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Original Research Article

Evaluation of Commercial Pheromones on the Population Dynamics of *Spodoptera frugiperda* (J. E. smith) and *Mythimna loreyi* (Duponchel) (Lepidoptera: Noctuidae)

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ABSTRACT The trapping efficacy of five commercially available sex pheromones manufactured in Korea, the Netherlands, North America, China, and Costa Rica was evaluated to determine the population dynamics of *Spodoptera frugiperda* and *Mythimna loreyi* and their relationships with the weather parameters of maize fields in Miryang, Gyeongnam Province, Korea in 2019. The results show that the sex pheromone manufactured in Costa Rica were more efficient at capturing *S. frugiperda* and *M. loreyi* than those manufactured in other countries. The lowest number of *S. frugiperda* moths were captured using sex pheromones manufactured in the Netherlands. We noted that more than four population peaks of both the moth species and weather parameters influenced the moth population dynamics in Miryang. A positive relationship was observed between the population of *S. frugiperda* and weather parameters, such as mean temperature, rainfall, and relative humidity, for sex pheromones manufactured in Korea. Furthermore, a positive relationship was recorded between the population of *M. loreyi* and wind speed for the sex pheromone manufactured in Korea. The results of this study suggest that the sex pheromones manufactured in Costa Rica are the best solution for the efficient capture of *S. frugiperda* and *M. loreyi* under typical weather conditions in the southern parts of Korea. In addition, the outcomes of this study are discussed in terms of population dynamics and integrated pest management for *S. frugiperda* and *M. loreyi* as alternatives to chemical management by maize producers. Further studies related to the continuous improvement in the capture efficiency of both moth species using sex pheromones are now needed.

Keywords : lures, management, manufacturer, population dynamics, weather parameters

The fall armyworm, *S. frugiperda*, is an intrusive noctuid transitory pest, native to tropical and subtropical regions of the Americas (Goergen *et al*., 2016; Luginbill, 1928; Sparks, 1979). Since its first detailed attack in 1797, a significant attack was recorded in Africa in 2016, when this pest was recognized in over 44 nations in sub-Saharan Africa (Goergen *et al*., 2016; Prasanna *et al*., 2018) and rapidly migrated into several Asian nations, including Bangladesh, China, Laos, Myanmar, Nepal, Sir Lanka, Thailand, and Vietnam (Bajracharya *et al*., 2019; Ma *et al*., 2019; Sharanabasappa *et al*., 2018). In Korea, *S. frugiperda* was first noticed on June 13, 2019, at Jeju Island, and has since spread to most provinces in Korea (Lee *et al*., 2020). *S. frugiperda* has several plant hosts, with more than 350 plant species known to be vulnerable to associated economic losses (Chapman *et al*., 2000; Montezano *et al*., 2018). Among these plant hosts, maize is the most vulnerable with yield losses due to *S. frugiperda* reported to be more than 70% (Baudron *et al*., 2019; Harrison *et al*., 2019; Johnson, 1987). Due to its long distance migratory behavior travelling up to 62.98 km (Ge *et al*., 2019), the risk of spread is high, as shown by the capture of *S. frugiperda* on Jeju Island Korea far from the continent.

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The rice armyworm, *M. loreyi* is a noctuid pest of several grain crops such as rice, wheat, barley, broom corn, maize, and cash crops, including sugarcane (Aloysius, 2012; El-Sherif, 1972). In Korea, *M. loreyi* is a serious economic pest of soybeans and maize (Jung *et al*., 2020). *M. loreyi* frequently occurs with the closely related species *M. separata* (Walker), and can cause significant crop damage and economic losses (Guo *et al*., 2003; Hirai, 1975; Jiang *et al*., 2014).

Several studies on *M. separate*, *S. exigua*, *Helicoverpa armigera*, and *Riptortus clavatus* have been undertaken in Korea (Jung *et al*., 2003, 2005, 2013, 2015), however, understanding of the population dynamics of *S. frugiperda* and *M. loreyi* remains limited despite being crucial for developing appropriate population monitoring tools, forecasting models, and management strategies. Species-specific sex pheromones play a crucial role in the decision-making process before the adoption of any management option such as the timing of pesticide application (Ahmad & Kamarudin, 2011; Cruz *et al*., 2012). In pest management programs, a variety of sex pheromones have been successfully used for insect monitoring, mass trapping, and mating disruption of a wide range of insect species (Ahmad & Kamarudin, 2011; Baker & Heath, 2005; Campion, 1983; Guerrero *et al*., 2014; Howse *et al*., 1998; Keathley *et al*., 2013; Ridgway *et al*., 1990; Spears & Ramirez, 2015). Thus, sex pheromones can contribute to integrated pest management strategies by modifying insect behavior and via the mass-capturing of adult insect pests (Ahmad & Kamarudin, 2011). The use of sex pheromone-baited traps is a common and well-established technique, especially for trapping lepidopterans (Mullen & Dowdy, 2001). As a newly invaded pest in Korea (Lee *et al*., 2020), strategies for *S. frugiperda* management remain understudied, and an evaluation of existing sex pheromones and traps in Korea has not been undertaken. Although *S. frugiperda* can only successfully breed in the summer and cannot survive over winter on the Korean peninsula due to extreme temperatures, there is a significant potential for population increases, spreading, and increased damage with the effects of rapid climate change (Maharjan & Jung, 2011). Indeed, the spread and persistence of these insect pests are closely related to geographical location, ecological environment, and climatic conditions on the Islands of Japan and in eastern China (Ma *et al*., 2019). Therefore, invasion by *S. frugiperda* and *M. loreyi* has seriously threatened the production of field crops in Korea, including soybean and maize, and ultimately, food security. Furthermore, there is an urgent need to monitor the populations of these moths to predict the invasion risk in Korea. Early population detection can offer many benefits and help reduce management costs by adopting proper spray timing and minimizing pesticide applications as well as the overall advancement of alternative pest management options. Therefore, we evaluated the capture efficacy of commercially available sex pheromones to better understand the population dynamics of *S. frugiperda* and *M. loreyi* and their association with a range of weather parameters in southern Korea.

MATERIALS AND METHODS

Study site

The study was conducted in 2019 in maize fields (1 - 2.5 ha) at the Department of Southern Area Crop Science, National Institute of Crop Science, Rural Development Administration, Miryang, Gyeongsangnam Province, 35° 49’N, 128° 74’E), Korea. The pheromone evaluation was conducted between April and November 2019 as part of a population dynamics study.

Selection of traps

To monitor the moths, funnel traps were used (Pherobank, green lid/green funnel/transparent bucket; 17 cm dia. × 23 cm H, 3960 BA Wijk bij Duurstede, Netherlands). Funnel traps are also known as universal moth traps (unitrap) and Multipher traps, and are commonly used for capturing lepidopteran insects (Epsky *et al*., 2008).

Evaluation of pheromones

One commercial trap design (funnel trap) and five types of commercial sex pheromones manufactured in different countries (Korea, Netherlands, North America, China, and Costa Rica) were evaluated under field conditions. Traps without lures were used as the controls. The funnel traps were baited with aggregated sex pheromones manufactured in different countries and used as treatments. The traps with lures were hung on steel rods using brackets approximately 1 m from the ground inside the maize fields. The positions of the traps were randomly assigned, maintaining at least

10 m between traps, and each trap was randomly rotated from its original position at 7 - 10 d intervals. The baited sex pheromones were replaced with new ones every month. The traps were first installed on April 20, 2019, in maize fields. Three funnel traps (field/country) were used to monitor the moths, and traps were replicated three times. Moths were collected and counted every 2 - 5 d in labeled bags.

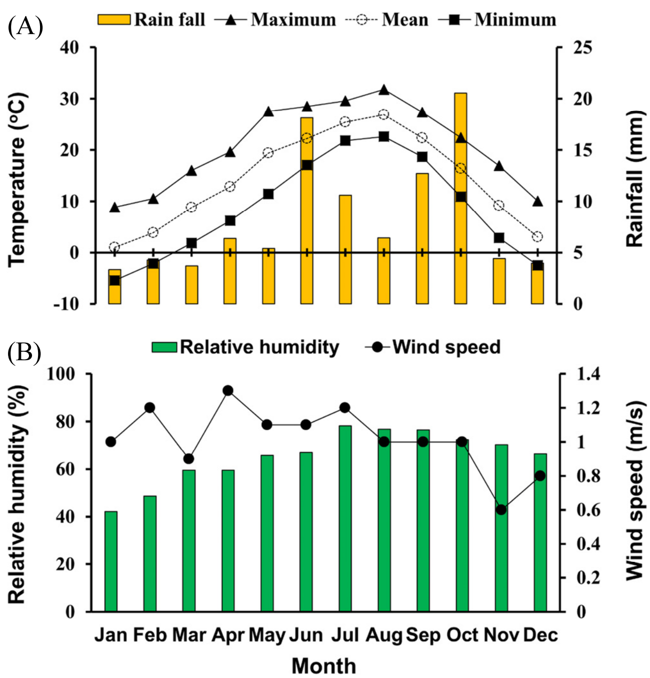

Fig. 1. Monthly weather conditions during the monitoring period in Miryang, Gyeongnam Province, during 2019. Maximum, mean and minimum temperature, and rainfall (A); relative humidity and wind speed (B) (KMA, http://data.kma.go.kr/).

Meteorological data

Weather data were obtained from the Korean Meteorological Administration (http://data.kma.go.kr/), focusing on the Miryang meteorological station in Gyeongsangnam Province, Korea. The weather conditions of the study area were evaluated to determine their relationships with the *S. frugiperda* and *M. loreyi* populations. Maximum temperature, minimum temperature, mean temperature (°C), relative humidity (%), rainfall (mm), and wind speed (m/s) were considered as summarized in Fig. 1.

Statistical analysis

Data on capture counts were square-root transformed to meet the assumptions of normality and homogeneity of variance, and the effectiveness of each pheromone was evaluated using one-way ANOVA and PROC GLM (SAS Institute, 2000). The treatment means were compared using Tukey's test for post-hoc analysis at $P > 0.05$. The correlations between the populations of *S. frugiperda* and *M. loreyi* and the weather parameters were analyzed using a General Linear Model (GLM). All analyses were performed using SAS software (SAS Institute, 2000).

RESULTS

Evaluation of pheromones

All treatments (sex pheromones) attracted both *S. frugiperda* and *M. loreyi* (Table 1), although the number of moths captured by each treatment was significantly different (*S. frugiperda*, $F_{4,\ 514} = 20.84$, $P < 0.0001$; *M. loreyi* $F_{4,\ 514} = 33.35$, $P < 0.0001$; total, $F_{4,\ 514} = 47.89$, $P < 0.0001$). The sex pheromones manufactured in Costa Rica captured

Table 1. Number (mean ±SE) of *Spodoptera frugiperda* and *Mythimna loreyi* moths captured in funnel traps with sex pheromones manufactured in different countries.

Country	No. of adults captured/ trap		
	S. frugiperda	*M. loreyi*	Total
Korea	0.065 ± 0.02b	0.194 ± 0.08c	0.259 ± 0.08c
The Netherlands	0.009 ± 0.01b	0.435 ± 0.11c	0.444 ± 0.11c
North America	0.065 ± 0.03b	2.065 ± 0.44b	2.130 ± 0.44b
China	0.037 ± 0.02b	0.204 ± 0.07c	0.241 ± 0.08c
Costa Rica	0.816 ± 0.20a	4.414 ± 0.78a	5.230 ± 0.79a

Means followed by the same letters in a column are not significantly different among pheromones (ANOVA, Tukey's [HSD] test, P <0.05)

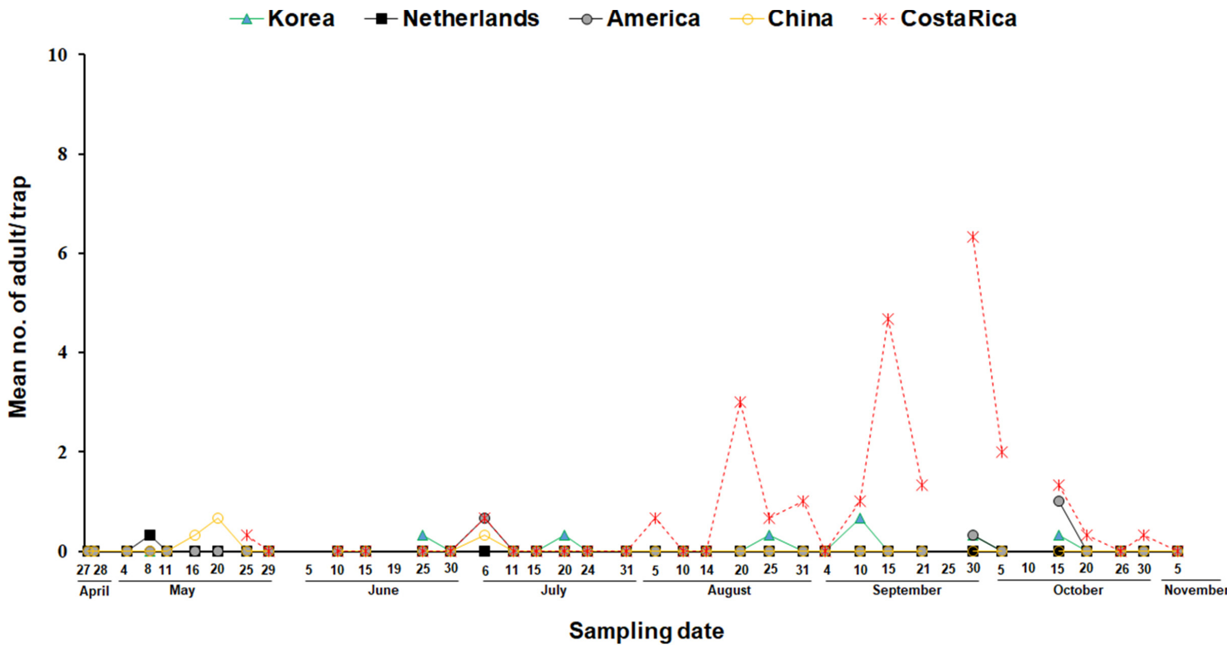

Fig. 2. Seasonal occurrences of *Spodoptera frugiperda* moths in funnel trap with different types of sex pheromones manufactured in Korea, the Netherlands, North America, China, and Costa Rica.

significantly more moths (0.816/trap) of both species, and the lowest number of moths (0.009/trap) were captured by those manufactured in the Netherlands. However, there was no significant difference in the number of *S. frugiperda* captured using the sex pheromones manufactured in Korea, the Netherlands, North America, and China, nor the number of *M. loreyi* captured using the sex pheromones manufactured in Korea, the Netherlands, and China.

Population dynamics of *S. frugiperda* and *M. loreyi*

S. frugiperda

Population dynamics data show that each sex pheromone recorded different moth population peaks. For the sex pheromones manufactured in Korea, Netherlands, North America, China, and Costa Rica, we noted five population peaks during June (4th week), July (3rd week), August (4th week), September (2nd week) and October (2nd week); one peak during May (2nd week); three peaks during July (1st week), September (4th week) and October (3rd week); two peaks during May (3rd week) and July (1st week); and more than five peaks during May (4th week), August (1st, 3rd, and 4th weeks), September (3rd and 4th weeks), and October (2nd and 4th weeks), respectively. In general, few moths were captured other than when using the traps with the sex pheromones manufactured in Costa Rica. For theses specific sex pheromones, during May, the first observed and re-observed in June and August, during August was the first, September was the second, and September had the third largest population increase, which then began to decline (Fig. 2).

M. loreyi

The traps with each of the sex pheromones recorded different moth population peaks. We noted one population peak during May (2nd week), and May (1st week) based on capture using the sex pheromones manufactured in Korea and China, respectively, whereas for those manufactured in the Netherlands, North America, and Costa Rica, two peaks were observed during May (4th week) and June (2nd week); five peaks were observed during May (2nd, 3rd, and 4th weeks), June (2nd week) and July (2nd week); and four peaks were observed during May (4th week), June (2nd week), July (1st week), and October (3rd week), respectively. At the beginning of May, the highest numbers of moths were trapped using the sex pheromones manufactured in North America and Costa Rica. For those manufactured in North America, the first, second, and third-largest population increases were observed in May, June, and July, respectively, while a fourth

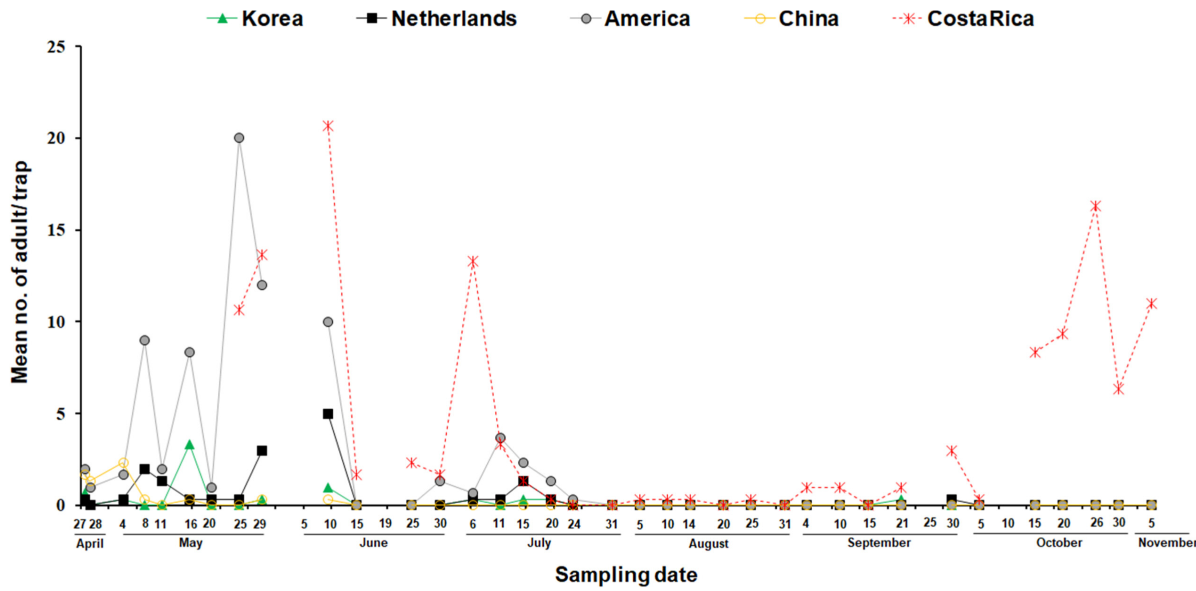

Fig. 3. Seasonal occurrences of *Mythimna loreyi* moths in funnel trap with different types of sex pheromones manufactured in Korea, the Netherlands, North America, China, and Costa Rica.

Table 2. Parameter interactions between captured *Spodoptera frugiperda* and *Mythimna loreyi* moths, mean temperature (°C) and rainfall (mm) during 2019.

Country of pheromone manufacture	Weather variable	Species	Linear regression model		
			y = ax + b	r^2	*P*-value
Korea	Mean temp.	SF	0.0132x − 0.0665	0.5630	0.0049
		ML	0.0149x − 0.0053	0.2344	0.1107
	Rainfall	SF	0.0209x − 0.0523	0.5972	0.0032
		ML	0.0095x + 0.1292	0.0398	0.5343
The Netherlands	Mean temp.	SF	0.0012x + 0.0007	0.0312	0.5829
		ML	0.0249x − 0.0678	0.2858	0.0734
	Rainfall	SF	-0.0016x + 0.0318	0.0241	0.6299
		ML	0.0253x + 0.0771	0.1242	0.2611
North America	Mean temp.	SF	0.0074x − 0.0193	0.1736	0.1779
		ML	0.0427x − 0.0387	0.1750	0.1760
	Rainfall	SF	0.0192x − 0.0733	0.4912	0.0111
		ML	0.0228x + 0.3825	0.0209	0.6540
China	Mean temp.	SF	0.005x − 0.0202	0.1358	0.2385
		ML	0.0045x + 0.1198	0.0109	0.7464
	Rainfall	SF	-0.0015x + 0.0633	0.0050	0.8278
		ML	-0.0041x + 0.2178	0.0040	0.8457
Costa Rica	Mean temp.	SF	0.0359x − 0.1626	0.3730	0.0349
		ML	0.6075x + 0.3299	0.1866	0.1608
	Rainfall	SF	0.0415x + 0.0058	0.2089	0.1352
		ML	0.1171x + 0.3206	0.2360	0.1093

SF- *S. frugiperda*; ML- *M. loreyi*; temp.- Temperature; Reg. $P < 0.05$.

Table 3. Parameter interactions between captured *Spodoptera frugiperda* and *Mythimna loreyi* moths, relative humidity (%), and wind speed (m/s) during 2019.

Country of pheromone manufacture	Weather variable	Species	Linear regression model		
			y = ax + b	r^2	*P*-value
Korea	RH	SF	0.0095x - 0.4975	0.4429	0.0182
		ML	0.0044x - 0.0778	0.0306	0.5866
	Wind speed	SF	0.1293x - 0.0098	0.0236	0.6335
		ML	0.854x - 0.6602	0.3339	0.0491
The Netherlands	RH	SF	8E-05x + 0.0128	0.0002	0.9643
		ML	0.008x - 0.2344	0.0448	0.5088
	Wind speed	SF	0.0456x - 0.0283	0.0191	0.6684
		ML	1.0213x - 0.7509	0.2100	0.1340
North America	RH	SF	0.0075x + 0.4049	0.2721	0.0820
		ML	0.009x - 0.0118	0.0118	0.7367
	Wind speed	SF	0.1249x - 0.0404	0.0215	0.6494
		ML	2.3565x - 1.8238	0.2316	0.1132
China	RH	SF	0.0023x - 0.1012	0.0451	0.5074
		ML	-0.0045x + 0.4778	0.0170	0.6863
	Wind speed	SF	0.1878x - 0.1399	0.0840	0.3609
		ML	1.0798x - 0.9145	0.2798	0.0770
Costa Rica	RH	SF	0.0291x - 1.5486	0.3711	0.0355
		ML	0.0604x - 2.6486	0.2267	0.1176
	Wind speed	SF	0.094x + 0.2552	0.0011	0.9181
		ML	-1.5898x + 2.9108	0.0451	0.5077

RH- Relative humidity; SF- *S. frugiperda*; ML- *M. loreyi*; Reg. $P < 0.05$.

population increase was also observed in October based on capture using the pheromones manufactured in Costa Rica (Fig. 3).

Relationship between moth populations and weather parameters

S. frugiperda

The numbers of trapped *S. frugiperda* moths varied in relation to weather parameters (Tables 2 and 3). Specifically, population increases were associated with increasing mean temperature ($F_{1, 10}$ = 12.88, P = 0.0049), rainfall ($F_{1, 10}$ = 14.83, P = 0.0032), and relative humidity ($F_{1, 10}$ = 7.95, P = 0.0182) based on trapping using the sex pheromones manufactured in Korea. Similarly, population increases were associated with increasing mean temperature ($F_{1, 10}$ = 5.95, P = 0.0349) and relative humidity ($F_{1, 10}$ = 5.90, P = 0.0355) based on trapping using the sex pheromones manufactured in Costa Rica.

M. loreyi

The numbers of trapped *M. loreyi* moths also varied in association with various weather parameters (Tables 2 and 3). For example, based on trapping using sex pheromones manufactured in Korea, population increases were linked to higher wind speeds ($F_{1, 10}$ = 5.01, P = 0.0491). However, we found no significant relationship between any weather parameter and the population dynamics of *M. loreyi* based on trapping using the pheromones manufactured in the Netherlands, North America, China, and Costa Rica.

DISCUSSION

The selection of monitoring tools (e.g., traps with sex pheromones) plays a significant role in the success of pest management programs. To overcome the problems caused by *S. frugiperda* and *M. loreyi*, timely prediction of the occurrence of these moth species can be achieved using sex pheromone-baited traps, enabling the early detection of infestation, and by formulating need-based insecticides and timely application programs (Witzgall *et al*., 2010). These approaches mean that insects infestation can be managed during its initial stages and therefore, economic losses can be minimized.

Several species-specific sex pheromones have been widely used to understand the population dynamics and spreading patterns of a diversity of insect species (Bae *et al*., 2017; Bae *et al*., 2019; Spears & Ramirez, 2015). In this study, we aimed to evaluate the effectiveness of commercial sex pheromones for evaluating *S. frugiperda* and *M. loreyi* population dynamics alongside the influence of a range of weather parameters.

Currently, commercial species-specific sex pheromone lures are widely used to control the populations of various insect species (Bae *et al*., 2017, 2019; Campion, 1983; Guerrero *et al*., 2014; Katherine *et al*., 2017; Keathley *et al*., 2013; Spears & Ramirez, 2015; Santanu *et al*., 2017; Witzgall *et al*., 2010). In our study, we found that sex pheromones manufactured in Costa Rica were the most effective at attracting *S. frugiperda* and *M. loreyi* moths, whereas those manufactured in the Netherlands were the least effective. This difference could be associated with multiple factors including species-specific effects, the type of dispenser used, pheromone release rates, lure longevity, and pheromone formulation alongside other possible unknown factors (Roger *et al*., 1989; Evenden & Gries, 2010). Indeed, the type of lure used and the components of different pheromones are known to be important factors affecting trap capture efficacy (Evenden & Gries, 2010; Malo *et al*., 2001; Roda *et al*., 2015; Reddy *et al*., 2018). Pheromone dosage is a key variable affecting moth trap efficacy, with higher doses typically leading to higher capture rates (Boo & Jung, 1998; Hand *et al*., 1987). However, the attractiveness of a particular pheromone does also vary according to species. For example, one-tenth of the standard dose of pheromone was found to provide a better indication of damage by leaf roller moth larva in orchards, and a wide range of pheromone blends has been reported to attract the diamondback moth, *Plutella xylostella* (Macaulay *et al*., 1986; Walker *et al*., 2003; Zilahi-Balogh *et al*., 1995).

The correlation analysis showed a positive relationship between *S. frugiperda* population and temperature, rainfall, and relative humidity based on trapping using the sex pheromones manufactured in Korea. Similarly, positive relationships between *S. frugiperda* and temperature and relative humidity were observed based on the sex pheromones manufactured in Costa Rica. In the case of *M. loreyi*, a positive relationship was also recorded with wind speed. Based on these results, temperature, rainfall, relative humidity, and wind speed have the greatest influence on the numbers of *S. frugiperda* and *M. loreyi* moths captured under agro-ecological conditions in southern Korea. Temperature is considered the most influential factor, affecting insect multiple life-history variables, insect activity, seasonality, and the behavior of field populations, population dynamics and phenology (e.g., timing of oviposition and development), and ultimately the prediction of future generations (Al-Mezayyen & Ragab, 2014; Amer *et al*., 2009; Angilletta, 2009; Ashley *et al*., 1987; Barfield & Ashley, 1987; Dahi, 2007; Danilevskii, 1965; Howe, 1967; Jaworski & Hilszczanski, 2013; Lamb, 1992; Plessis *et al*., 2020; Ragab, 2009; Régnière *et al*., 2012; Tobin *et al*., 2003). Indeed, insect species development is sensitive to temperature (Howe & Currie, 1964), and weather and geographical conditions are thought to have the greatest impact on a wide range of insect species including *H. armigera* (Dahi, 2007; Tahhan *et al*., 1982), *H. virescens* (Potter *et al*., 1981), *S. littoralis* (Taman, 1990), *Liriomyza huidobrensis* (Maharjan & Jung, 2016), and *Callosobruchus chinensis* (Maharjan *et al*., 2017). Furthermore, Groot *et al*. (2008) reported that sexual communication in several lepidopteran species is mediated by geographical variations and host strains.

Hagstrum & Hagstrum (1970) reported that insects develop quickly even at fluctuating temperatures, when the maximum and minimum temperatures are within their optimal range. Thus, by providing new data on the population dynamics of *S. frugiperda* and *M. loreyi* under local agro-ecological conditions in the southern parts of Korea, we provide important information that can support the development of location-specific integrated pest management strategies (Shanower *et al*., 1993). In addition, the long-term benefits of using sex pheromones based trappings over conventional insecticides can lead to longer-term reductions in pest populations (Witzgall *et al*., 2010).

Overall, we found that sex pheromones manufactured in Costa Rica were most effective at capturing *S. frugiperda* and *M. loreyi* moths in southern Korea. Weather parameters, such as temperature, relative humidity, and rainfall were also found to have a significant effect on the population dynamics of these species. This information can help the development of integrated pest management strategies, including the timing of insecticide application by maize growers. Further studies on the economic thresholds and damaging nature of both of the studied moth species are now needed to ensure the efficient and sustainable use of appropriate pest-management options to improve maize production in the southern parts of Korea.

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CONFLICT OF INTEREST

The authors have declared that they have no conflict of interest.

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