and pollination

Only 7.4% (n=11) of the interviewed farmers were aware of pollinators and they considered them as useful insects, but they did not know exactly how pollinators benefit the crops. Honeybees and butterflies were mentioned to be useful insects, but butterflies were also mentioned as crop pests. When asked about their strategy to conserve pollinators, only one farmer among the 11, who were aware of pollinators, had an intentional strategy, i.e. to avoid spraying pesticides in the morning. No one of the farmers practices bee keeping. We did not find pollinator awareness to relate with either type of crops grown, level of education nor household income.

Yield decline experiences and reasons

All farmers had experienced declines in their agriculture production due to various reasons. However, none of the farmers listed pollination deficiency among the factors contributing to yield decline. The major causes of decline in agriculture production (crop yield), were perceived by local farmers to be declining soil nutrients 60% (n= 89), poor seeds 44% (n = 64) and pests 41% (n=61) (Table 1, Figure 1D).

Table 1: Factors causing yield decline, according to farmers, and their significance, relative to reductions in field size (reference level). Results from a generalized linear mixed model (GLMM) with Poisson distributed errors.

	β	**SE**	**z**	**P**
(Intercept)	-3.56	0.22	-16.29	<0.01
Drought	0.51	0.28	1.85	0.06
Floods	0.98	0.26	3.83	<0.01
Pests	1.07	0.25	4.21	<0.01
Seeds	1.11	0.25	4.43	<0.01
Nutrients	1.43	0.24	5.90	<0.01

Discussion

The present study has revealed that crops that are moderately to totally dependent on insect pollination are crucial for small-scale farmers in Northern Tanzania, both for income and food for home consumption. Despite the prominence of maize cultivation, i.e. a crop that is wind pollinated, there is potential for small-scale farmers to increase their income from insect-pollinated crops, such as watermelon, which are grown on their own small fields, in proximity to their own homes. Importantly, we have documented that a large majority of local farmers are not aware of insect pollinators and their important roles in crop production. This lack of awareness pose threat to existing pollinators communities because current farm management practices are likely to change if farmers are introduced to new practices that offer quick increase in agriculture production.

Local farmers and farming systems

In general, the characteristics of the small-scale local farmers interviewed in our study area were similar to those reported by other scholars in Tanzania (Anderson et al. 2016) and other Sub-Saharan countries (Kuivanen et al. 2016). However, the amount of land owned by local farmers in our study area was low compared to other parts of Tanzania, as most of the productive land in the Arusha and Kilimanjaro regions is under conservation, i.e. national parks, and significant portions of the land is semi-arid (Mkonda et al. 2018, Riggio et al. 2019). The great majority of the farmers that we interviewed grew maize, both for food and for income. However, we found out that maize growers typically did not use their own land for this purpose, because maize often requires larger fields for higher production (Cairns et al. 2013). Due to field size limitation, the farmers usually rent or borrow land for maize production and the compensation is most often through splitting the harvest or forming partnership whereby one farmer provides land and the other provides labour. This sort of collaboration was also found by (Adjognon et al. 2017) as the main approach for local farmers in sub-Saharan Africa to access most of the applied agriculture inputs.

Household income and pollinator dependency

Our results show that, despite farmers growing many different crops for household consumption, only three different crops, i.e. maize, watermelon and tomatoes contributed substantially to average household income (respectively 32, 24 and 14%). These were crops were also grown by a majority of the interviewed farmers. In contrast to several previous studies (Rogers 1974, Mhando and Mbeyale 2010, Ruoja 2016), which found coffee to be the most important crop for most of the local farmers in this area of Tanzania, our study reveals that other crops, especially watermelon, are crucial for the local farmers (Segerstrom 2016). Perhaps declining global coffee price (Segerstrom 2016), pests (Magina et al. 2007), climate fluctuation (DaMatta et al. 2019), competition from giant producers (Lenzen et al. 2012) and lack of government support (Sambuoa et al. 2017) have necessitate for alternative crops. Replacement of coffee cultivation by annual fruit crops − such as watermelon −(Katega et al. 2014)− as observed by (Katega et al. 2014) in western Tanzania − suggests that, the demand for insect pollination will actually increase; coffee yield is moderately dependent on pollination (Delaplane et al. 2000), whereas crops such as watermelon or vanilla (*Vanilla planifolia*) are essentially dependent on pollinators (Lubinsky et al. 2006).

Apart from maize, watermelon and tomatoes, most crop types contributed little to household income, and we found that average income derived from different categories of crop plants, grouped according to level of dependence of insect pollination, did not differ significantly. However, in our previous studies in these same regions we have shown that, watermelon yields are limited by available natural pollination services (Sawe et al., submitted manuscript). Therefore, results from our present study signify that, household income resulting from agriculture activities can be increased if pollination services are improved.

Reliance on maize for both food and income by most of the local famers, appears to emerge from traditional/conventional reasons rather than economic analysis. For example, watermelon grown on 1/3 of a land used to grow maize, produces almost as equal economic benefits as maize grown on a borrowed land. Moreover, the cost associated with growing maize seems to be more than what farmers are aware. We could not quantify all the costs associated with the crops from farm preparation to harvesting as majority of the farmers do not keep records. However, it is obvious that, distance from home to the fields (for borrowed land), farm size (i.e. investing in a land for one season) increases the investment cost as previously reported (Chand et al. 2011, Myeni et al. 2019). Some farmers however mentioned that, they practice agriculture to save money rather than acquiring economic benefits. The reasoning here is that, since there is insufficient money to invest in agriculture, small investment is made each time a penny is acquired through other means, hoping for lumpsum during the harvest.

On the other hand, further results from this study shows that, animal pollinated crops grown and managed in small land around home for example watermelon and tomatoes may generate higher incomes. This implies that, local farmers can benefit from these crops which are grown on small areas around their home. Our previous study by (Sawe et al, II) shows that, watermelon (grown by most of the local farmers and with substantial household income) yields can be increased, i.e. number of marketable fruits could be doubled, if sufficient pollination is provided under the current levels of irrigation and fertilization. Apparently, our current findings and mentioned previous studies suggest that local farmers can benefit economically by focusing on their own small farms and improving pollination services in these. This is also backed by (Makuya et al. 2018) who observed that, smaller watermelon fields produced higher yields compared to bigger ones as a result of easy management and efficient use of agriculture inputs. Smaller field size and increased crop diversity may indeed contribute to conserving biodiversity while ensuring agricultural production. In a recent analysis of 435 European and North American agricultural landscapes along gradients of crop diversity and mean field size, Sirami et al. (2019) found a clear positive effect of decreasing field size, even stronger than increasing seminatural cover. They also found that increasing the number of crop types had a positive effect on multitrophic diversity, but the effect of increasing crop diversity depended on the amount of seminatural cover in the surrounding landscape (Hass et al. 2018, Sirami et al. 2019).

Household food production and pollinator dependency

We found that 67% the cultivated crop types used for household food production were moderately or more strongly dependent on insect pollination. We found that, local farmers derive their food from all grown crops and that not all crops grown were meant for selling purposes. Most of the farmers who cultivated “modest” pollinator dependant food crops used them for home consumptions; these included *egg-plants, bitter tomatoes and okra,* other crops cultivated for home consumption were vegetables. Yields from these vegetable crops were mentioned to be low and considered as bonus, because they are largely integrated in mixed cultures with some other important cash crop, and they did not require additional caretaking. Low harvest of these crops was thought to be a function of sowing poor-quality seeds stemming from the farmers’ own harvest in the previous season. Previous studies have shown that, seeds of poor quality used by majority of local farmers in sub-Saharan African countries is major bottleneck for agriculture productivity (Minot 2008, Lynam et al. 2010). This implies that, local farmers could improve the vigour of the produced seeds by improving pollination condition in their fields (Fijen et al. 2018). As the insects carry pollen across different plants of the same species, they contribute to increasing genetic variation among the plant individuals and thus decrease inbreeding depression resulting from selfing (Jones and Bingham 1995, Cardoso 2004).

Pollinators awareness

Our study has documented that a large majority of the local farmers were not aware of pollination and pollinating insects. The few farmers who mentioned to be aware of pollinating insects (7%) did not know how the insects improve the yield, and only one among them deliberately sprayed pesticides in the evening to protect pollinating insects. When the farmers were asked about the beneficial insects visiting their crops, they mentioned honeybees and butterflies, though butterflies were mentioned as pests as well. Honeybee visits were considered beneficial because they collect raw materials for honey production. The lack of pollination awareness among farmers was confirmed by the fact that they all reported to have experienced yield decline, but none thought pollination deficit could contribute to yield decline. Pests, fertilizers and lack of good quality seeds, were reported as the main pressing problems leading to decline in agriculture production. The level of education or type of crops grown did not seem to play a role in pollination awareness as reported by other scholars (Bhattacharyya et al. 2017, Schönfelder and Bogner 2017, Sieg et al. 2018). The few farmers aware of pollinators seemed to have acquired this information agriculture training programs or from other farmers. Our results are similar to observations made by (Kasina et al. 2009) in Kenya and by (Munyuli 2011) in Uganda. In contrast, (Hordzi 2014) found that majority of the local pigeon pea farmers in Ghana understood insect pollination and roles played by honeybees in cross-pollination.

Pollinators conservation

Since most of the farmers were not aware of the role of pollinating insects, they did not make any attempt to protect or conserve them. Except for one farmer who mentioned to spray pesticide in the evening to reduce impacts of affecting pollinating insects. A previous study by (Sawe, et al, paper I, II) on the same regions found watermelon yield to be limited by existing level of natural pollination services. Lack of awareness on insect pollinators and their role in crop production documented in the current study reveals their increased vulnerability to unsustainable agriculture practices such misuse of pesticides as observed by (Sawe et al, paper III).

Management implications

We conclude that there is an urgent need to increase awareness of insect pollination as a vital factor for agricultural productivity in Northern Tanzania. We recommend that agricultural authorities endeavour to enhance local farmers’ awareness of pollinators and their role as providers of important – and free – ecosystem services. This could be implemented by establishing special programs, aimed at increasing the farmers’ understanding of the diversity and ecological functions of pollinators, both in agricultural and (semi)natural habitats. This could also be achieved through for example creating a media coverage about the connections between agricultural productivity, food and nutritional security and the conservation of biodiversity, which remains unknown to majority local farmers.

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Appendix 1

Questionnaire used in interviews of 147 local farmers in the Kilimanjaro and Arusha regions in northeast Tanzania, after the 2018 crop growing season. The interviews were conducted by graduates acquainted with Swahili language.

Questionnaire

Enumerators name …………………………..

Part I

i. Full Name: ……………. Date: ………………………………
ii. Village name: ……………………. Ward …………………….. District: ………………..
iii. Age: ………………………….. Sex: ……………………
iv. Education: ……………………..
v. Number of persons that lived in your house: …………………………

Part II

vi. Total income earned last year: ……………………………….
vii. Percentage of income coming from agricultural production (crop production) ……………….
viii. Further income sources besides agricultural production (crop production) ……………………
ix. Field size ……………………………
x. Which crops do you grow ……………………………?
xi. Cost for associated with each crop and the market price………………….
xii. Are you practicing Monoculture or mixed culture ……………………………………?
xiii. Percentage of production sold on the market in 2018 ……………………………………
xiv. Is there any change in the yield in the crops you grow? …………………………………………
xv. How do you know crops yields are changing? …………………………………………………

xvi. Why are crop yields changing?

……………………………………………………………………..

xvii. Do you know pollinators or any beneficial insects visiting your plants?

……………………….

xviii. Do you know their roles? ………………………………….

xix. Which crops do they visit? ………………………………………….

xx. What are the most insects visiting insects on your crops?

…………………………………..

xxi. Do crops need pollination? ………………………………………………….

xxii. Why do you think crops need pollinators? …………………………………….

xxiii. How do you know? ……………………………………………………………

xxiv. Would it be useful to have more pollinators? …………………………………..

xxv. In your opinion, how could their abundance be increased?

………………………………..

xxvi. What practice do you use to conserve pollinators?

………………………………………..

xxvii. Do you practice conservation agriculture/pollinator management?

……………………………

- Mixed farming/agroforestry
- Hedgerow farming
- Bee keeping

Appendix 2

Table S1. A list of crops grown by 147 local farmers in surveyed areas, based on the farmers' response to the questionnaire in Appendix 1. Categorization of dependency of animal pollination for different crops follows Klein et al. (2007). Numbers in the parentheses are standard deviations. HH = household.

Crop name	Number of farmers	Pollination dependency	Average field size in ha	Average % HH income contribution
Amaranthus *(Amaranthus. sp)*	23	No	0.41 (0.20)	0.17
Avocado *(Persea Americana)*	4	Great	0.38 (0.14)	1.02
Banana *(Musa sp)*	35	Essential	0.74 (1.12)	0.13
Beans (*Phaseolu sp*)	53	Little	1.08 (0.83)	0.46
Bitter tomatoes *(Solanum aethiopicum)*	69	Modest	0.33 (0.19)	4.55
Cabbage *(Brassica sp)*	44	No	0.34 (0.15)	1.3
Cantaloupe *(Cucumis melo)*	5	Essential	0.60 (0.52)	0.7
Carrots *(Daucus carota)*	4	No	0.56 (0.13)	1.55
Cassava *(M. esculenta)*	1	No	0.25 (0.12)	0.04
Chilli (various chilli)	5	Little	0.25 (0.00)	0.13
Coffee *(Coffee arabica)*	3	Modest	0.83 (0.29)	0.35
Cucumber *(Cucumis sativus)*	62	Essential	0.71 (0.26)	3.8
Eggplant *(Solanum melongena)*	80	Modest	0.32 (0.19)	0.79
Maize *(Zea mayz)*	143	No	3.31 (1.10)	32.82

Mangoes *(Mangifera indica)*	13	Great	0.50 (0.35)	0.04
Okra *(Abelmoschus esculentus)*	22	Modest	0.34 (0.23)	0.22
Onions *(Allium cepa)*	31	No	0.80 (0.22)	2.49
Oranges *(Citrus sinensis)*	16	Little	0.42 (0.31)	0.01
Paprika *(Capsicum sp)*	10	Little	0.30 (0.11)	0.29
Passion *(Passiflora edulis)*	3	Essential	0.75 (0.66)	0.02
Peas *(Pisum sativum)*	6	Little	0.79 (0.33)	0.81
Irish potatoes *(Solanum tuberosum)*	4	No	0.94 (0.77)	0.21
Pumpkin *(Cucurbita pepo)*	2	Essential	0.50 (0.01)	0.05
Rice (*Oryza sativa)*	20	No	0.86 (0.38)	2.4
Sorghum *(Sorghum bicolor)*	14	No	1.09 (0.52)	2.6
Spinach *(Lactuca sativa)*	63	No	0.33 (0.17)	1.85
Squash (*Cucurbita pepo)*	5	Essential	0.70 (0.45)	0.57
Sunflower (*Helianthus sp*)	23	Modest	1.23 (0.64)	1.76
Sweet potatoes (*Ipomoea batatas*)	8	No	0.59 (0.30)	0.15
Tomatoes (*Solanum lycopersicum*)	103	Little	0.67 (0.25)	14.43
Watermelon (*Citrullus lanatus*)	93	Essential	0.57 (0.22)	24.29

ISBN: 978-82-575-1666-6
ISSN: 1894-6402

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