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Small Landholders Battle the Leaf Folder: Improving Livelihoods in the Solomon Islands

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SMALL LANDHOLDERS BATTLE THE LEAF FOLDER: IMPROVING LIVELIHOODS IN THE SOLOMON ISLANDS

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Abstract

Sweet Potato is an important staple food crop grown by subsistence farmers in the Solomon Islands. It plays an important food security role and a major source of nutrition and livelihood in the rural areas as well as urban areas in the country. However, the spread of agricultural pests, in particular, the green leaf folder pest (*Psara hipponalis)*, has significantly increased in recent years leaving many smallholder farmers with reduced yields and food insecurity. In this thesis, I reviewed the literature on the common mechanisms used to evaluate the drivers of pest presence and identified the major factors correlated with the presence of sweet potato leaf folder pest in four communities in the Western Province of Solomon Islands. Twenty garden surveys were conducted in each community by researchers from the American Museum of Natural History, with support from the Solomon Island Community Conservation Partnership, the World Vegetable Center and Ecological Solutions Solomon Islands, giving a total of 80 surveys. A structured questionnaire was used and consisted of three categories: pest presence, agrobiodiversity, and the use of cultural controls. Farmers were asked if they had seen the green leaf folder pest in their gardens in the ten days prior to their interview. The assessment of agrobiodiversity in the surveys covered the number of crops grown in the gardens visited. The use of cultural controls included questions on whether farmers use crop mulching, rotation or both activities, and whether farmers apply chemical pesticides in their gardens. Control variables including the presence of Braconid wasps and weather parameters such as temperature, precipitation and relative humidity were also included to evaluate their effect on pest presence.

A probit regression analysis was conducted to test the association between pest presence and climate and farmer-level factors. Practicing a combination of both mulching and crop shifting activities has shown to have the most significant effect in reducing the green leaf folder pest presence. In addition, crop diversification has also played a significant but a lesser role in determining the likelihood of observing the green leaf folder pest in the Solomon Islands. In contrast, the application of chemical pesticides as well as the presence of Braconid wasps did not show any significant effects on the green leaf folder pest in this study. Moreover, among weather variables, precipitation has shown to be the only statistically significant variable correlated with the green leaf folder presence in the Solomon Islands. Based on the findings of this study, the following recommendations can be made: (1) the application of cultural control activities such as using the combination of both mulching and crop shifting should be demonstrated to subsistence farmers to reduce the green leaf folder pest presence, and (2) improved varieties of major food crops such as taro and cassava should be introduced more widely to communities to limit the present of green leaf folder pest.

Executive Summary

Smallholder farmers produce most of the food consumed in developing countries, and manage over 80 per cent of the world's estimated 500 million small farms, contributing significantly to poverty reduction and food security (Nagayet, 2005). Smallholders and semi-subsistence farmers produce food products on a small scale with limited external inputs, while most of them depend on their farm productivity for their main household income and food security. However, small-scale farmers often face numerous risks to agricultural production such as pest and disease outbreaks.

Agricultural pests continue to be major constrains to food and agricultural production in many parts of developing countries and small-scale farms (Oliveira et al. 2014). Because smallholder farmers typically depend directly on agriculture for their livelihoods and have limited resources and capacity to cope with shocks, any reductions to agricultural productivity due to pests and disease outbreak can significantly alert their food security, nutrition, income and well-being (Harvey et al. 2014).

The spread of agricultural pests and diseases have significantly increased in recent years leaving many semi-subsistence farmers with reduced yields and food insecurity (Gowing and Palmer, 2008). Agricultural insects are responsible for destroying one fifth of the world's total crop production annually (Sallam, 2008). As a result, improved methods to control and assess the risks posed by agricultural pests are needed to enhance informed decision making.

Agriculture in the Solomon Islands

Agriculture is the most vital sector for the Solomon Islands national economy and is the main source of employment and livelihood in rural areas. Agriculture in Solomon Islands consists of three subsectors; subsistence smallholder farming, commercial farming and large plantations (Gay, 2009). Subsistence agriculture activities provide food crops, cash revenue, livestock and food and social security to approximately 85% of the rural population in the Solomon Islands. Most of the population lives in a semi-subsistence lifestyle based on subsistence production and small-scale income generation (Solomon Islands Ministry of Agriculture and Livestock, 2015).

Sweet potato is one of the major staple food crops in the Solomon Islands and has been facing some serious threats due to pest infestation and damage. Among all sweet potato insect pests, leaf folders largely contribute to the most damage of the crop (Ames De Icochea & Ames, 1997).The green leaf folder pest is an insect that feeds mainly on the leaves of sweet potato and is widely distributed throughout Asia, Africa and Australia and has recently been recorded in Solomon Islands. The outbreak of this pest has posed severe damages to sweet potato crops threatening the livelihood and food security for subsistence farmers in the Solomon Islands.

Modeling approaches

Understanding the damage mechanism and the drivers of pest abundance is an essential first step in order to limit the presence of agricultural pests. Different modeling approaches are used to predict pest abundance, ranging from empirical (e.g regression models) to process- based and highly mechanistic approaches including effects of photosynthesis and respiration (Hillel & Rosenzweig, 2011). Empirical models depend solely on direct observation, measurement and extensive data records of the presence, abundance and reproduction of that species. While mechanistic models offer the possibility to understand the mechanisms resulting in population patterns, and use more detailed variables and consider leaf photosynthesis responses to light, temperature and CO_2.

Study Methods

The goal of this research is to identify the major drivers correlated with the presence of the green leaf folder pest in order to reveal possible control methods in Solomon Islands. Regression analysis was conducted to identify the driving factors of the green leaf folder presence using data collected through researchers from the American Museum of Natural History, with support from the Solomon Island Community Conservation Partnership, the World Vegetable Center and Ecological Solutions Solomon Islands, under a wider research project titled 'Biocultural approaches to sustaining Solomon Islands customary land and sea'. A total of eighty surveys were conducted in four different communities in the Western Province of the Solomon Islands. A structured questionnaire was used and consisted of three categories: pest presence, agrobiodiversity, and use of cultural controls. Pest presence is a binary variable consisting questions on whether the farmers have observed the pest in the last 10 days prior to the survey or not. Agrobiodiversity included questions on the number of diverse crops grown in each garden visited. Cultural controls included questions on the use of mulching or crop shifting or a combination of both activities as well as the use of chemical pesticides.

Results

Dependent variable

A probit regression was used due to the binary-nature of the dependent variable, which was recorded in the surveys during the months of May, June and July of 2016. Farmers were asked if they have problems with *Psara hipponalis* in their gardens. We assumed that farmers would have answered the question differently if they were asked the same question on a different day.

Policy variables of interest

The study included data on agriobiodiversirty and cultural controls obtained from local farmers in the four communities in the Western Province of the Solomon Islands. These policy variables of interest are used to assess the importance of practicing different farmer-level methods in order to reduce pest presence and recommend policies for subsistence farmers in the Solomon Islands.

Agrobiodiversity

The results showed that an increase in the number of diverse crops grown in addition to sweet potato crop decreases the probability of observing the leaf folder pest by 2.7%. Farmers who observed the pest have on average grown fewer number of varieties as compared to farmers who did not observe the pest. On average, among the four communities, farmers grew approximately 9 varieties in addition to sweet potato. Those varieties have mainly included other staple crops such as cassava, banana and taro.

Cultural Controls

The farming techniques commonly practiced by farmers in those four communities are mulching and crop shifting. The marginal effect of using those two activities together was significant in the probit regression model ($P < 0.05$). As farmers use both mulching and shifting activities, the probability of observing the green leaf folder pest significantly decreases by 73%.

Controls

Weather variables can have a significant effect on pest development and abundance and were included as controls in this study. The climate variables in this study include daily minimum temperature, daily maximum temperature, daily mean temperature, daily average rainfall and daily average relative humidity. Precipitation was the only statistically significant climate variable (p-value < 0.05), and indicates a negative correlation with pest presence. Temperature and relative humidity on the other hand, did not show any significant correlation with the green leaf folder pest presence.

Policy Recommendations

Based on the findings of the study, the following recommendations for farmers in the Solomon Islands can be made: first, using a combination of both mulching and crop shifting should be demonstrated to subsistence farmers to reduce the green leaf folder pest presence. Using mulching alone or crop shifting alone is not helpful in reducing the presence of this pest. Second, the introduction of more diverse crops in addition to sweet potato crop is important in reducing the presence of the green leaf folder pest. Those diverse crops can include varieties of cassava and taro crops. Third, adopting locally viable integrated pest management practices and identifying pest tolerant varieties and good agricultural practices should be evaluated and introduced to small landholder farmers in the Solomon Islands.

In conclusion, it is important to investigate further the relationship between the drivers and the abundance of the green leaf folder pest using mechanistic modeling approach rather than numerical modeling. In addition, further studies using the dependent variable as pest abundance with the actual number of nymphs on sweet potato crops are needed to identify the major drivers of this pest. Lastly, a longitudinal study over a large time period is essential in order to account for landscape changes, deforestation, and climate change in the region.

Chapter 1: Introduction

Among various sectors in the Solomon Islands' economy, agriculture plays a significant role in generating jobs and income for the country. The majority of rural people in Solomon Islands depend solely on subsistence production of crops such as yams, taro, giant swamp taro, sweet potatoes, bananas and watermelon. This set of productions serves as their main diet and source of nutrition (UNEP, 2012). However, the agriculture sector faces large annual losses due to pests and diseases. The destruction caused by agricultural insect pests is one of the primary causes leading to reduced production of major crops (Fasi, 2009). Furthermore, with the introduction of new pests in Solomon Islands, the success of integrated pest management practices depends largely on the continuous efforts to study and observe the pest/crop relationship. One of the primary pests that have been recently recorded in the Solomon Islands is the green leaf folder. The green leaf folder (*Psara hipponalis*) is an insect pest that damages sweet potato leaves and poses a serious threat to the communities' food security and the livelihood of subsistence farmers.

In this thesis, my aim is twofold. First, I review the literature on the common mechanisms and models used to evaluate the drivers of pest presence in order to identify the data needs for a computable process model that might shed light on the effective policies to reduce crop damage. Second, based on some limited data available from the American Museum on Natural History researchers, I identify the factors that are correlated with the presence of sweet potato leaf folder pest in four communities in the Western Province of Solomon Islands. The results of my research may assist decision making and recommend effective policies that reduce the significant effects caused by leaf folder pest on sweet potato crops in the Solomon Islands. Moreover, identifying the possible drivers of leaf folder pest may also assist communities in the Solomon Islands to plan for effective garden practices, resource management and pest control strategies.

Pests as a threat to subsistence farming

Approximately 2.5 billion people live directly from agricultural production systems. They live as full time or part time farmers or as members of farming households that depend mostly on farming activities (FAO, 2008). Smallholders and semi-subsistence farmers produce food products on a small scale with limited external inputs, while most of them depend on their farm productivity for their main household income and food security. Smallholders produce most of the food consumed in developing countries, and manage over 80 per cent of the world's estimated 500 million small farms, contributing significantly to poverty reduction and food security (Nagayet, 2005). However, small-scale farmers often face numerous risks to agricultural production such as pest and disease outbreaks.

Agricultural pests continue to be major constrains to food and agricultural production in many parts of developing countries and small-scale farms (Oliveira et al. 2014). Because smallholder farmers typically depend directly on agriculture for their livelihoods and have limited resources and capacity to cope with shocks, any reductions to agricultural productivity due to pests and disease outbreak can significantly alert their food security, nutrition, income and well-being (Harvey et al. 2014).

The spread of agricultural pests and diseases have significantly increased in recent years leaving many semi-subsistence farmers with reduced yields and food insecurity (Gowing and Palmer, 2008). According to the Food and Agriculture Organization, agricultural insects are responsible for destroying one fifth of the world's total crop production annually (Sallam, 2008).

As a result, improved methods to control and assess the risks posed by agricultural pests are needed to enhance informed decision making such as, developing effective policies that prevent the spread of invasive pests and promoting cost effective pest management strategies. Methods of intervention to reduce the outbreak of pestilence are generally divided into three broad categories: chemical, biological and cultural (Plant & Mangel, 1987).

Chemical Methods of Control

Chemical methods of pest control have been widely used in agricultural settings for a long time and can either kill pests or inhibit their development. The advent of inexpensive and fast acting chemical pesticides has widely promoted the use of chemicals on different crops. However, despite the effectiveness of chemical pesticides, there are major constraints that limited their use (Brattsten et al., 1986). Target pests can build resistance to pesticides making them less effective over time. Resistance develops because repeated and intensive pesticide use kills the susceptible individuals in a population leaving only the resistant ones to reproduce. The offspring of these survivors will carry the genetic makeup of their parents. They will inherit the ability to survive the exposure to the pesticides and will become a greater proportion with each succeeding generation of the population (Jutsum et al., 1998). Moreover, the use of chemical pesticides frequently destroys other non-target organisms that act as natural controls of pest species. In addition, the residues of toxic chemicals can cause poisoning hazards and other health effects for humans and livestock (Brattsten et al., 1986). As a result, the need to find a more effective and an environmentally sensitive approach to control agricultural pests gained an extensive attention on the international policy agenda (Rebaude & Dangles, 2011). Therefore, the introduction of integrates pest management (IPM) has been advocated as an effective and ecologically sustainable intervention to achieve sustainable development in pest control.

Biological Methods of Control

Unlike chemical pesticides, biological control methods rely mainly on living organisms to control pests, such as predator, disease organism or other natural mechanism. Introduction of natural enemies is an active biological control method to control the population of different pests. Natural enemies of the pest, also known as biocontrol agents, include predatory and parasitoidal insects, vertebrates, nematode parasites, fungi, bacterial as well as viral pathogens (Metcalf et al., 1973). Strategies of biological control methods include: importation, or known as classical biological control, in which an exotic natural enemy is introduced to control pest infestation; augmentation, in which locally occurring natural enemies are released at a critical time of the season to achieve control; and conservation, in which measures are taken to increase existing natural enemies by providing resources and enhance the presence of existing natural enemies.

While biological controls can be effective and environmentally sound means of controlling pests, they can have negative impact on the environment and native ecosystem. Introduced predators do not always target only the intended pest species, which could lead to the introduction of invasive species into novel habitats. Thus, any new methods of biological control must be carefully considered before organisms are released into the environment.

Cultural Methods of Control

Cultural controls rely on practices that make the environment less desirable to pests and less favorable for their survival, dispersal, growth and reproduction. Those controls focus on the optimal design and management of agroecosystems in time and space such as, the use of companion crops, rotations, timing of seeding, harvesting and management of adjacent environments. Cultural controls are generally the cheapest of all control measures as they usually only depend of modification of normal production practices. However, they require long-term planning, skills, training and careful timing in order to achieve the highest effectiveness.

Although the three methods of intervention can show to decrease pest damage, their effectiveness varies relatively. Chemical pesticides are known for their speed and ease for controlling pests and usually destroy pests in a very short time. However, chemical pesticides lose their effectiveness in the long run once the pests develop resistance against those pesticides. Cultural and biological controls on the other hand, can have a long lasting effect as they work to alter the environment, the condition of the host, and the behavior of the pest to suppress and prevent infestation. Although cultural and biological control methods may not have an immediate effect and require more time to achieve the goal, their results can last much longer and are more sustainable than using chemical controls alone. However, choosing the best strategy requires taking into consideration the availability, affordability and the environmental side effects of each method. In addition, understanding the lifecycle of the pest and its vulnerability is an important aspect to develop sustainable strategies that can effectively attack the pest.

Structure of the Thesis

This thesis is divided to five main chapters. The second chapter provides background information on the Solomon Islands, including agriculture, socio-economic, cultural and geographical description of the populations affected by pests in Solomon Islands. Also, it present maps of the Solomon Islands and the specific regions where the data was collected. Chapter three reviews and critically examines the background literature of the different methods used to control pests, while focusing on cultural methods of control. Chapter four describes the simple simulation model and reveals the possible control methods in the Solomon Islands and details the results and implications of the study. The last chapter states the final conclusions drawn from the study and presents future policy recommendations.

Chapter 2: Agriculture in the Solomon Islands

Solomon Islands is an archipelago of 922 islands about 1,860 kilometers north east of Australia. It is located between 5 and 12 degrees south latitude and 155 and 170 degrees east longitude. The major islands are Guadalcanal, Malaita, Choiseul, Santa Isabel, New Georgia and San Cristolbal (Figure 1). The total land area is 28,369 square-kilometers, which makes Solomon Islands the second largest insular nation of the South Pacific, after Papua New Guinea (Pauku, 2009). The human population in the Solomon Islands was estimated at 581,318 in 2010, with an annual growth rate of 2.47% (FAO).

The climate of the Solomon Islands is moist tropical. Seasonal and daily temperatures vary throughout the year and in coastal regions maximum temperatures seldom exceed 32^0 C with minimums rarely below 23^0 C. Relative humidity fluctuates between 60 and 92 percent. Generally, rainfall is high and evenly distributed throughout the year.

Figure 1. Map of the Solomon Islands. Source: Noel Park (2004), Family Search Wiki.

The Solomon Islands economy has been described as a dual economy due to the importance of its large informal sector (Solomon Islands National Biosafety Framework, 2012). The vast majority of people derive their livelihoods from their own land, crop production, labor and natural resources. A report published by the World Bank indicates that the Solomon Islands gross national income per capita for the formal economy is less than $910, while 75% of the labor force is engaged in subsistence agriculture, with less than 25% in paid employment (World Bank, 2010).

The Solomon Islands have an agriculture driven economy. The primary sector (which includes including forestry, livestock and fisheries) account for about 70% of the GDP (SI National Statistics Office, 2013). Agriculture is the most vital sector for the Solomon Islands national economy and is the main source of employment and livelihood in rural areas. Agriculture in Solomon Islands consists of three subsectors; subsistence smallholder farming, commercial farming and large plantations (Gay, 2009). Subsistence agriculture activities provide food crops, cash revenue, livestock and food and social security to approximately 85% of the rural population in Solomon Islands. Most of the population lives in a semi-subsistence lifestyle based on subsistence production and small-scale income generation (Solomon Islands Ministry of Agriculture and Livestock, 2015).

Study Area: Western Province of Solomon Islands

The research project was conducted in four communities of the Western Province of Solomon Islands (Figure 2). The communities were Vavanga (Kolombangara), West Parara (Peave), Biche (Gatokae in the Vanavona Island), and Zaira (Vangunu).

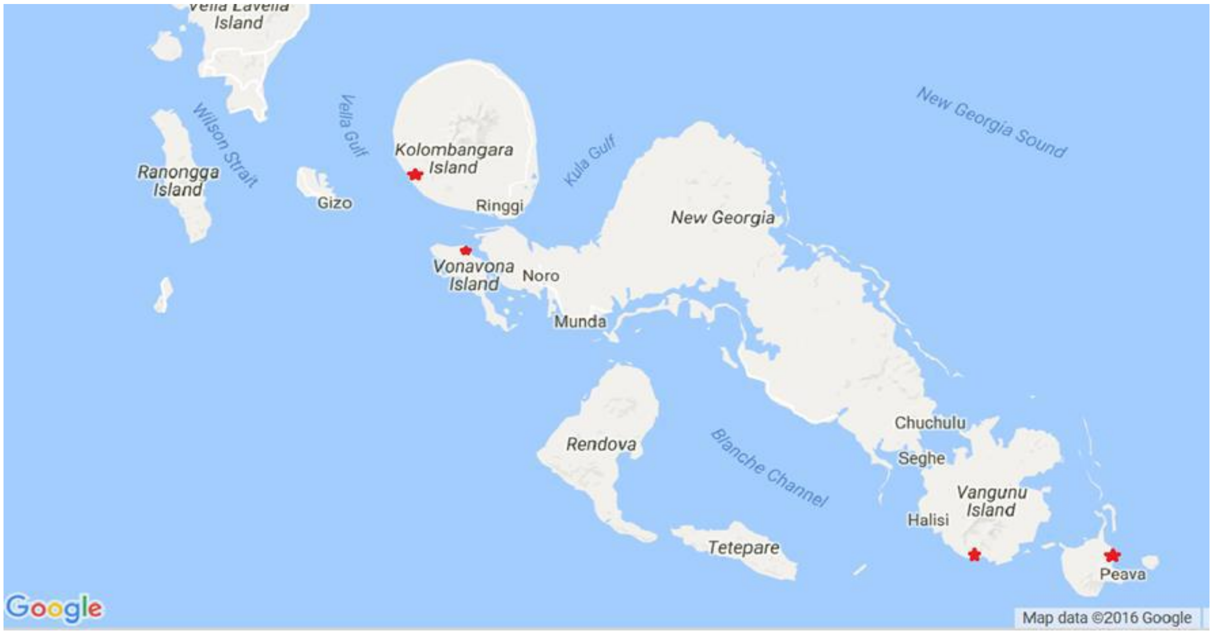

Figure 2. Map of Western Province with red stars indicating locations where data was collected

The Western Province is an archipelago of 11 islands with a total land area of approximately 5500 km^2, of which 80% is held by customary land owners, and the remaining 20% of land is held by the national government (Bennet et al., 2014). The province is comprised of two sets of islands (the Shortland Islands and the New Georgia group). The province has an ocean equatorial climate with a mean temperature of 27 °C with high humidity throughout the year. The average annual rainfall in Western Province ranges from 3500 mm to 6000 mm, and the highest rainfall is recorded in the southeast of the New Georgia group: Gatokae, Vagunu and southeast New Georgia from May to October during the trade wind season (Bennet et al., 2014).

The majority of the rural population in the Western Province depends on subsistence agricultural activities, which are often combined with cash cropping. Both monocropping and mixed cropping are practiced by farmers. Root crops and vegetables are part of the staple diet and supplement income gained from sale of cash crops such as copra and cocoa. Copra represents a major cash crop for smallholders in Western Province, with each household selling nearly 7000 tons per year. Cocoa is grown by small smallholders and supports 1038 households in the Province (Bennet et al., 2014).

Staple crops

The main subsistence crops in Solomon Islands are sweet potato (*Ipomoea batatas*), cassava (*Manihot esculenta*), yams (*Dioscorea alata*, *Dioscorea esculenta* and *Dioscorea rotunda*), taro (*Colocasia esculenta*), pumpkin and green vegetables. Those products play an important food security role and a major source of nutrition in the rural areas as well as urban areas.

One of the major problems faced by most smallholder farmers is pest infestation. According to the Pacific Islands Pests List Database, there are 2755 different pests flourishing in Solomon Islands (Table.1). Considering Solomon Islands' high dependency on agriculture, the outbreak of pests and disease can cause significant constraints to food production and household income. In 1993, 95% of taro production was reduced due to the outbreak of Taro Leaf Blight Pest, which caused significant economic crisis and food scarcity for thousands of farmers in the Solomon Islands. In 2014, total exports of copra, cocoa, sweet potatoes and cassava declined by 12.4 million (12%) in the first quarter of 2015 compared to 2014. Food imports, on the other hand, have also increased by 7% for basic food items such as rice, sugar products and canned food (Solomon Islands Ministry of Agriculture and Livestock, 2015).

Table 1. Some of the major pests in the Solomon Islands. (Source: Pacific Islands Pests List Database)

Crop	Pest
Taro	Alomae and Bobone
Cocoa, Coffee, Oil Palm, Rubber, Forest Trees	Brown root rot
Yam, Banana	Lesion nematodes
Peanuts, Sweet Potato, Beans, Taro, Tomato	Athelia wilt
Sweet potato, Wild Ipomoea	Weevil
Sweet potato, Wild Ipomoea	Leaf folder
Cocoa, Forest trees Cocoa	weevil borer
Rice, Wild Grasses	Brown plant hopper
Taro, Tomato	Cluster caterpillar
Yam	Scale
Pepper, Large Red Clilli Peper, Tomato, Eggplant	Sunscald
Banana, Plantains	Cordana leaf spot
Chili, Cassava, Pepper, Sliperi Kabis	White peach scale
Cocoa	Black pod

Sweet potato Green Leaf Folder (*Psara hipponalis*)

Green leaf folder or (*Psara hipponalis)* is an insect that feeds mainly on the leaves of sweet potato and is widely distributed throughout Asia, Africa and Australia and has recently been recorded in Solomon Islands (Jackson, 2015).

Life Cycle of the Sweet potato leaf folder

P. hipponalis moths usually lay eggs in groups on the upper surface of the sweet potato leaf. Approximately 90 eggs are laid per day (Reddy, 2015).

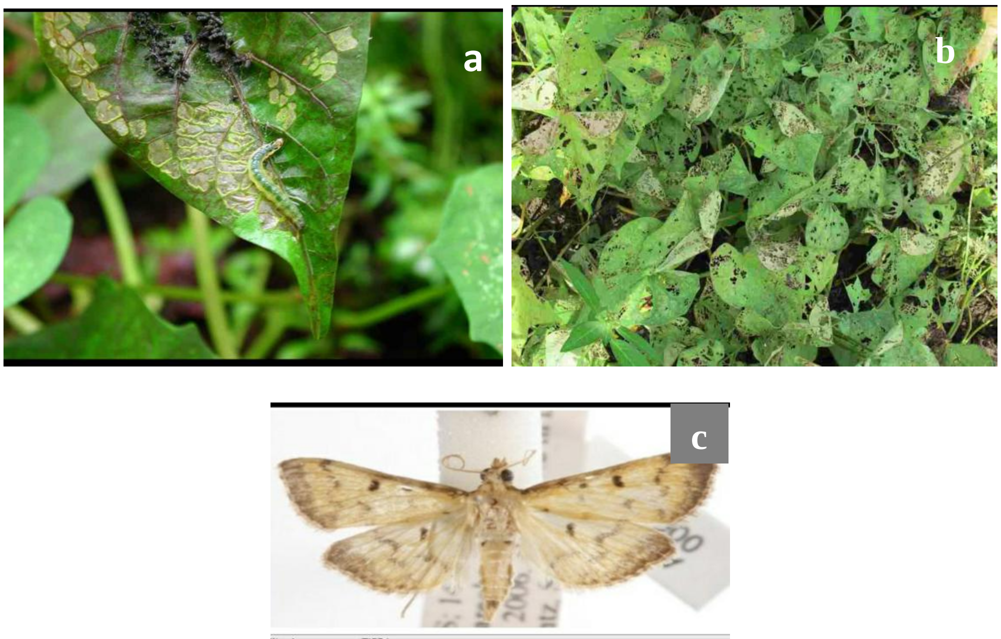

Figure 3 (a) An unfolded leaf showing a caterpillar of P. hipponalis which has made "windows" in the leaf by eating all but the wax layer. (b) Holes made in sweetpotato leaves by P. hipponalis. (c) Adult P. hipponalis

Eggs are usually shiny green, oblong and covered with a jelly like material. The incubation period lasts about 3-5 days and goes under five larval instars and each instar takes approximately 2-6 days (instar is a developmental stage of the insect until sexual maturity is reached). Larvae in the first instars are greenish-yellow with a dark brown head. Larvae in later instars become dark green and the integument appears moist and waxy. When fully grown, the size of larvae can reach 13 mm (Ames De Icochea & Ames, 1997). Larvae then turn to yellowish-white pupae, which later turn to become reddish brown. The pupal period lasts from 5 to 8 days before turning into adults. Adult moths are yellowish-brown with dark brown zigzag markings across their wings (Figure 3c). The wingspan is about 20 mm and the life span of the female moth is about 3 days (Amalin & Vasquez, 1993).

P. hipponalis occur in most sweet potato environments. Methods of control can include Braconid wasps, which are common natural enemies for the leaf folder population and cultural methods such as the use of insect-free planting materials (Ames De Icochea & Ames, 1997).

Symptoms

Sweet potato (*Ipomoea batatas*) is the major host for *P. hipponalis*. The larva (caterpillar) does the damage to the leaves and damage can occur at any stage of plant growth (Figure 3a.). It folds the leaf margin twice and spins webs close to the main veins of the leaves and on the upper surface of the leaves (Reddy, 2015). In most cases, there is one larva per leaf. The young larva feeds on the upper surface of the leaf leaving the lower epidermis intact. As the larva matures, it eats through the leaf creating small lace-like holes (Figure 3b). The leaves then dry up, die and drop off (Amalin & Vasquez, 1993).

Chapter 3: Literature Review

Sweet Potato (*Ipomoea batatas*)

Sweet potato (*Ipomoea batatas*) is the seventh most important food crop worldwide and the second most important of all root and tuber crops after white potato (*Solanum tuberosumone*) with an annual production of 100 million metric tons (FAO, 2013). It is one of the world's major crops, especially in developing countries, where it ranks third in value in production and fifth in caloric contribution to human diet (Elameen et al., 2008). Approximately 92% of the world's sweet potato production is in Asia and the Pacific Islands (Jansson & Raman, 1991).

Sweet potato is an important staple food in areas of subsistence farming and is a drought tolerant crop capable of producing high yields under a wide range of agro-climates and farming systems. The growth cycle of sweet potato is the shortest among all root crops. The crop is normally harvested when the leaves turn yellow, approximately four months after planting. It is used as a staple food for human consumption, animal feed and for industrial starch extraction and fermentation (Jannson & Raman, 1991).

Despite the economic and nutritional value of sweet potato, there are many constraints that limit the production of sweet potato world-wide. The outbreak of insects, nematodes, and diseases contribute to a major loss of sweet potato production (Hue and Low, 2015). Losses due to insect feeding may often reach to 80% destruction, especially because sweet potatoes are usually grown in low input agricultural systems and small-scale farms. There are approximately 280 insects and mite species that attack sweet potato crop around the world (Jansson & Raman, 1991). Among all sweet potato insect pests, weevils (Cylas spp.), leaf folders and sweet potato butterfly (*Acraea acerata*) contribute to the most damage of the crop (Ames De Icochea & Ames, 1997).

Pest controls for sweet potato

Methods to control insect infestation on sweet potato crops have been focused on the use of integrated pest management strategies. However, since the majority of sweet potato production is grown in developing countries, certain IPM methods such as biological control agents may not be available. As a result, approaches for controlling sweet potato pest infestation have been directed toward the use of remedial measures on a pest-by-pest basis, and in most cases, management has relied mostly on the use of cultural practices (Ames De Icochea & Ames, 1997; Jansson & Raman, 1999). Cultural practices include the selection of healthy planting material from well adapted varieties, crop rotation, intercropping and field sanitation.

For example, cultural control has been the most promising method of an integrated pest management strategy for subsistence sweet potato farmers in Kenya (Smit & Matengo, 1995). Cultural practices including crop sanitation and crop rotation have shown the most effectiveness in reducing the damage caused by sweet potato weevil infestation. Similarly, a trial in Sierra Leone in Sub Saharan Africa was conducted during two cropping seasons in 2011 and 2012 to evaluate the effects of cultural practices (mulching and manipulation of harvesting dates), used by small-scale sweet potato farmers, on crop damage by sweet potato weevil (Mansaray et al. 2014). The study concluded that mulching sweet potato at the rates of 3-5/ha significantly reduced sweet potato infestation in the field, decreased tuber damage and led to an increase in yield and number of sweet potato tubers produced.

In addition to crop mulching and shifting cultivation, crop diversification has shown to be an effective cultural control method to reduce pest infestation. Several studies carried out in the USA, Europe and Australia have explained the role of crop diversity in reducing insect pest infestation by reducing pest colonization rate, reducing pest tenure time, and increasing pest mortality due to the enhancement of the abundance and diversity of natural enemies (Medeiros et al., 2009; Hooks and Johnson, 2003; Ponti et al., 2007). Another study was conducted in Brazil to test the effect of presence of diverse wild crops on the abundance of tomato pests, mainly the South American Tomato Pinworm pest (SATP) (Medeiros et al., 2009). The study concluded that diversification of tomato crops had significantly decreased SATP abundance and increased the abundance and diversity of predaceous arthropods, which are predators of SATP. Similarly, Yaku (1992) concluded that sweet potato weevil population was significantly reduced when diversifying sweet potato crops with multiple crops such as corn and soybean.

Other studies indicate that insect pests that have a broad host range may not be reduced by diversifying crops (Andrew, 1991). For example, Smith McSorley (2000), and Smith et al. (2001) found no reduction in silverleaf whitefly pest (*Bemisia tabaci*) abundance when diversifying crops with eggplant and squash. Thus, understanding the pest/host relationship in addition to the physiology and epidemiology of each pest is an important aspect when applying crop diversification methods.

However, the challenge with controlling sweet potato pests by using cultural control methods remains in the lack of knowledge and information among small-scale farmers on the major drivers of pests and the interaction with their hosts. There is limited understanding among sweet potato growers of pest driving factors, population dynamics and field conditions necessary to correlate insect damage with causal factors. This makes it difficult for subsistence growers to predict which fields are likely to require management, and further impedes the development of effective controls. Therefore, it is widely agreed that introducing integrated management programs that combine together different tactic of control methods into on program, to understand the ecology and biology of pests and crops is very essential in order to apply successful methods of control (Smit & Matenfo, 1995; Mancini et al., 2006). In addition, integrated pest management practices provide farmers with adequate knowledge and informative trainings on the different pests, their ecology, and the importance of performing suitable strategies to prevent and reduce pest infestation (Okonya et al. 2014).

Integrated Pest Management

Integrated pest management is defined as “an ecosystem approach to crop production and protection that combines different management strategies and practices to grow healthy crops and minimize the use of pesticides” (FAO). An effective integrated pest management strategy will reduce economic losses and decrease the dependency on hazardous chemicals. Crucially, the success of IPM depends mainly on understanding the ecology and biology of pests in order to apply compatible methods that will significantly reduce the effects of pest infestation.

In addition, understanding the interactions between plant, pest, pest control and the environment is an essential step for developing efficient pest control strategies (Kogan, 1998). Most pests develop interactions with the host plants they attack that are triggered by specific signals that identify a susceptible host leading to the establishment of a parasitic competitive interaction and resulting in crop damage. Studies have illustrated that the adoption of a more ecological approach, in which the interactions between pests and their host plants are fully understood within the context of the local agroecosystem, could lead to the development of more effective and sustainable IPM strategies (Thomas, 1999; Stotz et al., 1999; Witmer, 2007). Moreover, identifying the risks and damages caused by agricultural pests, and understanding the pest/host relationship will help farmers make informative decisions by choosing the most effective, practical, economical, and environmentally sound IPM strategy. If the tactic is successfully adopted, it will reduce the dependency on toxic chemicals and promote the use of cultural controls such as sanitation, crop rotation and harvesting procedures (Hilje et al. 2001).

Sanitation

Sanitation practices play an important role in pest management because they limit the resources pests need to survive and reproduce. In crop production, sanitation includes such practices as removing weeds that harbor pest insects, destroying diseased plants materials or crop residues, and the removal of alternate hosts (Hue & Low, 2015). Many insects reproduce on weeds or other alternate hosts and then attack the main crops. Thus, applying sanitation practices is an essential method to reduce insect pest infestation. The removal of wild host plants such as *Calystegia soldanella*, *C. hederacea* and *Ipomoea indica* for example has shown promising results in reducing weevil infestation in sweet potato crops in Japan (Komi, 2000).

Crop Rotation

Crop rotation is effective against pests that have a limited ability to disperse or that cannot survive for more than one or two seasons without suitable host crops. An effective rotation is achieved when a crop of one plant family is followed by one from a different family that is not a host crop of the pest to be controlled. This method can disrupt the normal life cycle of a pest, reducing its populations and damage (Rechcigl & Rechcigl, 2016).

Crop rotation has shown successful results in reducing pest infestation for different crops such as corn and sweet potato. Corn rootworm insects were significantly reduced by 38% when corn field were rotated with soybeans crops as compared to no rotations crops in Eastern Nebraska (Hill & Mayo, 1980). Moreover, Rajasekhara Rao et al. (2006) reported a low incidence of *C. formicarius* (sweet potato weevil) pest when sweet potato crops were rotated with cowpea, maize, or yam. Similarly, a study by Pillai et al. (1987) showed that rotating sweet potato with rice resulted in tenfold reduction of sweet potato weevil infestation as compared to monoculture of sweet potato in Kerala, India.

Mulching

Studies have shown that implementation of cultural practices such as crop rotation, mulching, and shifting agriculture increase the incidence of natural enemies, reduce pest pressure and enhance crop production (Poveda et al. 2008; Sharma, 2012). Poveda et al. (2008) have shown that practicing cultural controls such as mulching activities reduce pest pressure by 53% and enhance natural enemies by 52%. Similarly, Sharma (2012) demonstrated that mulching of soil surface with crop residue increased the abundance of generalist predators and reduced insect damage to cotton crops.

However, the effect of mulching activities alone is still not very understood in the literature. Some studies revealed significant differences in pest populations after performing mulching activities, while other studies failed to do so. A study on the effects of mulching on *jassid* (leafhopper) population revealed some encouraging results when comparing leafhopper abundance before and after mulching activities (Ranga Rao and Shanower, 1999). A 50% reduction in *jassid* population and injury in mulched area was observed compared to non-mulched crop. In contrast, the observations of the groundnut leafminer indicated no significant effects of mulching throughout the cropping period.

Modeling approaches

Understanding the damage mechanism and the drivers for pest infestation is an essential task to perform successful protection measures. Models have been developed for a number of insects and plant diseases to reduce crop damage and to predict the need for and timing for control applications. Different models to predict the drivers of pest infestation use different variables including pest population growth, natural enemy/ host and parasitoid densities, mortality and distribution, and environmental/climatic variables (Thomas, 1999; Sen et al., 2016; Lima et al., 2009). Those models can serve as a tool to gain an understanding of the processes underlying the behavior of pest-host interaction system, and to use this understanding to provide recommendations to the growers for strategies to reduce or avoid the damage of pest infestation (Plant & Mangel, 1987). Models are known for their flexibility allowing for a gradual introduction of complexity and can serve as a tool to improve decision making (Lima et al., 2009). Therefore, modeling systems are one of the essential means of understanding along with observational data to understand complex systems.

Different modeling approaches are used to predict pest abundance and yield production, ranging from empirical (regression methods as a function of climate variable, etc.) to process-based and highly mechanistic approaches including effects of photosynthesis and respiration (Hillel & Rosenzweig, 2011).

Empirical Approach

Empirical models depend solely on direct observation, measurement and extensive data records of the presence, abundance and reproduction of that species (Kearney & Porter, 2009). These models are widely used to link population levels with habitat traits in a descriptive way, leading to a better knowledge of habitat preferences of insect species. Empirical approaches to predict pest abundance usually include equations that predict pest abundance over time with influencing factors such as temperature, rainfall, relative humidity, and other non-environmental drivers (Rosenzweig, 2011). Numerical models and regression analysis in particular, are often used to reveal the link between landscape elements and pest populations. They allow the researcher to characterize spatial patterns and to identify the explanatory variables using a correlative approach.

Munyuli (2013) used regression to identify factors influencing the abundance of cereal aphids and armyworms wheat pests. In addition to temperature, precipitation and relative humidity, agricultural variables at the landscape scale such as wheat crop area, crop diversity, fertilizer input and yield of wheat, were included. Similarly, Samiee et al. (2009) used regression analysis to identify the drivers of different wheat pests and included cultural practices and IPM adoption in their regression equation.

Regression methodology is generally good at hindcasting and using historical data to link pest abundance with stable environmental conditions and variables. However, this approach is less successful when used to predict pest and disease outbreaks when new conditions present themselves in the future, such as elevated CO_2 levels and climate change (Hillel & Rosenzweig, 2011).

Mechanistic Approach

Mechanistic models offer the possibility to understand the mechanisms resulting in population patterns, and to evaluate the role of habitat and other factors (Vinatier et al., 2011). Mechanistic process-based models consider the dynamic interactions between crops and pest damage, with time as an explicit variable. Those interactions include effects of photosynthesis, transpiration, and state variables such as crop biomass, and leaf area expansion (Dent, 2000; Hillel & Rosenzweig, 2011). Unlike numerical models, mechanistic models use more detailed variables and consider leaf photosynthesis responses to light, temperature and CO_2. These models can also account for new conditions such as climate change and potential responses of the farmers to those changes. Moreover, if a pest is to be modeled mechanistically to make inference on its distribution and damage, then the behavioral, morphological and physiological traits of the species must be taken into consideration. Complex mechanistic models can also include functions that describe relationships of pest abundance and management practices and genetic traits that may change over time, which allows considerations of how adaptive management strategies may affect pest abundance under current or future climate scenarios (Hillel & Rosenzweig, 2011).

Various studies have used a mechanistic modeling approach to predict the effects of pests and diseases on crop production (Dent, 2000; Vinatier et al., 2011; Waggoner & Berger, 1987; Johnson, 1992). A study by Johnson (1992) for example developed a mechanistic growth model to evaluate the effects of potato leaf hopper pest on potato crops. The model included variables such as solar radiation, biomass of green leaf area, temperature, rate of leaf growth and rate of defoliation. Pest sub-models were also developed to evaluate the factors of potato leaf hopper abundance. The pest sub model included the behavioral and physiological variables of the pest itself, such as daily estimates of the density of nymphs on sweet potato leaves, nymphal feeding intensity, lesion expansion, solar radiation and water availability. Moreover, mechanistic models can be developed to assess the risk of pest establishment in order to take the necessary measurements and management practices to reduce crop damage (Kumar et al., 2014).

The choice of the modeling strategy depends mainly on the available variables and the research question. Mechanistic models have shown great results in explaining the biophysical processes instead of simply quantifying relationships between input and output variables with empirical functions (Colbach, 2010). They can also test a large range of scenarios including potential combinations of cropping system components that do not yet exist in farming practice. However, mechanistic models usually require a large number of parameters, which sometimes cannot be estimated for a large number of diverse species (Colbach, 2010).

Chapter 4: Methods & Results

Many studies have used statistical modeling to predict pest abundance (Dent, 2000; France & Thornley, 1984; Hillel & Rosenzweig, 2011). In line with much of the literature, regression analysis was conducted to identify the driving factors of *P. hipponalis* population in Solomon Islands.

Data collection

Garden surveys and interviews were conducted by researchers from the American Museum of Natural History, with support from the Solomon Island Community Conservation Partnership, the World Vegetable Center and Ecological Solutions Solomon Islands, under a wider research project titled 'Biocultural approaches to sustaining Solomon Islands customary land and sea'. Twenty community surveys were conducted with local farmers in each of the four communities of the Western Province of Solomon Islands (Vavanga, West Parara, Biche, and Zaira). All surveys were conducted following a random selection of garden samples in a structured manner to ensure representation of major garden mosaics in each community. The community questionnaires in the 20 gardens in each community were conducted in Pidgin, the local common language, during the months of May, June and July of 2016. Interviews were held with at least five local farmers in each community whose gardens were surveyed prefaced by an informed consent procedure. A structured questionnaire was used and consisted of three categories: pest presence, agrobiodiversity, and use of cultural controls.

Methods

I used a probit regression to assess the effects of cultural practices and crop diversity on *P. hipponalis* presence, while controlling for weather-related variables and natural enemies:

$$Y = \phi\,(Bo + B_1\,T_{min} + B_2\,T_{max} + B_3\,T_{mean} + B_4\,Precip + B_5\,Hum + B_6\,CC1 + B_7\,CC2 + B_8\,CC3 + B_9\,CP + B_{10}\,CD + B_{11}\,Wasp)$$

where Y represents the occurrence or the absence of *P. hipponalis*, T_{min} represents daily minimum temperature (C˚), T_{max} represents daily maximum temperature (C˚), T_{mean} represents daily mean temperature (C˚), Precip represent daily average precipitation (mm), Hum represent daily average relative humidity (%), CC1 states whether the farmer uses mulching or not (0 indicates no use, 1 indicates use of mulching) , CC2 states whether the farmer uses crop shifting or not (0 indicates no use, 1 indicates use of crop shifting), CC3 is the product of both CC1 and CC2 (0 indicates no use, 1 indicates using both mulching and crop shifting), CP states whether the farmer uses chemical pesticides or not (1,0), CD states the number of different crops grown in the garden in addition to sweet potatoes, Wasp indicates whether the farmer recorded wasps in their gardens or not (1,0).

Dependent variable

A probit regression was used due to the binary-nature of the dependent variable. Since the coefficients in the probit model do not represent the marginal effects of the corresponding variable, one to partially differentiate the dependent variable. For example, to estimate the marginal effect of the minimum temperature on pest presence, I used the following equation:

$$\frac{\partial Y}{\partial Tmin} = B_i\,\phi\,(Bo + B_1\,(T_{min}) + B_2\,(T_{max}) + B_3\,(T_{mean}) + B_4\,(Precip) + B_5\,(Hum) + B_6\,(CC1) + B_7\,(CC2) + B_8\,(CC3) + B_9\,(CP) + B_{10}\,(CD) + B_{11}\,(wasp)$$

Farmers were surveyed during the months of May, June and July of 2016 and were asked if they have observed *Psara hipponalis* in their gardens. We assumed that farmers would have answered the question differently if they were asked the same question on a different day. Based on the life cycle of the pest, *Psara hipponalis* is usually abundant during high temperature seasons (May through October in the Solomon Islands), thus, the chance of recording the pest during the months of the survey is higher, disregarding any other effects.

Policy variables of interest

The study included data on agrobiodiversity and cultural controls obtained from local farmers in the four communities in the Western Province of the Solomon Islands. These policy variables of interest are used to assess the importance of practicing different farmer-level methods in order to reduce pest presence and recommend policies for subsistence farmers in the Solomon Islands.

<u>Agrobiodiversity</u>

Agrobiodiversity was captured by identifying and recording different crops and the number of varieties in each garden using a prepared recording form. Farmers in each community were asked about the specific number and types of crops grown in their gardens in addition to sweet potatoes at the time of the survey.

<u>Cultural Controls</u>

Crop rotation and mulching activities can also have an effect on pest and diseases development, as well as nutrient availability (Dogliotti Moro et al., 2013; Leoni et al., 2013). In addition, increasing fertilizer input has a major influence on the material flow in the agroecosystem. Nitrogen fertilizers may significantly increase the populations of different pests due to the availability of nutrients. Cultural controls were captured by asking the farmers whether they practice mulching, crop shifting or apply chemical pesticides in their gardens. They were asked questions like whether they use soil improvements such as mulching and shifting cultivation and whether they let their land rest, use fire, and whether they use pesticides and herbicides.

Controls

Since weather variables can have a significant effect on pest development and abundance, I included them in the regression model as controls. Temperature increases may influence crop pest interactions and pest populations by speeding up pest growth rate, which increases reproductive generations and decreases pest mortality (Cerri et al., 2007). Precipitation and relative humidity may also influence the vital rates, developmental time and fecundity of different pests (Wang et al., 2015; Pan et al., 2014).

The climate variables in this study were obtained from Munda Region Weather Station through researchers at the American Museum of National History. Those variables include daily minimum temperature, daily maximum temperature, daily mean temperature, daily average rainfall and daily average relative humidity. Minimum temperature represents the lowest value of all minimum temperature values for the last 10 days prior to the time of survey for each farmer. Similarly, maximum temperature for each observation represents the highest value among the maximum temperature values for the last 10 days prior to the time of the survey. The reason for choosing 10 days-time lag was based on the peak activity of the green leaf folder pest, which is often 10-12 days. Moreover, mean temperature, precipitation and relative humidity, represent the average value for the last 10 days prior to the time of the survey. For example, if a farmer was interviewed on June 12th, the precipitation value represents the average of all rainfall values from June 3rd to June 12th.

Climate is a principle driver in most pest abundance models (Kearney & Porter, 2009). Although other physical factors such as soil type, moisture, and hydrology could be included, insects are most intimately connected to climatic conditions. Temperature increases may influence crop insect interactions by speeding up the insect growth rates, which in turn increases reproductive generation per crop cycle, and thus increases the crop vulnerability to severe insect infestation (Cerri et al., 2007). The choice of daily climatic data was based on the evaluation of previous studies on the importance of accuracy of weather data using daily measures to account for any possible variability. Research has shown that anything beyond daily data proved unworthy and inaccurate as they are either over estimating or underestimating the yield simulation (Murthy, 2004).

In addition to the presence of nutrients, the abundance of Braconid wasps, which are natural enemies for the green leaf folder pest, is important in determining the abundance of this pest. The presence of Braconid wasps was also controlled for in this model by asking farmers whether they recognize any kind of beneficial insect population in their gardens

Results

I present the results of my research below. I begin with two key in-sample observations before discussing the regression results.

Descriptive Results

Gardening Practices

While gardening practices varied among individual farmers in this survey, two commonly practiced farming techniques by farmers in these four communities are mulching and crop shifting. 63% of farmers who only use mulching have reported to observe the green leaf folder pest in their gardens, while only 22% did not observe the pest. 16% of the farmers who use crop shifting activities have reported to observe the pest, while 22% of them have not. Only 2% of farmers who use both mulching and crop shifting activities have reported to observe the green leaf folder pest, while 52% of the farmers who use both types of cultural control have not observed the pest in their gardens (Fig. 4).

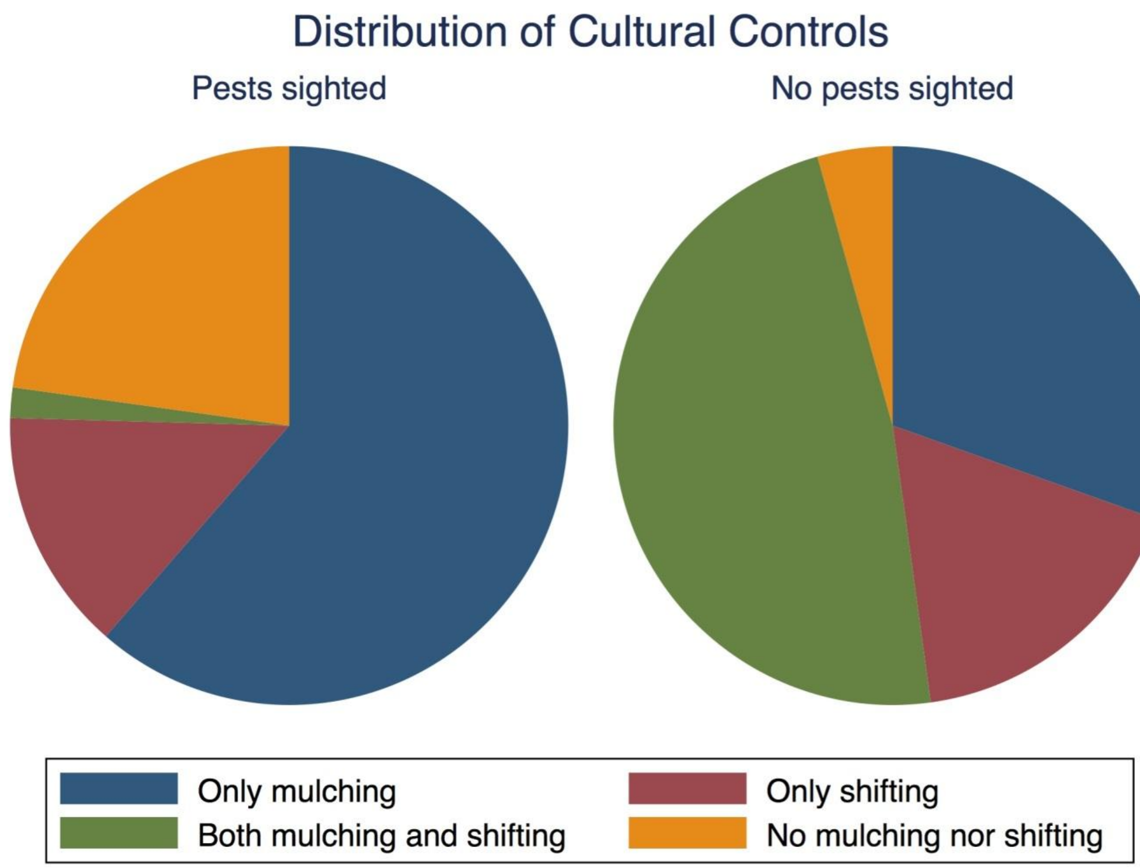

Figure 4. Comparison between farmers who used cultural control methods (mulching, crop shifting, both mulching and shifting and no use of cultural control) and observed the green leaf folder pest, and farmers who also used cultural control methods but did not observe the pest.

These observations suggest that mulching is unlikely to deter the presence of the green leaf folder while shifting cultivation might assist moderately.

<u>Agrobiodiversity</u>

While the measurement of agrobiodiversity typically includes varieties of both wild and cultivated crops, the assessment of agrobiodiversity in this survey only covered crops grown in gardens visited. On average, among the four communities, farmers grew approximately 9 varieties in addition to sweet potato. Those varieties have mainly included other staple crops such as cassava, banana and taro (Fig.5).

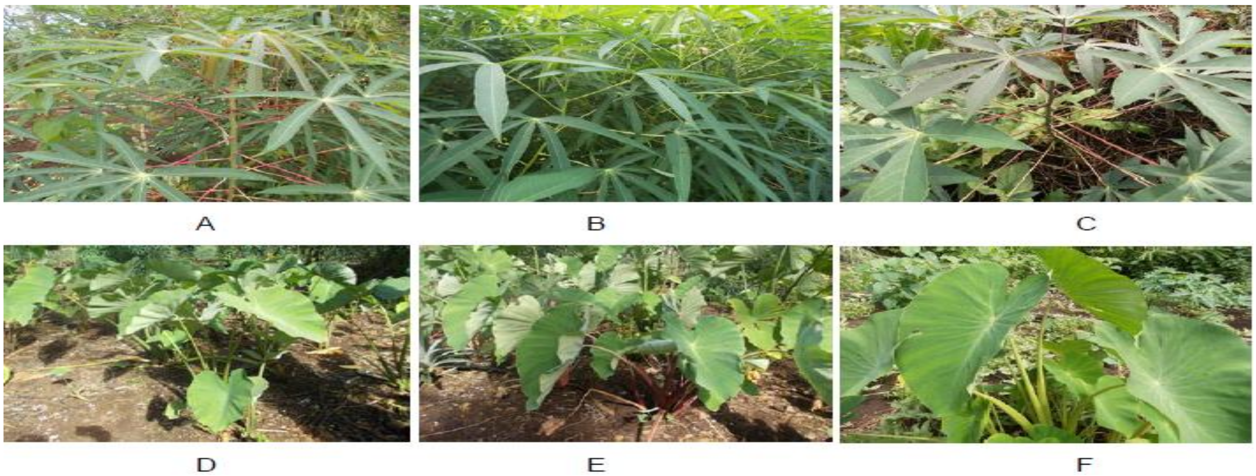

Figure 5. Diversity of cassava varieties (A-C) and taro varieties (D-F) found in gardens at Biche. Source: Iramu, E., & Tikai, P. (2016). A Report on Garden Surveys Conducted at Focus Communities of the American Museum of Natural History in the Western Province of Solomon Islands. World Vegetable Center (AVRDC), Honiara, Solomon Island.

Our data also shows that farmers who observed the pest cultivated a fewer number of varieties compared to farmers who did not observe the pest (Fig.6).

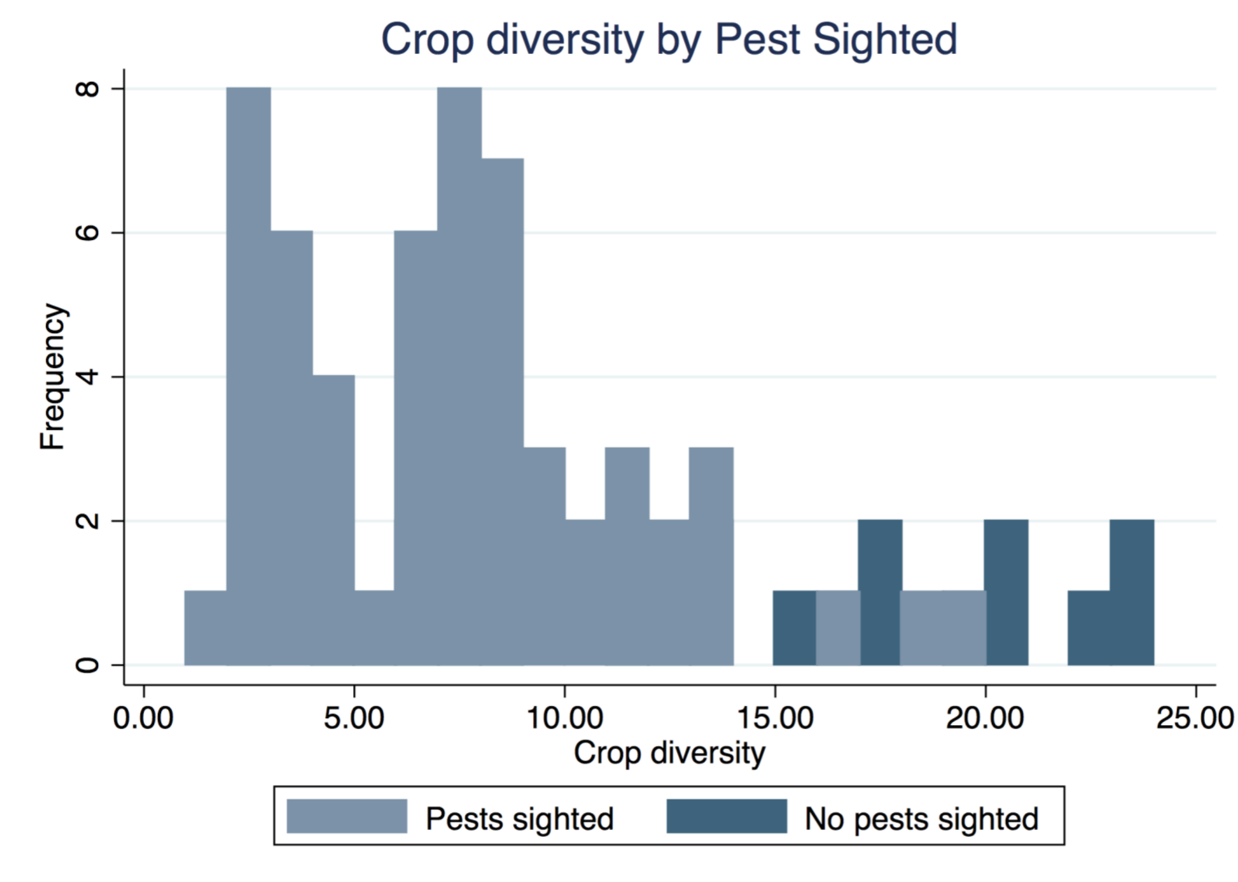

Figure 6. Comparison between farmers who observed the green leaf folder pest in their gardens with the number of different crops grown in their gardens, and farmers who did not observe the green leaf folder pest with the number of different crops grown in their gardens. On average, farmers who did not observe the green leaf folder pest grow a higher number of crop varieties in their gardens.

Regression Results

Based on findings in the literature, the variables related to cultural controls, chemical pesticides, crop diversity and the present of wasps are however, expected to be negatively correlated with pest presence. A review of the literature also suggests that mean and maximum temperatures are expected to be positively and significantly correlated with pest presence while precipitation and relative humidity on the other hand, are expected to be differently correlated with different pests.

My analysis shows that all the coefficients have the expected signs (Table. 2).

*Table 2. The probit regression analysis including the coefficients, p-value, and the marginal effects. ** indicates (p-value<0.05), *** indicates (p-value<0.01)*

Pest	Coef.	P-value	Marginal Effects
Mulching	0.581	0.499	0.130
Crop Shifting	-0.571	0.595	-0.136
Both mulching and shifting	-2.343	0.009***	-0.733
Chemical Pesticides	0.238	0.749	0.044
Crop Diversity	-0.129	0.099	-0.027
Braconid Wasp	-0.591	0.602	-0.154
Minimum Temperature	-1.601	0.220	-0.328
Maximum Temperature	2.153	0.246	0.441
Mean Temperature	0.425	0.895	0.087
Precipitation	-0.271	0.017**	-0.055
Relative Humidity	-0.036	0.737	-0.007

Policy Variables

Mulching and Shifting Cultivation

The marginal effects of the household data obtained from the surveys are also shown in table 2. While mulching or shifting are not statistically significant (with p-values of 0.499 and 0.595 respectively), practicing both mulching and crop shifting is likely to decrease the likelihood of observing the green leaf folder pest by 73% (p-value = 0.009). As mentioned in the literature review above, practicing both mulching and shifting can enhance the presence of natural enemies and reduce pest infestation.

Agrobiodiversity

An increase in the number of diverse crops grown is weakly significant (p-value = 0.099), and decreases the probability of observing the leaf folder pest by 2.7%. Based on the studies presented in the literature review chapter, crop diversification can reduce pest presence by reducing pest colonization rate, and increasing pest mortality due to the enhancement of the abundance and diversity of natural enemies.

Chemical Pesticides

On the contrary, the use of chemical pesticides increases the likelihood of observing the pest by 4%. However, this variable is not statistically significant with a p-value of 0.794.

Controls

Braconid Wasps

Braconid wasps, which are natural enemies for the green leaf folder pest, are negatively correlated with pest presence. The presence of Braconid wasps decreases the probability of observing the green leaf folder pest by 15%. However, the marginal effect of Braconid wasps is not statistically significant with a p-value of 0.602.

Temperature Variables

All temperature coefficients signs in my results are as expected. The minimum temperature marginal effect of -0.328 indicates that as minimum temperature increases, the green leaf folder pest presence is less likely to be observed. The maximum temperature marginal effect of 0.441 indicates that as maximum temperature increases, pest presence is more likely to be observed by the farmers. Similarly, the mean temperature marginal effect of 0.087 indicates that as mean temperature increases, the probability of observing the leaf folder pest also increases by 42%. However, the marginal effects of all temperature variables are not statistically significant with p-values of 0.220, 0.246, and 0.895, for minimum, maximum and mean temperatures respectively.

The results of all minimum, maximum, and mean temperatures in this study did not show a significant correlation with pest presence. The non-significant maximum and mean temperature results in my study are surprising as most studies have shown that higher temperatures influence multiple biological characteristics of insect pests such as life span, fecundity, fertility, abundance, incubation period and development rate (Ju et al., 2011; Zheng et al. 2008; Infante, 2000).

A study in the UK showed that warmer weather conditions are more likely to increase the probability of the insect pest leaf miner (Liriomyza huidobrensis) (Baker et al. 1996). Rice leaf folder pest has also shown to be temperature sensitive, and higher temperatures significantly decreased its developmental time. A study by Padmavathi et al. (2013) showed that development of the rice leaf folder at 7 constant temperatures revealed decreases in developmental time from egg to adult with increases in temperature. At 32° C, total development was completed in 21.8 days, while it took 65.4 days at 18° C.

Moreover, extreme temperatures with an upper threshold of 36.5° C and a lower threshold of 11.2 ° C can negatively affect the survival and development of leaf folder insects (Padmavathi et al. 2103). According to a study by YuanSong et al. (2013), the optimal temperature ranges for leaf folder pests are 22-32° C. The average maximum temperature in this study is 31.61 ° C and the average mean temperature is 27.98 ° C, making an optimal temperature setting for the green leaf folder pest development.

However, the low statistical power of the p-values of the temperature parameter in the present study can be explained due to the time period of the study and the low range of variation. Surveys were conducted only in the three months (May, June and July) of 2016, thus temperature parameters were relatively stable in the time period of the survey. This low range of variation might explain the low statistical power of this variable and the difficulty to show a significant effect in the probit regression model.

Precipitation and Relative Humidity

The marginal effect of precipitation shows a statistically significant negative correlation with pest presence (p-value 0.017). As average precipitation increases, the green leaf folder pest is significantly less likely to be observed on sweet potato crops. Similarly, relative humidity shows a negative correlation with pest presence. As relative humidity increases, the likelihood of observing the green leaf folder pest decreases. However, the marginal effect of relative humidity on pest presence is not statistically significant (p-value <0.05)

The coefficient signs of those two variables indicate a negative relationship with pest presence, which is not entirely consistent with the work of other researchers. Different studies show variable results regarding the effect of precipitation on pest presence. The results in this study imply that as precipitation increases, the likelihood for observing the green leaf folder pest decreases. A significant reduction in tropical pests' abundance during dry seasons has been observed in multiple studies (Janzen and Schoener 1968; Janzen 1973; Wolda 1977). However, several groups of insect pests are known to decline in number during wet seasons and heavy rain incidence (Robinson and Robinson 1970; Boinski and Fowler 1989; Pinheiro et al. 2002). Thus unlike temperature, variation in precipitation can have different effects on different pests.

In line with the present results, Kalode (1974) concluded that high rainfall is unfavorable for leaf folder population increase. Similarly, Abraham et al. (1973) found a significant negative correlation between precipitations and stem borer infestation (*Tryporyza incertulas*). The percentage of stem borer infestation has also been shown to be negatively correlated with relative humidity, although in the present study relative humidity was not significant. The negative correlation between precipitation and the green leaf folder in this study can be explained due to the high sensitivity of this insect to rainfall. Some insect pests, in particular, foliage insects that are directly exposed to changes in the surrounding environments, can be sensitive to precipitation and are killed or removed from crops and leaves by heavy rains (Petzoldt and Seaman, 2006).

In contrast to the present results, a study by Chakraborty and Deb (2015) concluded an insignificant but positive relationship between rainfall and relative humidity and the paddy leaf folder *(Cnaphalocrocis medinalis)* pest population in West Bengal, India, between the years of 2005 and 2008. Similarly, Khan et al. (2004) have concluded that leaf folder larval abundance was highest when average relative humidity and rainfall were 75.70% and 13.90 mm respectively. However, the positive relationship between rainfall and relative humidity and pest abundance was also insignificant. Moreover, different studies have also shown insignificant results of the effects of rainfall on leaf folder pest abundance (Sasaba and Kiritani, 1971; Chakraborty and Deb, 2011). Contradicting with our results, none significant correlation was observed between precipitation and plant leafhopper abundance in Bangladesh between the years of 1998 and 2007 (Ali et al. 2014).

Different studies presented above, concluded varied results regarding the effects of climate variability on pest abundance. However, based on this study, we can conclude that surprisingly temperature plays a lesser role in determining the presence of the green leaf folder pest, while precipitation significantly decreases the presence of this pest.

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Chapter 5: Conclusion and Recommendations

The present study highlights the major influencing factors associated with the green leaf folder pest (*Psala Hipponalis*) presence in the Solomon Islands. A probit regression analysis was conducted to assess the association between pest presence and climate and farmer-level factors. Practicing a combination of both mulching and crop shifting activities has shown to have the most significant effect in reducing the green leaf folder pest presence. In addition, crop diversification has also played a significant but a lesser role in determining the likelihood of observing the green leaf folder pest in the Solomon Islands. In contrast, the application of chemical pesticides as well as the presence of Braconid wasps did not show any significant effects on the green leaf folder pest in this study.

Although this study did not show a significant effect of temperature on pest presence, other studies have shown a strong association between higher temperature and pest abundance. Thus, more studies using a site-specific climate data to determine the effect of climate on pest abundance are needed.

Recommendations and Future Work

This study included two parts: the climate aspect and the house-hold level activities both as potential drivers for the green leaf folder pest presence on sweet potato crops. Although the specific impact of climate change on pest presence is difficult to predict, precipitation showed a significant correlation with the green leaf folder pest. Based on the findings of house-hold level activities on other hand, several recommendations to subsistence farmers in the Solomon Islands can be made:

Recommendation 1: Combine the use of mulching and crop shifting

The application of cultural control activities such as using the combination of both mulching and crop shifting should be demonstrated to subsistence farmers to reduce the green leaf folder pest presence. Using mulching alone or crop shifting alone is not helpful in reducing the presence of this pest. Thus, it is important to emphasize the use of both activities together.

Recommendation 2: Encourage farmers to cultivate a wide variety of crops

Improved varieties of major food crops such as taro and cassava should be introduced more widely to communities to limit the present of green leaf folder pest. The introduction of those crops could also increase the present of natural enemies and enhance sweet potato crop production.

Recommendation 3: Adopt viable integrated pest management practices

Based on the literature review presented in this study, damage by the green leaf folder pest is one of the key limiting factors on sweet potato production and crop quality. Therefore, adopting and formulating locally viable integrated pest management practices and identifying pest tolerant varieties and good agricultural practices should be evaluated and introduced to small landholder farmers in the Solomon Islands.

While this study is able to yield answers to some critical questions, there remain vitally important issues that were outside the scope of the study. In particular, it is important to investigate further the relationship between the drivers and the abundance of the green leaf folder pest using mechanistic modeling approach rather than numerical modeling. A mechanistic approach will provide a detailed understanding of the mechanisms resulting in pest abundance through considering the interaction processes between sweet potato crops and the green leaf folder damage. However, this type of modeling requires more detailed data, which this study lacked, such as number of nymphs present on the leaves, leaf area, light exposure, and more specific data on the morphology and physiology of the green leaf folder pest itself.

In addition, having access to site specific climate data on a finer scale is essential to have more reliable results. For this study, climate data was for the whole Munda region and did not vary by the site of the interview, thus some of my results can be tentative. Moreover, further studies should have the dependent variable as pest abundance with the actual number of pest on sweet potato crops. In this study, due to data limitations, the dependent variable was pest presence, which could be unreliable as farmers recall whether they observe the pest or not. Furthermore, collecting more control variables such as proximity to forests and deforestation is important for future studies. Lastly, a longitudinal study over a large time period is essential in order to account for landscape changes, deforestation, and climate change in the region.

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