Pest control practices of farmers in Taiwan and implications for non-target wildlife

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Abstract

Pests cause devastating losses on agricultural industries worldwide. Common pest management practices include using chemical products. The efficacy of these toxins remains inconclusive, however, and their application can have adverse effects on non-target wildlife from both direct and indirect exposure. In parts of Taiwan, threatened species may be at considerable risk since they inhabit areas with agricultural activity. Therefore, in this exploratory study, we surveyed farmers using a structured questionnaire in Miaoli County, northwestern Taiwan, in agricultural areas that overlap with the distribution of the locally endangered leopard cat (*Prionailurus bengalensis*), whose diet comprises a high proportion of rodents. Based on the completed questionnaires of 126 farmers, the majority stated they use at least two different types of chemical pest control products. Furthermore, pest-related factors, such as perceived worst pest, total pest problem, and number of pests, were all important determinants for pest control behavior. Farmers whose crops were afflicted by rodents were more likely to use rodenticides in addition to other types of pesticides. These agricultural areas, which include vegetable cropland, pose a risk of poisoning to non-target wildlife, like the leopard cat, through various exposure pathways including consumption of contaminated prey and dermal contact. Farmers also expressed support to use less chemical-based pest products, but not to stop using them entirely. Therefore, there may be opportunities to implement ecologically based control practices to mitigate risks to wildlife and promote increased environmental health.

Keywords: pests, farmer perceptions, control practices, rodenticides, pesticides, non-target wildlife

1. Introduction

Pests come in many shapes and sizes, encompass a variety of taxonomic groups, and pose major threats to food security on a global scale (Gray et al., 2009; Bruce, 2010). The pervasiveness of pests and their ability to inhabit a multitude of climates has had drastic costs on crop yields and the agricultural industry as a whole (Singleton, 2003; Savary et al., 2019; Trebicki & Finlay, 2019). Annual crop yield losses to pests typically range from 20% to 50%, but can be as high as 80%, depending on the crop and the country (Oerke, 2006; Bruce, 2010; Deutsch et al., 2018).

To mitigate the adverse effects of pests and maximize agricultural productivity, chemical-based pest control methods are often employed (Oerke, 2006; Gray et al., 2009). Chemical pesticides are broadly defined and encompass a variety of categories, such as insecticides, rodenticides, fungicides, herbicides, nematicides, among others. Insecticides and rodenticides have been found to be the most acutely toxic categories of pesticide to non-target vertebrate organisms (Hallman et al., 2014; Rich et al., 2020; Kaczyński et al., 2021). For instance, to match the diversity of insect pests, dozens of insecticides have been developed with varying modes of action that may target single (narrow-spectrum) or multiple (broad-spectrum) pest species (Ware & Whitacre, 2004; Chang et al., 2005). Despite the global decline in usage, acetylcholinesterase-inhibiting insecticides (carbamates and organophosphates), which are among the most toxic, continue to be used in many parts of the world (Nauen & Bretschneider, 2002; Chang, 2005; Rich et al., 2020). Moreover, even though more recently developed insecticides, such as neonicotinoids, are less toxic than carbamates and organophosphates, they can still have adverse impacts on both non-target invertebrates and vertebrates (Goulson, 2013; Hallman et al., 2014).

Control strategies for rodent pests can include the usage of anticoagulant rodenticides (ARs); where first-generation anticoagulant rodenticides (FGARs) were initially distributed, but due to the developed resistance from rodents over time, second-generation anticoagulant rodenticides

(SGARs) were subsequently introduced (Meerburg et al., 2008; Hong et al., 2019). SGARs have higher toxicity and potential for adverse environmental effects (Rattner et al., 2014; Elliot et al., 2014).

The consistent and widespread use of both FGARs and SGARs has not only resulted in resistant populations of rodents (Lund, 1984; Lu, 1986; Rost et al., 2009; Meerburg et al., 2014), but also toxicity exposure to non-target wildlife (Rattner et al., 2014; Lohr & Davis, 2018). Non-target wildlife can be affected by direct consumption of poisonous baits or secondary exposure via predation or scavenging of poisoned animals (Rattner et al., 2014; Van den Brink et al., 2018). It is even possible for non-target wildlife to become poisoned through tertiary exposure, such as the consumption of a poisoned mesopredator (Eason et al., 1999; Brakes & Smith, 2005).

Chemical-based pesticides (e.g. insecticides, herbicides, fungicides) can result in acute toxicity of non-target wildlife through multiple routes of exposure, which includes inhalation, dermal contact, and ingestion (Hudson & Haegele, 1984; Berny, 2007). Pesticide residues can consequently proliferate through consumer food chains, especially when exposure to lower trophic levels is consistently high (Franke et al., 1994; Liao et al., 2020). Therefore, for predators that readily consume rodents, such as small carnivores and raptors, ARs and other pesticides can represent a major source of secondary poisoning and threaten their conservation (Van den Brink et al., 2018; Hong et al., 2019).

In Taiwan, agriculture constitutes a major component of the economy, accounting for almost 2% of the national GDP (COA, 2020). Farm crops amount to almost half of all agricultural production, comprised predominantly of the products fruit (37.4%), vegetables (26.3%), and rice (15.3%) (COA, 2020). Similar to other Asian countries (Singleton, 2003), rice is an integral food source in Taiwan and in recent years over 1.5 million metric tons have been produced annually (COA, 2020). The paramount importance of these plant crops has implications for pest management and the types of products applied. Hundreds of insecticides and numerous fungicides are registered and approved by Taiwan's Council of Agriculture (COA), including organophosphates and carbamates (Chang et al., 2005; Cheng et al., 2015). Moreover, many of these pesticides are widely used in the agricultural areas of Taiwan (Cheng et al., 2015; Lin et al., 2020). Both FGARs and SGARs have been used to control rodents as pests in agriculture and in urban areas, especially with the launch of an anti-rodent campaign in the 1980s where farmers were provided with SGARs annually free of charge (Lu et al., 2003; Hong et al., 2019). The amount of free ARs provided by the government has since declined chiefly due to conservation initiatives, but they are still supplied to farmers upon request and can also be acquired by other means (Hong et al., 2018). Hence, it is probable that non-target wildlife face risks of exposure to chemical-based pest products. One such species is the locally endangered leopard cat (*Prionailurus begalensis*).

Despite being protected under Taiwan's Wildlife Conservation Act, leopard cats still face several threats, and their once extensive distribution of the island of Taiwan is now limited to fragmented regions of the north-western part of the island (Pei et al., 2014; Chen et al., 2016). The cats are the only indigenous felid remaining in Taiwan and have recently become a conservation priority. They occupy low-elevation habitat and are often observed in modified landscape, including farmland and rural settlements (Chen et al., 2016; I.N. Best, unpublished data). Leopard cats' main prey items are small mammals, notably rats and mice (Chuang, 2012; Hunter & Barrett, 2015). Recently, toxicology reports revealed that deceased leopard cat individuals, victims of road-kill, had traces of SGARs and other pesticides, and had therefore suffered from secondary exposure poisoning (K.J.C. Pei, unpublished data). Hong et al. (2019) also reported the presence of AR concentrations in liver samples of raptor species in Taiwan and the highest concentrations were detected in the rodent-eating species the black-winged kite (*Elanus caeruleus*). The previously mentioned research confirms that top-level predators in Taiwan do face the threat of poisoning via exposure to ARs and other toxins, and reinforces the need to better understand the locations that may reflect high risk and the pest management behaviors that engender these risks.

Human dimensions and wildlife management studies have been conducted in Taiwan before: illegal hunting of and attitudes toward small carnivores (St. John et al., 2015), attitudes toward the conservation of leopard cats (Best & Pei, 2020), attitudes toward the reintroduction of the clouded leopard (Greenspan et al., 2020), and opinions of farmers toward organic farming practices (Petway et al., 2019), but to our knowledge no study has focused on the relationship between pest management of farmers and sources of risk to threatened wildlife. In this exploratory study, we surveyed farmers in an agricultural region in which an endangered species, the leopard cat, is distributed. We collected information from farmers concerning the types of pests that afflict their crops, their perceived knowledge of these pests, and their behaviors for pest control practices. This study provided novel information on the relationship between pests and crop type, factors that may motivate farmers' pest control behavior, and areas where non-target wildlife may be at high risk of toxic exposure. Finally, this research established a basis for determining stakeholder willingness to alter their pest control techniques, transitioning from chemical-based to ecologically-based management.

2. Material and methods

2.1 Study area

The study was conducted from June to October 2020 in the townships Tongxiao, Yuanli, Sanyi, and Zhuolan of Miaoli County, northwestern Taiwan (Figure 1). Miaoli County has ample agricultural activity with its economy largely dependent on this food production. The population of Miaoli is 548,863 and roughly 26% are engaged in agricultural activity, which also includes recreational purposes (Miaoli County Government, 2019). Additionally, 33% of the land is designated as farmland for agriculture (Miaoli Land Use, 2020). With respect to crop production in townships, Yuanli and Tongxiao townships grow rice, Sanyi township produces vegetables, and Zhuolan township produces predominantly fruit (Miaoli County Government, 2020). The townships were selected for the study due to the variation in landscape features, crop type and agricultural practices, as well as the distribution and presence of small carnivores, specifically the leopard cat (Pei et al., 2014; Chen et al., 2016; I.N. Best, unpublished data). Additionally, the townships Yuanli, Sanyi, and Zhuolan have been found to have high soil contamination of pesticides based on the hazard index (HI) of chemical residuals (Liao et al., 2020). Therefore, an objective of this study was to assess the extent of rodenticide and pesticide usage by farmers, and to determine any implications for downstream toxicity towards the locally endangered leopard cat and other non-target wildlife.

2.2 Data collection

We utilized a structured questionnaire for this social survey (Available from I.N. Best). The questionnaire was first drafted in English and then translated to Mandarin Chinese. Preliminary tests of the questionnaire were conducted on eight farmers to help identify any issues or lacking content. Based on the feedback, the questionnaire was revised and included statements and questions to collect data pertaining to socio-demographic variables of participants, information about their farms and farming practices, types of pests and extent of pest-related damages, and pest control practices and behavior. Questions requesting information on the usage of specific rodenticides or pesticides, such as chemical name or brand name, were not included due to sensitivity issues, since some products have been banned. Overly sensitive topics may motivate participants to misreport or avoid the content all together (Tourangeau & Yan, 2007; Nuno & St. John, 2015). Rodenticides and pesticides were distinguished from one another in the questionnaire, and pesticides were defined as insecticides, fungicides and herbicides. The questionnaire was designed to take a participant roughly 15-minutes to finish.

Most of the questionnaires were distributed with the help of the local farmer's association centers in each township of the study area, which enabled access to the target demographic group and facilitated sampling a wide representation of farmers. The farmer's association provides services for farmers locally, which includes technical advice and sale of agricultural products. All questionnaires were accompanied with a cover letter stating the scope of the survey, affiliated research institutes, anonymity of participant identity, and voluntary consent to participate in the study. We also collected questionnaire responses by employing quasi-random sampling. In the agricultural areas of the townships of the study area, we would ask a random selection of farmers if they would be willing to complete the questionnaire.

2.3 Data analysis

The responses of each returned questionnaire, which were in Mandarin Chinese, were translated into English. After going through all returned questionnaires and data cleaning, questionnaire responses from 126 farmers were retained. For a complete list of predictor variables used in the analyses described below, refer to Table 1.

Based on the information provided by the farmers concerning the main crop they grow, we were able to group their responses into three main crop types: rice, vegetables, and fruits. Since crop type was found to be highly associated with township ($\chi^2_4 = 105.20$, $p < 0.001$), crop type was used as a proxy for agricultural landscape differences. Types of pests that are problematic for farmers were compared together to establish which pest farmers perceived as the worst (referred to as *worst pest*, Table 1). A cross tabulation and Pearson chi square test was run to test for an association between worst pest and crop type. We were also able to determine how problematic farmers viewed each type of pest throughout their crop production process, ranging from no problem to a dual problem. For each participant, we calculated the cumulative score of problems caused by the pests: rodents, insects, fungi, plants, and other. If a farmer reported that a pest caused damage to their crops during either the growing (pre-harvest) or storing (post-harvest) stage, but not both, a value of 1 was scored for that pest. A value of 2 was scored for a pest if a participant reported that damage was caused to their crops during both the growing and storing stages. Therefore, cumulative scores could range from 0 to 10 (referred to as *total pest problem*, Table 1). The total number of pests reported by each farmer were also determined, which included the same pests as in *total pest problem* (referred to as *number of pests*, Table 1). For the variables *total pest problem* and *number of pests*, since the interval between each value in their range could not be confirmed to be equal, we treated the variables as ordinal categorical (Casacci & Pareto, 2015; Midega et al., 2016). Generalized linear models (GLM) with an ordinal logistic link function were run to test for differences between each type of crop for the dependent variables *total pest problem* and *number of pests*. GLMs are a robust form of analysis with applications of transformation for many types of data that are not normally distributed (Hamada & Nelder, 1997). Farmers also provided estimates on annual crop loss caused by pests (referred to as *percent crop loss*, Table 1), so a GLM was performed with the predictor variables *crop type*, *worst pest*, *total pest problem*, and *number of pests* included as main effects.

Only three farmers stated they only use rodenticides, therefore, when we established a variable for chemical pest control product usage (referred to as *product usage*), we excluded these three responses. Farmers were assigned to the groups 'none' (no chemical pest control product usage), 'pesticides only' (use of insecticides, herbicides, and/ or fungicides), or 'both' (use of rodenticides and pesticides). To determine what factors (Table 1) contributed to farmer pest control product usage cross tabulations and chi-square tests were performed.

We also totaled the number of different pest control chemical products (e.g. rodenticides, fungicides, insecticides, herbicides) for each farmer (referred to as *# different products*). This variable was treated as ordinal categorical. A GLM with an ordinal function was used to determine the effect of each predictor variable on *# different products*. Since there was missing data for many of the predictor variables, to avoid an accumulation of missing data and subsequently alter any significant effect, separate models were performed between each predictor variable and the dependent variable *# different products*. We included both variables *product usage* and *# different products* in the scope of the main text because of the different implications for risks to non-target wildlife. ARs and other pesticides may result in different exposure pathways of toxicity (Berny, 2007; Rattner et al., 2014). To test for the effect of *product usage* and *# different products* on *percent crop loss*, a GLM was run with both variables included as main effects.

We assessed willingness to use less and/ or stop using rodenticides and pesticides, based on Likert scores for statements from the questionnaire. Separate statements were included for willingness to use less and willingness to stop using pest control product categories (i.e. rodenticides and pesticides). The variables for these statements (hereafter referred to as *use less* and *stop using*) were analyzed individually due to the different implications for farmers; some participants may be willing to use less but not willing to stop using altogether. Only responses from farmers who stated they currently use rodenticides and/ or pesticides were included in the analysis. We also queried participants on how effective they perceive these pest control products to be. The Likert scale for these statements ranged from 1 (strongly disagree) to 5 (strongly agree). If farmers selected "uncertain" these responses were excluded from the analysis. Relationships between these dependent variables were determined using Spearman rank correlation (Spearman, 1904). Participants also provided responses for reasons and/ or incentives to change the amount of chemical pest control products (please see Table S3 for the full list).

For all cross tabulations, when necessary, Fisher's exact tests were used for quality control of the data (Upton, 1992). For each statistical analysis performed significance was considered at $\alpha = 0.05$. All statistical analyses were completed with SPSS *v.26.0* (IBM, Armonk, USA).

3. Results

3.1 Farmer background information

For a list of the socio-demographic factors and background information of the farming practices of the participants, please refer to Table S1. Based on the responses, most of the participants were male (67.3%, *n* = 107), with around a third (32.7%) female. Roughly three-quarters of the participants' (*n* = 126) main income was stated as farming. The most abundant crop type of the participants was fruit (53.2%, *n* = 126), followed by rice (27.8%) and then vegetables (19.0%).

3.2 Agricultural and pest landscape

Fungi was most commonly ranked as the worst pest for participant farming practices (37.3%), followed by insects (35.7%), rodents (19.8%), and other types of pests (3.2%). No farmers selected plants as their worst pest, and 4.0% claimed pests were not a problem. *Worst pest* was significantly associated with crop type ($\chi^2_8 = 36.78$, $p < 0.001$; Figure S1). The worst pest for rice (*n* = 35) was tied between rodents and insects (both 37.1%). The worst pest for vegetables (*n* = 24) was insects (45.8%) followed by rodents (37.5%). Finally, participants reported that their fruit crops (*n* = 67) were most afflicted by fungi (58.2%), and then insects (31.3%).

The average score of *total pest problem* for farmers was 2.9 ± 0.1 (Median = 3.0, IQR =2.0, *n* = 126). *Total pest problem* was not significantly associated with crop type (Wald $\chi^2_2 = 0.42$, $p = 0.810$). The mean number of different pests during the farmer's crop production was 2.3 ± 0.1 (Median = 2.0, IQR = 1.0, *n* = 123). Insects were the most common pest reported by farmers (77.8%), followed by fungi (65.1%), rodents (55.6%), plants (22.2%), and other pests (11.9%). *Number of pests* did not differ between crop type (Wald $\chi^2_2 = 0.63$, $p = 0.729$).

The average estimated annual crop loss due to pests reported by farmers was 15.7% ± 1.3 (range = 0 – 50%, *n* = 93), but there were no significant differences between crop type (Wald $\chi^2_2 = 4.19$,

p = 0.123) or worst pest (Wald χ^2_4 = 5.06, p = 0.281). Estimated annual crop loss was not affected by *total pest problem* (Wald χ^2_5 = 9.76, p = 0.082), but it was by *number of pests* (Wald χ^2_3 = 8.54, p < 0.05). Farmers that reported two or more pests also reported a higher estimated annual crop loss (Figure S2).

3.3 Pest control practices and behavior

One-third of the farmers in the survey stated they currently use rodenticides (33.3%, n = 126). Contrarily, over three-quarters of the participants indicated they use pesticides (77.8%, n = 126). More specifically, 38.0%, 55.4%, and 64.5% of farmers stated they use herbicides, fungicides, and insecticides, respectively (all n = 121). 31.0% of the farmers responded that they use both rodenticides and pesticides, and 46.8% used pesticides only (both n = 126). Only 3 farmers indicated that they only use rodenticides and 25 stated that they do not use any chemical pest control product (both n = 126).

Education, crop type, worst pest, total pest problem, and number of pests were found to be significant explanatory variables of *product usage* (all p < 0.05, Table 2). Farmers with more formal education were less likely to use both rodenticides and pesticides and more likely to use no chemical pest control products (Figure 2). Additionally, farmers that grow vegetables and rice, as well as ranked rodents as their worst pest were more likely to use both categories of pest control products, whereas farmers that grow fruit and ranked fungi as their worst pest had higher proportions of using only pesticides (Figure 2). Farmers who were scored to have higher *total pest problems* had a higher propensity of using both rodenticides and pesticides (Figure 2). Farmers that reported three or four different pests were found to have a higher likelihood of using both rodenticides and pesticides (Figure S3).

The average number of different products used by farmers was 1.9 ± 0.1 (Median = 2.0, IQR = 2.0, n = 121; Figure S3). Worst pest, total pest problem, and number of pests had significant effects on *# different products* (all $p < 0.05$, Table 3). Farmers who ranked rodents as the worst pest, were scored to have a higher overall pest problem, and reported a higher number of pests were found to use more pest control products (Figure 3).

Percent crop loss was not affected by *product usage* (Wald $\chi^2_1 = 1.77$, $p = 0.183$) or *# different products* (Wald $\chi^2_3 = 2.84$, $p = 0.417$).

3.4 Willingness to change pest control practices and behavior

Among the farmers that stated they currently use rodenticides, almost half indicated agreement for willingness to use less (45.9%, $n = 37$), though, far less participants were willing to stop using rodenticides altogether (24.3%, $n = 37$; Table 4). Additionally, over half of the farmers stated they think rodenticides are effective (54.7%, $n = 37$; Table 4). The average Likert scores (1-5) for *use less rodenticides* and *stop using rodenticides* were 3.24 and 2.70, respectively. *Use less rodenticides* and *stop using rodenticides* were also significantly correlated ($p < 0.001$; Table S2). When queried about reasons for willingness to change rodenticide use practices, the most common response was to help protect the environment (29.0%, $n = 62$), followed by protecting other's health (19.4%), protecting personal health (16.1%), and financial compensation (i.e., receiving financial payments to change the usage of the pest control product; 16.1%).

Almost two-thirds of the farmers who informed they use pesticides were willing to use less pesticides (65.6%, $n = 93$; Table 4). Only a small proportion of the participants indicated agreement to stop using pesticides (19.4%, $n = 93$; Table 4). 71.4% of the participants stated they think pesticides are effective ($n = 91$). The mean Likert scores for *use less pesticides* and *stop using pesticides* were 3.58 and 2.62, respectively. The two variables were also positively correlated ($p <$ 0.005; Table S2). *Stop using pesticides* and *think pesticides are effective* were negatively correlated ($p < 0.05$; Table S2). Additionally, *stop using rodenticides* and *stop using pesticides* were positively correlated ($p < 0.001$; Table S2). The most frequently selected reasons for participants changing their pesticide use practices were protecting other's health (26.6%, n = 169), protecting personal health (23.7%), helping to protect the environment (23.1%), and financial compensation (11.2%).

4. Discussion

In this exploratory study, farmers indicated that fungi and insects were the most damaging pests for fruit and vegetables, respectively. Furthermore, rodents were ranked as the worst pest, alongside insects, for the crop type rice. Therefore, it is clear that certain pests are more likely to afflict particular crop types. Our findings are consistent with other studies where farmers have reported rodents to be very problematic pests for rice production (Tuan et al., 2003; Brown et al., 2008; Stuart et al., 2011), insects for vegetable crops (Obopile et al., 2008; Abang et al., 2014; Nyangau et al., 2020), and fungal infections for fruit crops (Ann et al., 1999; Amata et al., 2009; Lahlali et al., 2021).

Overall, insects were the most commonly reported pest in our survey. This is not surprising as insects encompass a very large and diverse taxonomic group making them candidate pests for a plethora of crop varieties (Dhaliwal et al., 2010; Rajendran & Singh, 2016). Fungi were the second most common pest selected by farmers, which may be due to the large number of fruit farmers in our sample. Fungi, which can be responsible for rot and other crop diseases, can afflict a variety of fruit crops (Ann et al., 1999; Byrde & Willetts, 2013).

One-third of the farmers in this survey responded that they currently apply rodenticides. Only three of these farmers stated that they do not use any other pesticide. This demonstrates that farmers who use rodenticides most likely use other pesticides. The use of some type of pesticide (e.g. insecticides, fungicides, or herbicides) was very prevalent among the farmers in our survey, and around half of the farmers claimed to only use pesticides. Since many of the participants were fruit farmers with fungal problems for their crops, the need to apply fungicide would be understandably high. This also likely helps explain the significant associations between *product* *usage* and the explanatory variables *crop type* and *worst pest*; farmers who grow fruit and reported fungi as their worst pests were more likely to just use fungicides. Fruit rot due to fungi can cause considerable damage to fruit crops with substantial economic losses (Ann et al., 1999; Byrde & Willetts, 2013). Additionally, farmers that grow vegetables and ranked rodents as their worst pest had a high proportion of using both rodenticides and pesticides. Therefore, it is likely that the crops that are afflicted by rodents are also damaged by other pests, such as insects, resulting in the usage of different pest control products. Different species of insects will target a diverse selection of crops and rodents are known to be problematic for various crops of leafy vegetables and rice (Adler, 1995; Singleton, 2003; Oerke, 2006; Lehmann et al., 2020). Therefore, it is probable that in many agricultural systems, including the current study area, crops are at risk to multiple pests, and farmers will respond accordingly with reactive measures to minimize crop loss (Oerke, 2006; Stuart et al., 2011; Tomass et al., 2020).

The only socio-economic variable associated with *product usage* was education. In our survey we found that farmers with more formal education were less likely to use both pesticides and rodenticides, and more likely to not use any chemical pest control products. This result is consistent with other wildlife management research, where higher educated individuals are more likely to support ecological and conservation initiatives (Gifford & Nilsson, 2014; Mkonyi et al., 2017; Best & Pei, 2020). This subset of participants in the present study claimed to not use pesticides for environmental protection, therefore, it is likely that they already practice environmentally-friendly farming. Despite the above finding, all the other significant explanatory variables for both *product usage* and *# different products* were farming-related and contingent on the severity of the pest problem.

Total pest problem and *number of pests* were found to be strong predictors for both *product usage* and *# different products*; farmers that reported a more severe pest problem and higher number of pests used more chemical pest control products. These findings could indicate that perceived pest severity results in an increased usage of pest control products (Savary et al., 2017; Zhang et al., 2018). Moreover, if farmers observe more crop damage that they perceive to be from multiple sources of pests their responses may be reactive exemplified by the application of multiple pesticides to minimize further crop losses (Singleton, 2003; Zhang et al., 2018; Tomass et al., 2020). Additionally, farmers may follow community patterns in their pesticide use behavior (Bagheri et al., 2019; Petway et al., 2019), which was found to be an important consideration for pesticide usage in the present study (I.N. Best, unpublished data).

Intuitively, farmers who reported more pests afflicting their crops also had higher estimations for annual crop losses. However, the difference between two, three, or four pests was non-significant, which likely indicates that certain pests are more damaging for certain crop types (Oerke, 2006; Savary et al., 2019). We also found that estimated percent crop loss was not affected by the variables *product usage* or *# different products*. A possible explanation for this finding could be that farmers also suffered losses to their crop yields by factors other than pests, such as climatic conditions and inclement weather (Oerke, 2006; Iizumi et al., 2018). Also, the variables *product usage* and *# different products* did not take into account the intensity and amount of each chemical product used and frequency of application, so farmers could use fewer products, but apply them more often in larger quantities. Therefore, future studies should further investigate additional fine-scale information of farmers' pest control practices.

The results of this study have highlighted areas where non-target wildlife may be especially at risk to chemical poisoning. Vegetable and rice farmers were more likely to use both rodenticides and pesticides compared to fruit farmers. Additionally, farmers perceived rodents to be more problematic for rice and vegetable crops, which could represent high rodent activity in these modified habitats. Rodents like the lesser ricefield rat (*Rattus losea*) and striped field mouse

(*Apodemus agararius*) have been recorded to be prolific pests of crops including leafy vegetables, sweet potato, and rice in western Taiwan (Ku & Lin, 1980; Adler, 1995). These two species are common items of a leopard cat's diet (Chuang, 2012) and are widely distributed throughout lowland Miaoli County (I.N. Best, unpublished data). Rodent specimens from Miaoli County have also been tested for the presence of rodenticides and pesticides. Samples of hair, liver, intestine, and stomach were assayed for concentrations of the chemical products, and hair samples were frequently found to have traces of pesticides, including fungicides and insecticides belonging to the chemical groups organophosphates and carbamates (Pei, 2019). These results support the propensity of rodent exposure to pesticides through dermal contact and illuminate the potential risk of secondary intoxication of pesticides for predators of rodents. Moreover, the same research (Pei, 2019) also detected concentrations of an FGAR (coumatetralyl) and four SGARs (brodifacoum, bromadiolone, difenacoum, flocoumafen) in liver samples, as well as insecticides (carbofuran, chlorpyrifos) in stomach samples from leopard cat road-kill specimens that were collected in Miaoli County. Therefore, in addition to secondary intoxication of rodenticides, leopard cats and other non-target wildlife face threats of poisoning of pesticides due to their widespread application.

If rodent activity is high in certain crop land, leopard cats may be attracted to these regions and these agricultural fields could reflect an ecological trap (Rotem et al., 2011). Radio-tracking of leopard cats in southern Miaoli County, inclusive of our study area, has uncovered that farmland, which includes vegetable crop fields and fruit orchards, are preferential foraging sites for the cats (Pei et al., 2020). Leopard cats were observed to spend entire nights hunting in farmland, thus, they could face exposure to pesticides via direct pathways (e.g. inhalation, dermal contact, ingestion) and by consuming prey that has also likely been in contact with the chemical products (Berny, 2007).

Leopard cats and other non-target mammals could be at risk to pesticide exposure and toxicity via their grooming behavior (Mayer et al., 2020). Farmers from our survey reported observing the small carnivore species ferret badger (*Melogale moschata*) and masked palm civet (*Paguma larvata*) in their farmland (I. N. Best, unpublished data). If these mammals traverse through areas that have recently been sprayed with chemical pesticides, they could be subject to dermal exposure, which could result in an uptake pathway through oral grooming (Mayer et al., 2020). Liao et al. (2020) found that the highest concentration of pesticide residuals from soil samples collected throughout Miaoli County were in the townships Tongxiao, Yuanli, Sanyi, and Zhuolan, which overlaps with our study area. In addition to acute poisoning, toxicity from chemical pest products can be sublethal with detrimental impacts on neurology, behavior, and reproduction (Brakes & Smith, 2005; Fraser et al., 2017; Rich et al., 2020). For instance, leopard cat individuals victim to roadkill may have had neurological impairments as a result of pesticide toxicity, which may have affected their vigilant behavior and agility when crossing roadways (Liao et al., 2020). In order to help protect non-target wildlife, especially the endangered leopard cat, alternatives intended to moderate the use of chemical-based pest control should be explored, such as ecologically-based pest management (EBPM). EBPM aims to develop control strategies centered on the ecology and biology of the pest and that management should consider ecosystem services, such as biodiversity and natural enemies via biological control (Singleton et al., 1999; Zhao et al., 2016; Martínez-Sastre et al., 2020). However, effective execution of this will require the compliance and support of stakeholders, the farmers.

Among the farmers who currently use rodenticides and pesticides, many were found to be willing to reduce their usage and application. However, far less participants were willing to stop using rodenticides and pesticides altogether; less than one-quarter for each. The majority of the farmers in our survey stated that their main source of income is from farming, so the absence of effective pest management could result in considerable economic losses. Farmers that are financially dependent on their crop yields may be far less motivated to risk suffering additional crop losses due to reductions in their pest control practices (Cooper & Dobson, 2007; Zasada, 2011). Therefore, to encourage farmers to reduce their usage of chemical pest control products or even transition entirely from synthetic pesticides, efficient and economically feasible alternatives need to be clearly communicated to these stakeholders (Sherman & Gent, 2014; Bagheri et al., 2019).

More than half of the participants using rodenticides thought they were effective, and almost three-quarters agreed pesticides were effective. Moreover, perceived effectiveness of pesticides was negatively correlated with willingness to stop using pesticides. These perceptions of the efficacy of the chemical-based pest control products may influence the farmers' decisions to change their pest control behavior, specifically to stop using the products. If a farmer's intention is to maximize their crop yield, they may be less inclined to give up or even modify practices they perceive promotes productivity (Bagheri et al., 2019). However, other studies surveying farmers have reported that pest management should be multifaceted to be most effective, not just relying on chemical-based solutions (Brown et al., 2008; Flor & Singleton, 2011; Stuart et al., 2011). In the present study, environmental protection and protecting human health were among the most popular incentives for changes to the amount of both rodenticide and pesticide usage. These findings imply that the famers in Miaoli County are concerned about the health of their environment, community, and person. Therefore, a strategy to increase support for a reduction of chemical-based pest management could be to further educate the farmers on the ecological hazards associated with the products, such as the adverse impacts on non-target wildlife (Flor & Singleton, 2011). These educational campaigns could also introduce a platform for integrating EBPM. The government resources and support networks that are already established, including the farmer's association centers, for farmers in Taiwan (COA, 2020) could also help promote awareness of EBPM with relevant educational guides on the ecological factors of pests. EBPM has been found to be effective in preventing crop damage in other parts of Asia (Singleton et al., 2005; Brown & Khamphoukeo, 2010; Jacob et al., 2010; Zhao et al., 2016). Therefore, with proper design and training the adoption of EBPM could be beneficial for sustainable agriculture and wildlife conservation.

5. Conclusions

To date, the relationship between behaviors of farmers for pest control management and risk factors for wildlife in Taiwan remain relatively unexplored. This study highlights the pests that afflict damage to different crop types in the Miaoli agricultural area and the subsequent pest control practices employed to mitigate these losses. Pest-related factors were strong predictors of farmers' pest control behaviors. In agricultural areas where farmers applied rodenticides, they were also likely to use pesticides. Therefore, the combination of various chemical pest control products poses a critical risk for non-target wildlife, which includes the leopard cat. Although most farmers were opposed to terminating their use of rodenticides and/ or pesticides altogether, there was apparent support for incurring reductions of the chemical products. Farmers appeared to be empathetic to protecting their community and environment from the hazards associated with chemical pest control products, and further educational programs and support could incentivize the integration of EBPM.

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Tables

Table 1. Definitions and coding for predictor variables associated with socio-economic factors and farming practices of participants

Predictor	Definition	Type of variable and coding
Age	Age of participant	Ordinal. 1 = 18-25, 2 = 26-35, 3 = 36-45, 4 = 46-55, 5 = 56-65, 6 = 65+
Gender	Gender of participant	Nominal (binary). 1 = Male, 2 = Female
Education	Highest level of education participant has completed	Ordinal. 1 = Elementary school, 2 = Junior high school, 3 = High school, 4 = University/ College, 5 = Graduate studies
Main income	The main source of income for the participant	Nominal (binary). 1 = Farming, 2 = Other
Ownership of farm	Whether a farmer owns their farmland or not	Nominal (binary). 0 = No, 1 = Yes
Farming experience	The number of years a participant has been farming	Ordinal. 1 = 1-10, 2 = 11-20, 3 = 21-30, 4 = 30+
Pets	Whether a participant has pets (dogs and/ or cats)	Nominal (binary). 0 = No, 1 = Yes
Farm animals	Whether a participant keeps livestock and/ or poultry	Nominal (binary). 0 = No, 1 = Yes
Crop type	The main crop grown by farmers grouped into categories	Nominal. 1 = Rice, 2 = Vegetables, 3 = Fruit
Crop storage	Whether a farmer stores their crops before distribution/ sale	Nominal (binary). 0 = No, 1 = Yes
Worst pest	The pest farmers perceive as the worst/ causes the most damage to their crops	Nominal. 0 = None, 1 = Rodents, 2 = Insects, 3 = Plants, 4 = Fungi, 5 = Other
Total pest problem	The cumulative extent of problem of pests (rodents, insects, fungi, plants, other)	Ordinal. 0 = None, … 10 = Worst (dual problem from all pests)
Number of pests	The number of pests that affect the crops of a farmer	Ordinal. 0 = None, … 4 = Maximum number of pests scored
Percent crop loss	The estimated percentage of crop loss from pests reported by farmers	Numerical (continuous)

Table 2. Chi square test statistics determining associations between independent variables and dependent variable *product usage* (none, pesticides only, both: rodenticides and pesticides). Significance is indicated in bold.

Variable	*n*	χ^2	*df*	*P*
Age	117[a]	10.75	10	0.384
Gender	104[a]	2.27	2	0.322
Education	120[a]	15.51	8	**<0.05**
Main income	123	4.06	2	0.132
Ownership	121[a]	0.88	2	0.643
Farming experience	114[a]	10.83	6	0.094
Pets	122[a]	2.79	2	0.248
Farm animals	121[a]	0.08	2	0.962
Crop type	123	10.59	4	**<0.05**
Crop storage	123	1.51	2	0.470
Worst pest	123	50.21	8	**<0.001**
Total pest problem	123	39.27	12	**<0.001**
Number of pests	120	27.99	8	**<0.001**

Notes: 'Rodenticide use only' was excluded from the analysis due to limited sample size of 3 farmers. Here 'pesticides' includes insecticides, fungicides, herbicides, and other. [a] indicates lower total *n* value due to missing data, participants left these questions blank.

Table 3. Separate ordinal GLMs between each factor (independent variable) and the dependent variable *# different products* (rodenticides, insecticides, fungicides, herbicides, other). Significance is indicated in bold.

Model	Factor	Wald χ^2	*df*	*P*
1	Age	3.70	5	0.593
2	Gender	0.32	1	0.573
3	Education	6.12	4	0.191
4	Main income	2.04	1	0.153
5	Ownership	0.10	1	0.750
6	Farming experience	4.16	3	0.245
7	Pets	1.64	1	0.200
8	Farm animals	0.00	1	0.985
9	Crop type	0.67	2	0.751
10	Crop storage	0.79	1	0.374
11	Worst pest	24.21	4	**<0.001**
12	Total pest problem	44.02	6	**<0.001**
13	Number of pests	32.75	4	**<0.001**
14	Percent crop loss	0.48	1	0.488

Notes: Models were run separately for each factor to test the effect with full available data and to avoid influencing the model due to too many missing data values.

Table 4. Distribution of farmer pest control behaviors; use of rodenticides and pesticides, as well as mean Likert scores for statements (1-5), and agreement for perceived effectiveness, willingness to use less or stop using.

			Likert	% of farmers		
Behavior	***n***	**Freq. (%)**	**score**	**Disagree**	**Neutral**	**Agree**
Use rodenticides	126	42 (33.3)				
Think they are effective	37		3.57	2.7	43.2	54.1
Willingness to use less	37		3.24	24.3	29.7	45.9
Willingness to stop using	37		2.70	51.4	24.3	24.3
Use pesticides	126	98 (77.8)				
Think they are effective	91		3.77	1.1	27.5	71.4
Willingness to use less	93		3.58	14.0	20.4	65.6
Willingness to stop using	93		2.62	52.7	28.0	19.4

Figure legends

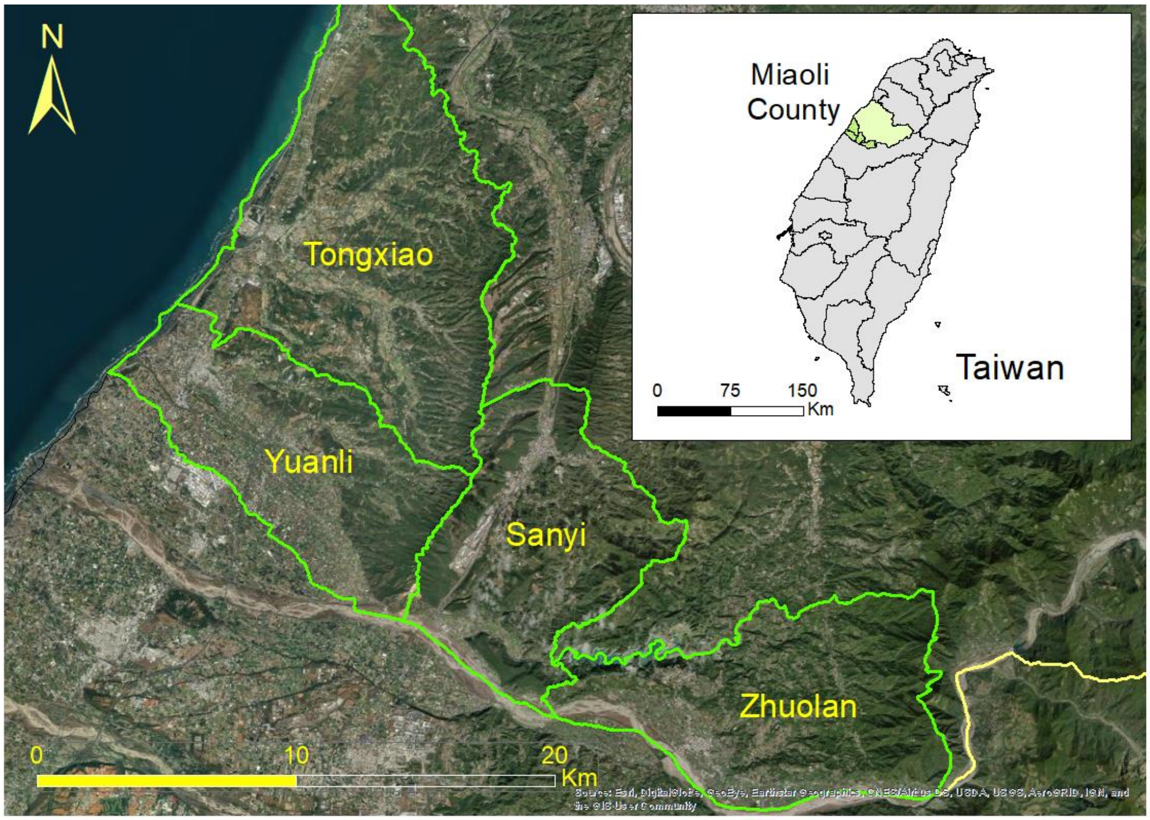
Figure 1. Map of townships Zhuolan, Sanyi, Yuanli, and Tongxiao in Miaoli County, Taiwan, where sampling for the survey was conducted. Satellite basemap imagery (Esri, 2021).

Figure 2. Pest control product usage (none, pesticides only, both: pesticides and rodenticides) of farmers compared between A) education (n = 120), B) crop type (n = 123), C) worst pest (n = 123), and D) total pest problem (n = 123), from participants of the survey in Miaoli County (June – October 2020).

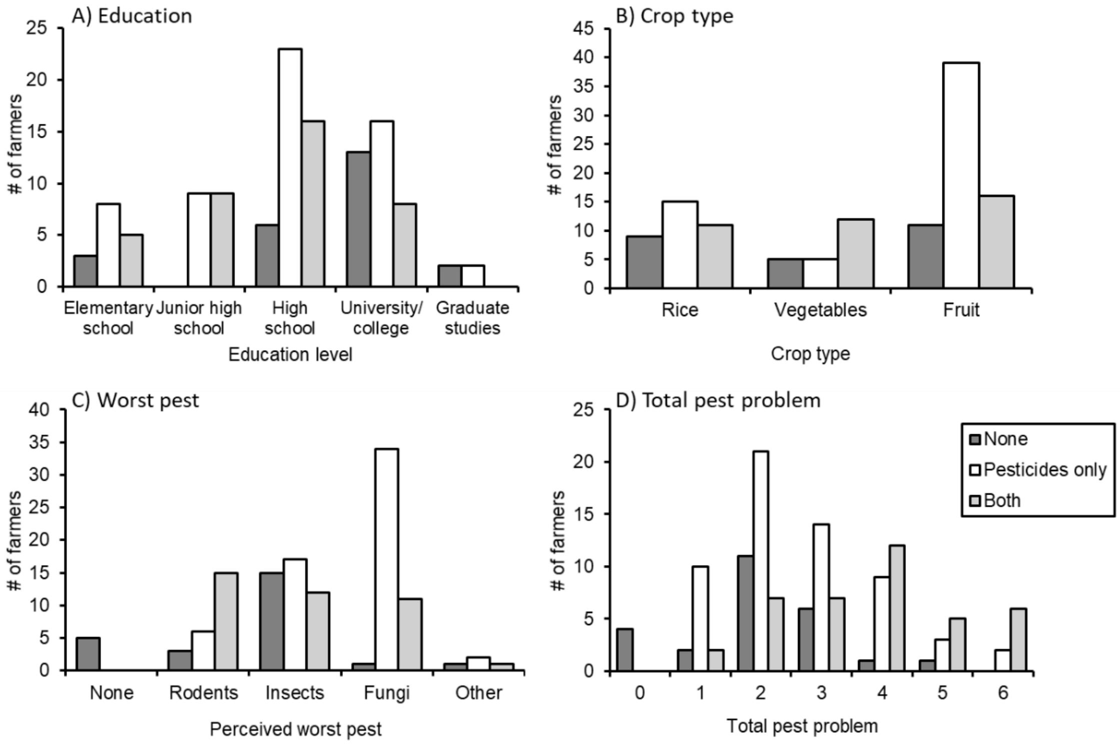
Figure 3. Number of different pest control products (*# different products*, 0 – 4) of farmers compared between A) worst pest (n = 121), B) total pest problem (n = 121), and C) number of pests (n = 118), from participants of the survey in Miaoli County (June – October 2020).

Figures

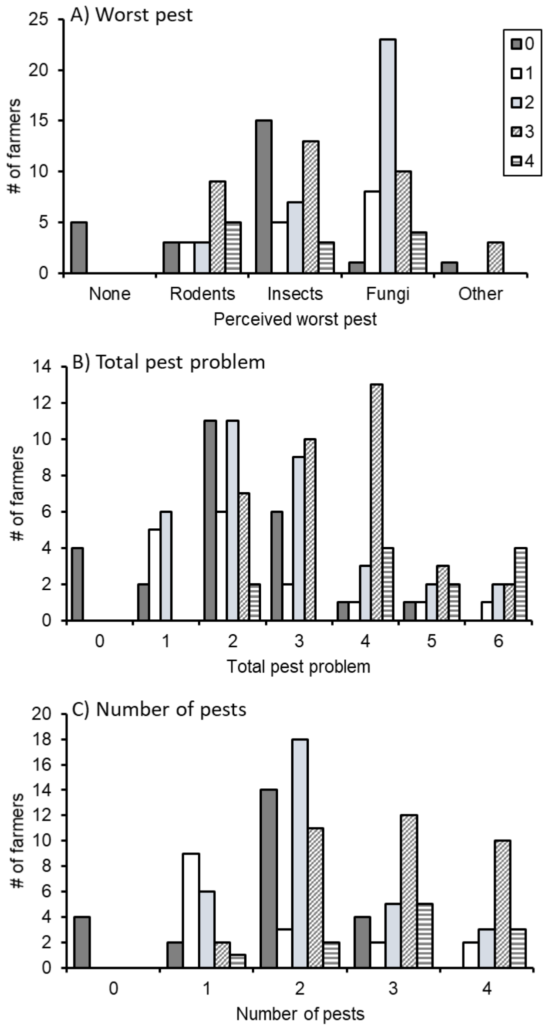
[Figure 1]



[Figure 2]


A) Education
B) Crop type
C) Worst pest
D) Total pest problem
# of farmers
Elementary school
Junior high school
High school
University/ college
Graduate studies
Education level
Rice
Vegetables
Fruit
Crop type
None
Rodents
Insects
Fungi
Other
Perceived worst pest
0
1
2
3
4
5
6
Total pest problem
None
Pesticides only
Both

[Figure 3]


A) Worst pest
# of farmers
0
1
2
3
4
None
Rodents
Insects
Fungi
Other
Perceived worst pest
B) Total pest problem
# of farmers
Total pest problem
C) Number of pests
# of farmers
Number of pests

Supplementary material

Tables

Table S1. Socio-economic factors of farmers and background information about participants' agricultural practices in Miaoli County, Taiwan.

Variable	*n*	%	Variable	*n*	%
Township	126		**Main income**	126	
Sanyi	30	23.8	Farming	94	74.6
Zhuolan	54	42.9	Other	32	25.4
Yuanli/ Tongxiao[b]	42	33.3	**Ownership of farm**	124[a]	
Age	120[a]		Yes	90	72.6
18-25	2	1.7	No	34	27.4
26-35	14	11.7	**Farming experience**	117[a]	
36-45	22	18.3	1-10	45	38.5
46-55	21	17.5	11-20	21	17.9
56-65	41	34.2	21-30	21	17.9
65+	20	16.7	30+	30	25.6
Gender	107[a]		**Pets**	125[a]	
Male	72	67.3	Yes	61	48.8
Female	35	32.7	No	64	51.2
Education	123[a]		**Keep farm animals**	124[a]	
Elementary school	16	13.0	Yes	34	27.4
Junior high school	18	14.6	No	90	72.6
High school	45	36.6	**Crop type**	126	
University/ college	38	30.9	Rice	35	27.8
Graduate studies	6	4.9	Vegetables	24	19.0
Main occupation	126		Fruit	67	53.2
Farming	95	75.4	**Crop storage**	126	
Other	31	24.6	Yes	100	79.4
			No	26	20.6

Notes: [a] indicates lower total *n* value due to missing data, participants left some questions blank. [b] townships joined due to low sample size from Tongxiao, close proximity between two townships, and similar types of crops grown.

Table S2. Spearman rank correlation matrix of farmers' willingness to change their rodenticide and pesticide usage. Significant values displayed in bold.

	Effect. Rodentic.	Use less rodenticides	Stop using rodenticides	Effect. Pestic.	Use less pesticides	Stop using pesticides
Effect. Rodentic.	1					
Use less rodenticides	0.000 1.000	1				
Stop using rodenticide	-0.307 0.069	0.669 **<0.001**	1			
Effect. Pestic.	0.267 0.127	0.192 0.285	-0.139 0.441	1		
Use less pesticides	-0.058 0.743	0.278 0.111	0.298 0.087	-0.001 0.996	1	
Stop using pesticides	-0.004 0.983	0.310 0.075	0.582 **<0.001**	-0.224 **<0.05**	0.312 **<0.005**	1

Notes: Effect. Rodentic. = think rodenticides are effective. Effect. Pestic. = think pesticides are effective

Table S3. Reasons and incentives selected by farmers to be willing to change their use (use less/ stop using) of rodenticides and pesticides

	Use less/ stop using …	
Reason/ Incentive	**Rodenticides**	**Pesticides**
Financial compensation	10 (16.1)	19 (11.2)
Environmental protection	18 (29.0)	39 (23.1)
Protection of personal health	10 (16.1)	40 (23.7)
Protection of other people's health	12 (19.4)	45 (26.6)
Perceive them as ineffective	3 (4.8)	2 (1.2)
Other	0 (0.0)	7 (4.1)
None, not willing	9 (14.6)	17 (10.1)
Total	62 (100)	169 (100)

Notes: Percentages are displayed in brackets.

Figures

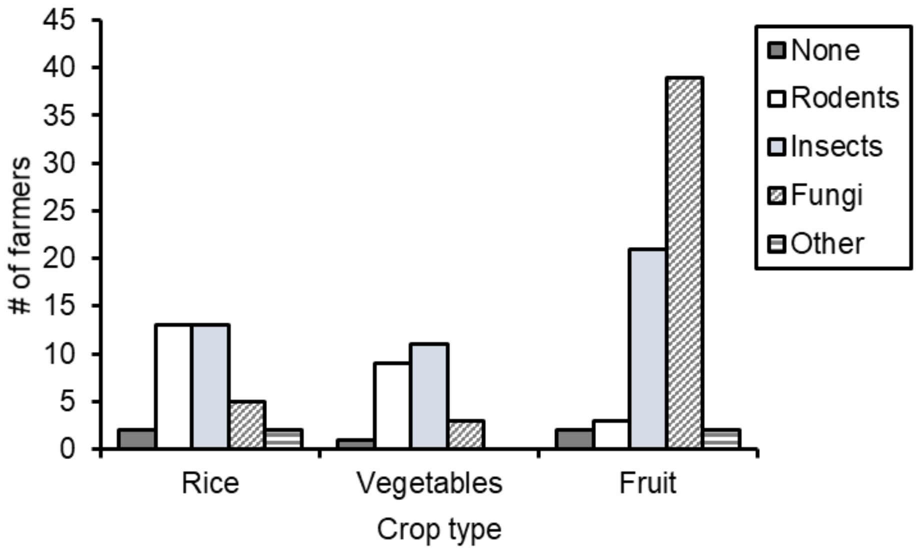


Figure S1. Perceived worst pests ranked by farmers compared with categorized crop type (n = 126), from the survey conducted in Miaoli County (June – October 2020).

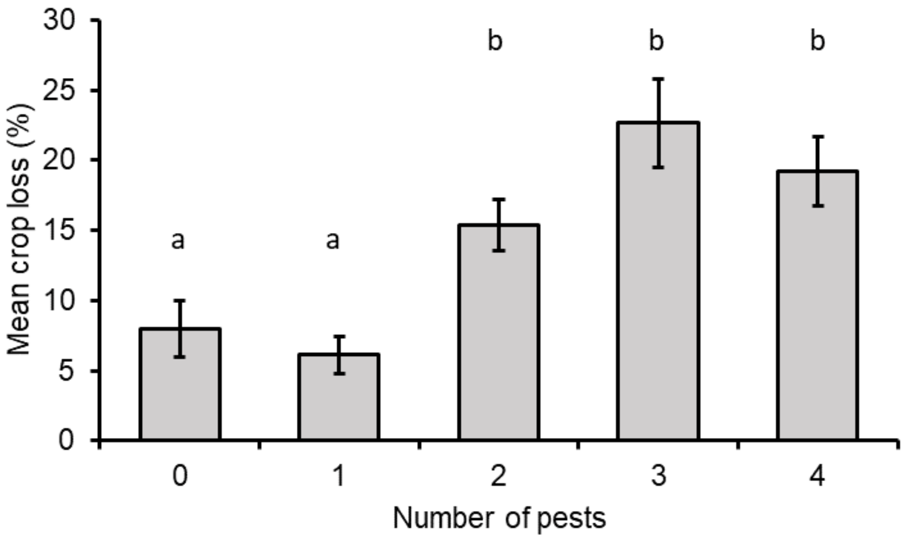


Figure S2. Mean estimated annual crop loss (%) reported by farmers compared between number of pests that afflict farmers' crops (n = 91), from the survey conducted in Miaoli Country (June – October 2020).

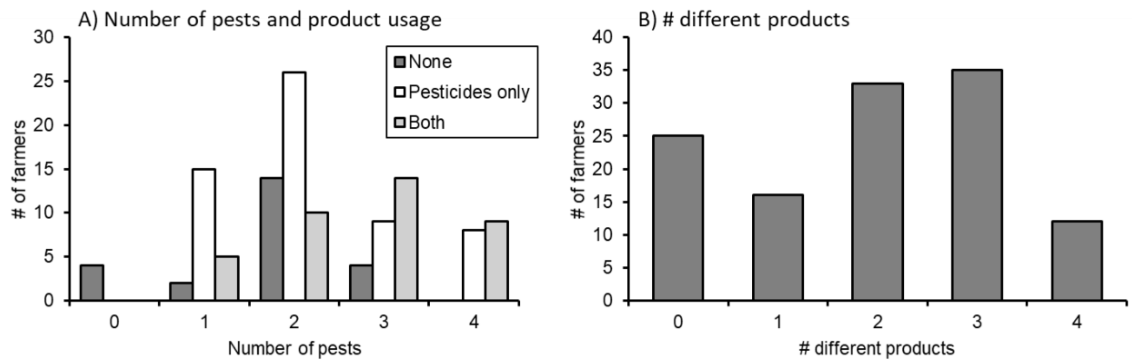


Figure S3. Pest control behaviors of farmers. A) Product usage (none, pesticides only, both: pesticides and rodenticides) of farmers compared between number of reported pests (n = 120), B) # of different products used by farmers (n = 121), from the survey conducted in Miaoli County (June – October 2020).