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# Leveraging environmental and landscape effects on the *Spodoptera frugiperda* abundance and attack rates' spatial distribution

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**Abstract**

*Spodoptera frugiperda* is a new invasive pest in Indonesia; in its larval stage, it attacks maize plants and can cause high-yield losses. Differences in the distribution and attack of *S. frugiperda* in each region depending on climate factors and cultivation practices. This study examines the distribution of S. frugiperda and the effects of landscape structure and environmental factors on the abundance and intensity of the attack. This study was conducted from August to October 2020 on maize plantations in the Tuban Regency. Collection of S. frugiperda larvae was carried out on maize crops aged 2-6 weeks after planting by hand-collecting on plots of 10 m x 20 m. Landscape parameters were determined by vegetation mapping by buffering within a radius of 500 m from the centre point of the maize plot using ArcGIS 10.5 software. Land use is determined based on Sentinel-2 satellite imagery data using the Google Earth Engine cloud computing platform. Vegetation, water, and built-up land index bands are used as input for classification. Observed environmental data includes; altitude and average monthly rainfall. The spatial distribution of *S. frugiperda* abundance and percentage levels of attack was interpolated using an ordinary type kriging method with spherical kernels in ArcGIS 10.5 software. The influence of landscape parameters and environmental factors was analyzed using a generalized linear model in R statistical software. The kriging results showed that the highest abundance and intensity of *S. frugiperda* attacks were concentrated in areas with low elevations with an aggregate distribution pattern. Altitude and rainfall have a negative and significant relationship, while landscape parameters have a positive and significant relationship to the abundance of *S. frugiperda*. Increasing the area of semi-natural habitat can increase the abundance and attack rate of *S. frugiperda*. Thus, semi-natural habitats can provide resources for pests.

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## INTRODUCTION

A geographic information system (GIS) is a computer system for recording, storing, querying, analyzing and displaying geospatial data (Chang, 2017). Geospatial data describe the location and attributes of spatial features (Liebhold et al., 1993). The ability to layer and analyze multiple layers of spatial data provides an opportunity to explore the spatial properties of insect populations (Dminić et al., 2010). In contrast, geostatistics is a branch of applied statistics in which sample values and locations are used to describe and model spatial patterns (Liebhold et al., 1996). GIS technology enhances our ability to study and understand large-scale spatial structures and dynamics of insect populations (Schell & Lockwood, 1997), which are affected by heterogeneous environments (Dminić et al., 2010). By employing GIS, it is possible to relate insect density to particular characteristics of certain area, facilitating the identification of factors associated with insect abundance (Duarte et al., 2015a; Duarte et al., 2015b).

Although the advent of GIS has enabled entomologists to compile and manipulate spatial reference data, the characterization and modelling of spatial patterns still require adequate statistical tools (Liebhold et al., 1993). Geostatistics is a statistical method that has been successfully applied to study several insect species spatial distribution and damage (Wright et al., 2002). The basic tool of geostatistics is the semivariogram, which correlates the distance between sample pairs with the semivariance statistic (the variation between pairs) for all possible pairs at each suggested distance (Ellsbury et al., 1998). The combination of GIS and geostatistics can improve the manipulation of geospatial data because GIS facilitates the analysis of spatial exploration data, and geostatistics provides methods of interpolation, generalization, and environmental modelling (Burrough, 2001).

The fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is a new invasive pest species in Indonesia (Herlinda et al., 2022). The fall armyworm entered Indonesia for the first time in 2019 in West Sumatra (Sartiami et al., 2020). Currently, this pest has spread to various regions in Indonesia starting, from Lampung, West Java, Bengkulu, East Kalimantan, and South Sumatra (Trisyono et al., 2019; Ginting et al., 2020; Hutasoit et al., 2020). The primary hosts of this pest are the Poaceae family, such as maize, rice, sugarcane, sorghum, and millet (Casmuz et al., 2010; Montezano et al., 2018). The fall armyworm is polyphagous by attacking more than 300 host plants and causing economic losses to cultivated plants of up to 8.3-20.6 million tonnes per year (Shylesha et al., 2018). Damage to maize crops in Africa can reduce crop yields by up to 250-630 million US dollars per year (Bateman et al., 2018). The same thing happened to maize in Ghana and Zambia, with 22-67% (Day et al., 2017), 32-47% in Ethiopia (Kumela et al., 2018), and 11.57% in Zimbabwe (Baudron et al., 2019). This large percentage of damage and loss must be anticipated by mapping the distribution pattern of *S. frugiperda*.

Knowledge of the distribution of this species can facilitate monitoring activities for the presence of *S. frugiperda*, considering that the imago of this pest has good flying abilities (Ge et al., 2021; Chen et al., 2022). Mapping the distribution of *S. frugiperda* can also be used to determine the type of habitat preferences. This can facilitate the control that will be carried out. It is important to study the spatial distribution of this pest to explain its distribution pattern and growth rate. In addition, these studies are essential for developing integrated pest management (Hernández-Mendoza et al., 2008), thus ensuring the optimization of sampling and pest control strategies (Rios et al., 2014). The geostatistical approach holds promise for applying appropriate methods as a basis for strategies in integrated pest management of *S. frugiperda* (Farias et al., 2008), to reduce the risk of damage and loss of maize yields.

The configuration of semi-natural habitats in agricultural landscapes has the potential to improve biological pest control (Jordon et al., 2022). Agroecological approach known to be effective in controlling *S. frugiperda* is the management of semi-natural habitats (Harrison et al., 2019). So we predict that semi-natural habitat influences the abundance and attack rate of *S. frugiperda*. The main objective of this study was to identify the spatial distribution of the abundance and percentage of *S. frugiperda* attack rates and their relationship with landscape structure.

## MATERIALS AND METHODS

### Time and study site

The research was conducted from August to October 2020 on maize plantations in Sub-District of Bancar, Kerek, Montong, Singgahan, Soko, Jatirogo, Palang, Tuban Regency, East Java. Five villages were selected for each sub-district, a representative area with a large enough maize field.

**Collection of *S. frugiperda* and observation of attack levels**

A sampling of *S. frugiperda* was carried out on maize crops aged 2-6 weeks after planting by hand-collecting on a plot size of 10m x 20m. Determination of plant age was determined based on the behavior of *S. frugiperda*, which generally began to attack plants from 2 weeks (Trisyono et al., 2019) to 6 weeks (Supartha et al., 2021) after planting. The size of the observation plots is determined based on the area of land that is the location of the observations (Tepa-Yotto et al., 2021). The samples of *S. frugiperda* collected were in the larval stage, and the number of individuals was counted. Observation of the percentage of attack rate of *S. frugiperda* was observed directly from 50 maize crops based on the number of plants attacked against the number of plants observed, referring to Sisay et al., (2019) with the formula:

$$\%\ \text{attack rate} = \frac{The\ number\ of\ plants\ affected}{The\ number\ of\ plants\ observed}$$

**Determination of landscape and environmental factors**

Landscape determination was carried out by mapping vegetation and land use, referring to the method used by Ruas et al., (2022) by buffering the area within a 500 m radius from the centre point of the maize patch using the buffer tool in the ArcGIS 10.5 (ESRI, 2016). The landscape parameters used for the class area (CA) are cropland (including paddy fields and dry land agriculture) and semi-natural habitats (covering shrubs and plantation forests). Observed environmental parameter data include; altitude (masl) obtained from digital elevation model data/DEM with 0.27 arc-second (8.3 m) resolution, available on the Geospatial Information Agency/BIG website (http://tanahair.indonesia.go.id/portal-web) and average monthly rainfall obtained from the dataset of Climate Hazards Group Infrared Precipitation with Station Data (CHIRPS) from August to October 2020, via the Climate engine website (https://app.climateengine.com/climateEngine).

**Land use mapping**

Land use maps were analyzed by classifying surface reflectance imagery of Sentinel-2 (S2-SR) using maximum likelihood classifier in the ArcGIS 10.5. The final median imagery was derived from date-filtered and cloud-masked S2-SR collection was downloaded using the Google Earth Engine/GEE cloud computing platform with the JavaScript programming language (Gorelick et al., 2017). The date range for image acquisition was filtered the to sampling period (August 1, 2020 to October 31, 2020) with QA60 band selected for cloud masking (<20%). The area of interest (AOI) used is a rectangle covering the area of Tuban Regency and its surroundings. The band used as input for classification is a combination of the original and index bands. Native input bands include bands 4, 5, 6, 7, 8, and 8A. Meanwhile, the index bands used to consist of vegetation, water, and built-up land index bands, including: Normalized Difference Vegetation Index (Rokni & Musa, 2019), Difference Vegetation Index (Díaz & Blackburn, 2003) Enhanced Vegetation Index (Huete et al., 2002), Soil Adjusted Vegetation Index (Huete, 1988), Atmospherically Resistant Vegetation Index (Kaufman & Tanré, 1992), Specific Leaf Area Vegetation Index (Lymburner et al., 2000), Normalized Difference Built-up Index (Zha et al., 2010), Ratio Vegetation Index (Major et al., 2007), Inverted Red-Edge Chlorophyll Index (Bhattarai et al., 2020), and Advanced Vegetation Index (Mngadi et al., 2021).

Classification of land use uses seven classes: bodies of water, shrubs, forests, settlements, dry land agriculture, paddy fields, and open land. The training sample was created with initial guidance in the form of a land use map from the Ministry of Environment and Forestry/KLHK 2019 for the East Java region, which was then verified using ESRI basemap imagery with a more detailed resolution. The total training sample made was 2560 polygons consisting of bodies of water (299 polygons), shrubs (494 polygons), forests (380 polygons), settlements (316 polygons), dry land agriculture (551 polygons), rice fields (285 polygons), and open land (235 polygons). At the final layouting stage, a build-up area and administrative maps from BIG were situated overlaid the land used map to provide more clearance concerning natural and anthropogenic features surrounding the observation sites.

**Data analysis**

Analysis of the spatial distribution of the abundance and attack rate of *S. frugiperda* used geostatistical analysis. It was interpolated using the ordinary type kriging method with spherical kernels in ArcGIS 10.5 (ESRI, 2016). To determine the effect of landscape parameters and the influence of environmental factors on the abundance and attack rate of *S. frugiperda* on maize, it was analyzed using a generalized linear model with Poisson distribution using the glm function (package `stat`) in R statistics software (R Core Team, 2022).

## RESULTS AND DISCUSSION

Kriging can create population distribution maps that depict hotspots for pest control strategies (Duarte et al., 2015b). The results of the kriging map show that the highest abundance of *S. frugiperda* is concentrated in the northern part of the map, shown in red (Figure 1). This area is the Bancar sub-district, where the area tends to have a low altitude (10 - 29 masl). The highest attack rates are also concentrated in the north and north-northeast parts of the map, where these areas are the Bancar sub-district and the Kerek sub-district (Figure 2). If adjusted to the land use map (Figure 3), areas with an abundance and a high percentage of attacks tend to have very low elevations compared to areas with higher elevations. The generalized linear model result evidences this. (Table 1), which shows that altitude negatively affects the abundance of *S. frugiperda*.

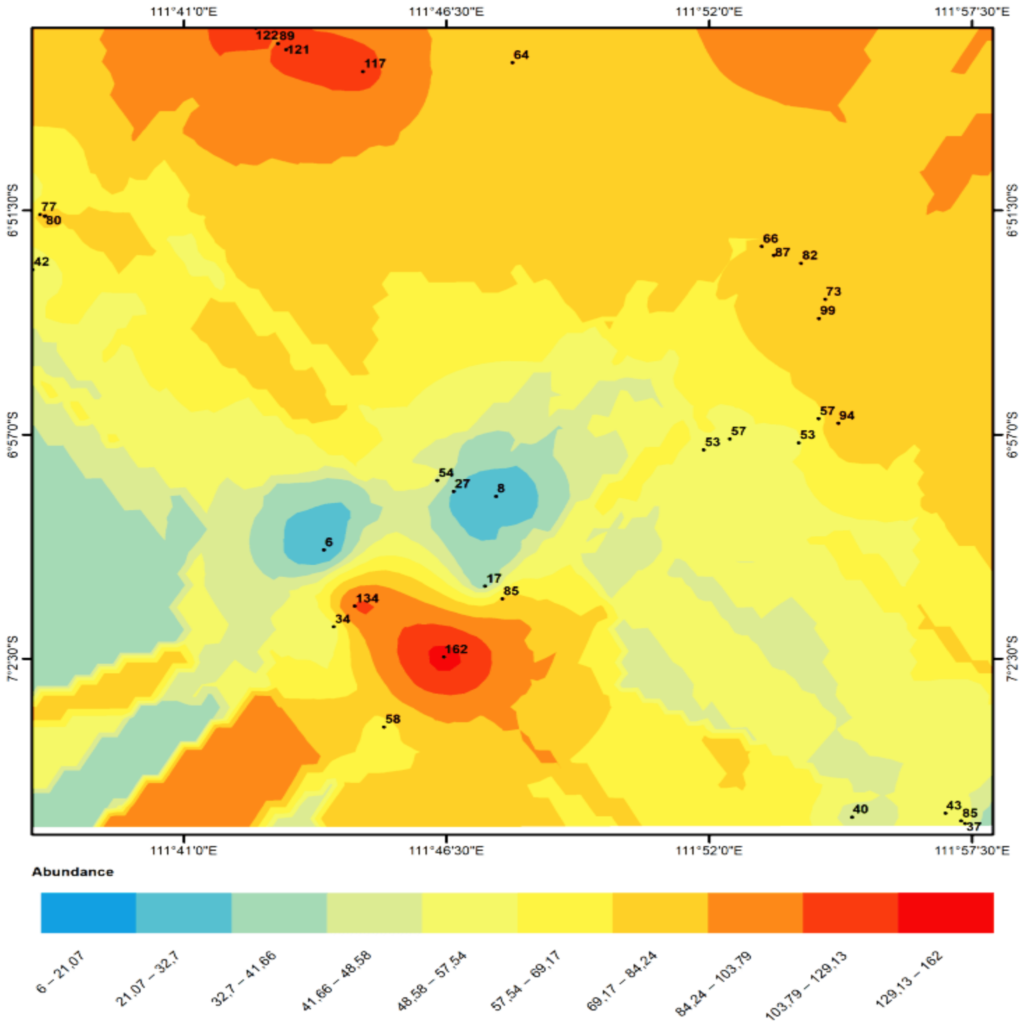


**Figure 1.** Spatial interpolation by kriging of *S. frugiperda* abundance

The presence of insects, including *S. frugiperda*, in a habitat, is also inseparable from environmental factors such as altitude and rainfall (Wyckhuys & O'Neil, 2007a). The level of damage to maize plants as a result of *S. frugiperda* attack is closely related to the altitude (Mengesha et al., 2021), where the level of attack is generally lower at higher altitudes (Wyckhuys & O'Neil, 2006), and the level of attack is highest levels generally occur in the lowlands (Wyckhuys & O'Neil, 2007b).

Generally, altitude affects the distribution and abundance of pests. Studies of other types of non-native pests also show that the highest pest infestation is in lowland areas (Poggetti et al., 2019). However, the altitude factor, of course, will depend on the identity of the pest in the area (Jonsson et al., 2014). In addition to altitude, the analysis results also show that rainfall affects the abundance and intensity of *S. frugiperda* attacks. Therefore, rainfall is often used as a key variable affecting the presence of pests (Li et al., 2021) or as a prediction model for the distribution of *S. frugiperda* (Baloch et al., 2020; Cokola et al., 2020; Jiang et al., 2022; Timilsena et al., 2022). The results of the analysis of the generalized linear model showed that rainfall has a negative effect on the abundance and attack rate of *S. frugiperda*. The results of this study are similar to those by Early et al. (2018), who showed that rainfall has a negative effect on *S. frugiperda* infestation, where rainfall can affect the survival of the larvae and pupae of the pest. Like other insect pests, *S. frugiperda* is known to be affected by weather conditions in different seasons (Caniço et al., 2020). When weather conditions are unfavourable for its development and reproduction, *S. frugiperda* will migrate to more suitable locations for its survival (Westbrook et al., 2015).

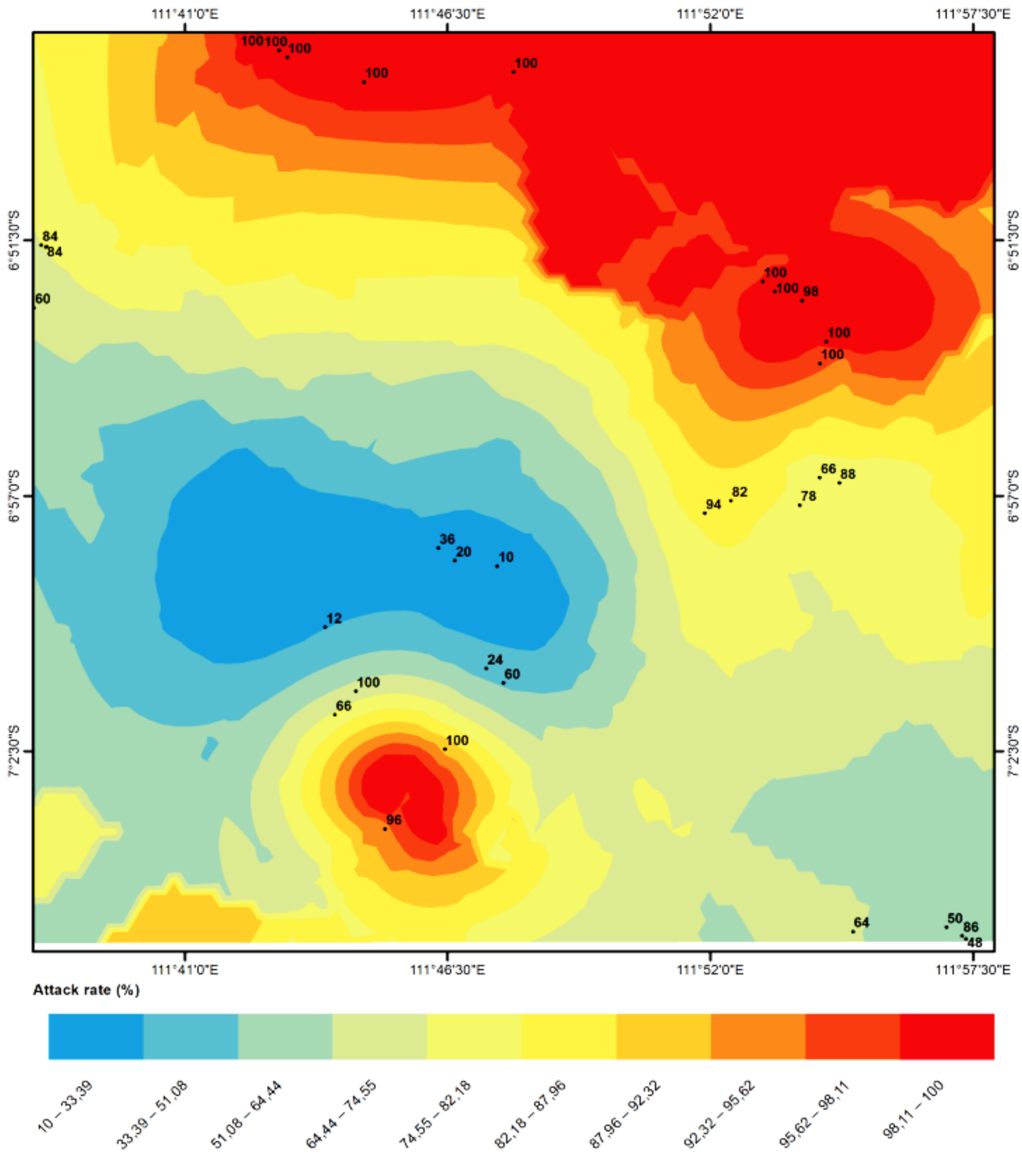


**Figure 2.** Spatial interpolation by kriging of *S. frugiperda* attack rate

The generalized linear model analysis results show that landscape composition affects the abundance and attack rate of *S. frugiperda* on maize (Table 1). The increase in semi-natural habitats substantially increase the abundance of *S. frugiperda* ($P < 0.01$) and its attack rate ($P < 0.05$). Partial effects of croplands in governing *S. frugiperda*'s distribution were also recorded in this study. Croplands exhibited similar controls with semi-natural habitat on abundance (P < 0.01) but did not influence the level of attack.

**Table 1.** Analysis of the generalized linear model of the relationship between the abundance and attack rate of *S. frugiperda* with class area (CA) semi-natural, cropland, altitude and rainfall. Significance level: $***P < 0.001$; $**P < 0.01$; $*P < 0.05$

| Variable | Abundance | | | % attack rate | | |
|---|---|---|---|---|---|---|
| | Estimate | SE | P | Estimate | SE | P |
| (Intercept) | 2.0310 | 0.6858 | 0.003061 ** | 4.6358 | 0.6420 | $5.17e^{-13}$ *** |
| CA semi-natural | 0.0433 | 0.0064 | $1.46e^{-11}$ *** | 0.0130 | 0.0059 | 0.0287 * |
| CA cropland | 0.0361 | 0.0075 | $1.85e^{-06}$ *** | 0.0081 | 0.0071 | 0.2538 |
| Altitude | -0.0016 | 0.0004 | 0.000105 *** | 0.0003 | 0.0004 | 0.3334 |
| Rainfall | -0.0111 | 0.0009 | $< 2e^{-16}$ *** | -0.0101 | 0.0009 | $< 2e^{-16}$ *** |

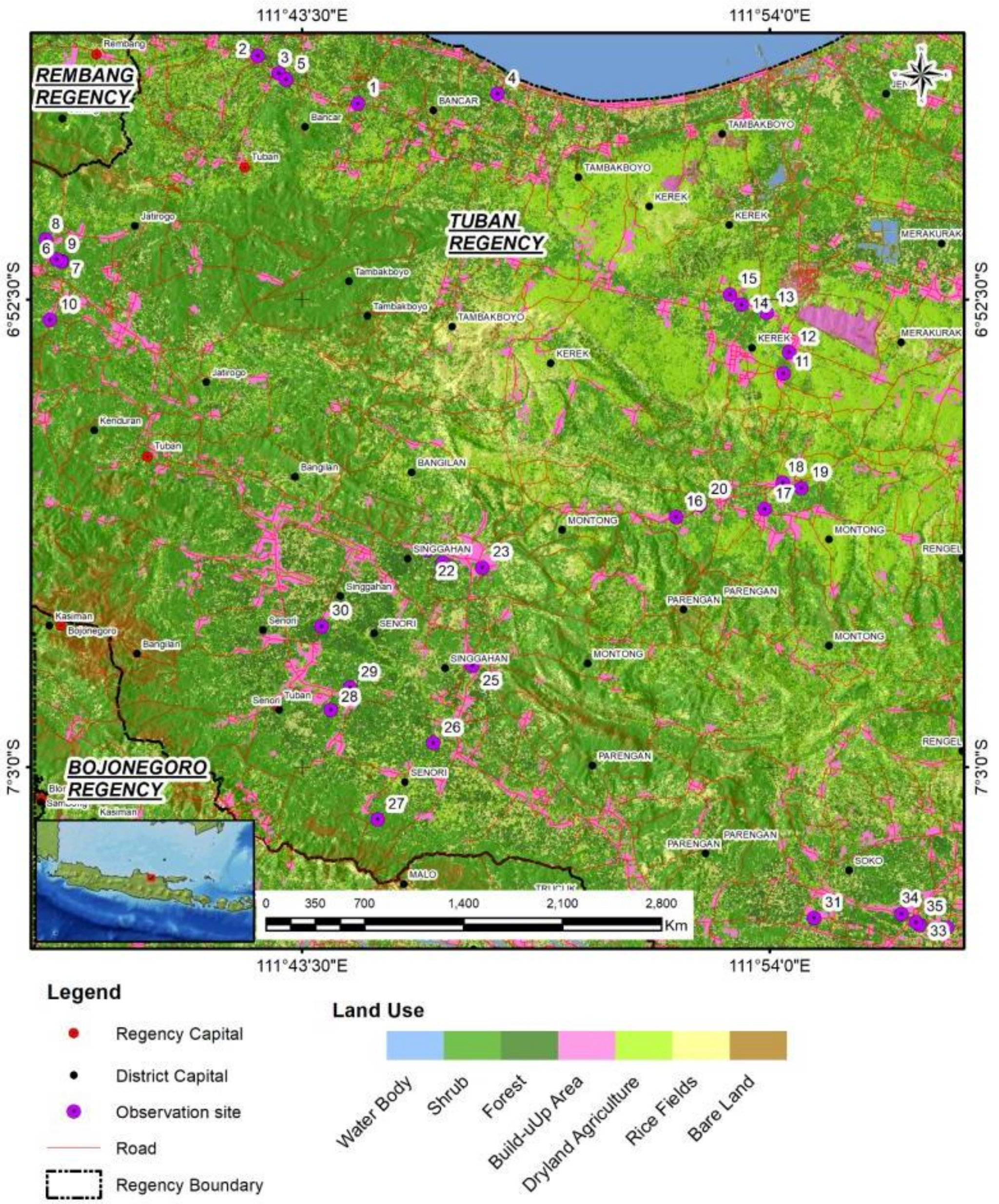


**Figure 3.** Landuse mapping at the study sites and its surrounding areas

Landscape composition can directly influence pest abundance by affecting their distribution and reproduction or indirectly by influencing the presence of natural enemies (Veres et al., 2013).

However, the results of this study differ from several other studies, which show that the composition of the landscape where the class area of semi-natural habitat is high can reduce pest infestation. A study by Alignier et al., (2014) shows that a higher proportion of semi-natural habitats in agricultural landscapes improves biological pest control. So that the complexity of the landscape, characterized by a high proportion of semi-natural habitats, is often used as the key to biological pest control (Schirmel et al., 2018). However, this study's results support Birkhofer et al., (2016) who showed a positive effect between the abundance of aphids and landscape complexity where aphids increased in areas with a higher proportion of semi-natural habitats. In addition, the research results by Santoiemma et al., (2018) also showed that *Drosophila suzukii* populations were high in complex landscapes, and the level of damage to cherries due to *D. suzukii* attacks increased in semi-natural habitats. Many plant pests also benefit from semi-natural habitats (Chaplin-Kramer et al., 2011), so natural habitats fail to enhance biological control services and may even increase pest populations (Tscharntke et al., 2016). Semi-natural habitats can also become a major source of pests by providing plants as alternative hosts (Midega et al., 2014) or a suitable environment at several stages of their life cycle (Tscharntke et al., 2016).

## CONCLUSION

Based on the kriging results, the highest abundance and intensity of *S. frugiperda* attacks were spread in the northern part, areas with low altitudes with an aggregate distribution pattern. Environmental factors such as altitude and rainfall did not significantly impact the abundance and attack rate of *S. frugiperda*. The increase in semi-natural habitats and agricultural land areas affected the abundance and attack rate of *S. frugiperda*

## AUTHOR CONTRIBUTION

## Author contribution

**Mihwan Sataral**: Perform data analysis, interpret data, and write and finalized manuscript.
**Rosyid Amrulloh**: Write a draft.
**Dita Megasari**: Designing and conducting experiments, collecting data, and writing draft.
**Syaiful Khoiri**: Designing and conducting experiments, Write a draft.
**Muh Zulfajrin**: Perform data analysis, interpret data, and write and finalized manuscript.
**F.Fahri**: Write and revise draft.

All authors agree and are responsible for the writing in the manuscript and approve the final version.

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## CONFLICT OF INTEREST

The authors declare that no known competing financial interests or personal relationships could have appeared to influence the work reported in this paper.

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## REFERENCES

Alignier, A., Raymond, L., Deconchat, M., Menozzi, P., Monteil, C., Sarthou, J. P., Vialatte, A., & Ouin, A. (2014). The effect of semi-natural habitats on aphids and their natural enemies across spatial and temporal scales. *Biological Control*, *77*, 76–82. https://doi.org/10.1016/J.BIOCONTROL.2014.06.006

Baloch, M. N., Fan, J., Haseeb, M., & Zhang, R. (2020). Mapping potential distribution of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in Central Asia. *Insects*, *11*(3), 1–10. https://doi.org/10.3390/INSECTS11030172

Bateman, M. L., Day, R. K., Luke, B., Edgington, S., Kuhlmann, U., & Cock, M. J. W. (2018). Assessment of potential biopesticide options for managing fall armyworm (*Spodoptera frugiperda*) in Africa. *Journal of Applied Entomology*, *142*(9), 805–819. https://doi.org/10.1111/jen.12565

Baudron, F., Zaman-Allah, M. A., Chaipa, I., Chari, N., & Chinwada, P. (2019). Understanding the factors influencing fall armyworm (*Spodoptera frugiperda* J.E. Smith) damage in African smallholder maize fields and quantifying its impact on yield. A case study in Eastern Zimbabwe. *Crop Protection*, *120*, 141–150. https://doi.org/10.1016/J.CROPRO.2019.01.028

Bhattarai, R., Rahimzadeh-Bajgiran, P., Weiskittel, A., & MacLean, D. A. (2020). Sentinel-2 based prediction of spruce budworm defoliation using red-edge spectral vegetation indices. *Remote Sensing Letters* , *11*(8), 777–786. https://doi.org/10.1080/2150704X.2020.1767824

Birkhofer, K., Arvidsson, F., Ehlers, D., Mader, V. L., Bengtsson, J., & Smith, H. G. (2016). Organic farming affects the biological control of hemipteran pests and yields in spring barley independent of landscape complexity. *Landscape Ecology*, *31*(3), 567–579. https://doi.org/10.1007/s10980-015-0263-8

Burrough, P. A. (2001). GIS and geostatistics: Essential partners for spatial analysis. *Environmental and Ecological Statistics*, *8*(4), 361–377. https://doi.org/10.1023/A:1012734519752

Caniço, A., Mexia, A., & Santos, L. (2020). Seasonal dynamics of the alien invasive insect pest *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) in Manica Province, Central Mozambique. *Insects*, *11*(8), 1–12. https://doi.org/10.3390/INSECTS11080512

Casmuz, A., Juarez, M. L., Socıas, M. G., Murua, M. G., Prieto, S., & Medina, S. (2010). Review of the host plants of fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Revista de La Sociedad Entomológica Argentina*, *69*((3-4)), 209–231. https://www.biotaxa.org/RSEA/article/view/28610

Chang, K.-T. (2017). Geographic information system. *International Encyclopedia of Geography: People, the Earth, Environment and Technology*, 1–9. https://doi.org/10.1002/9781118786352.WBIEG0152

Chaplin-Kramer, R., O'Rourke, M. E., Blitzer, E. J., & Kremen, C. (2011). A meta-analysis of crop pest and natural enemy response to landscape complexity. *Ecology Letters*, *14*(9), 922–932. https://doi.org/10.1111/J.1461-0248.2011.01642.X

Chen, H., Wang, Y., Huang, L., Xu, C. F., Li, J. H., Wang, F. Y., Cheng, W., Gao, B. Y., Chapman, J. W., & Hu, G. (2022). Flight capability and the low temperature threshold of a chinese field population of the fall armyworm *Spodoptera frugiperda*. *Insects*, *13*(5), 1–11. https://doi.org/10.3390/INSECTS13050422

Cokola, M. C., Mugumaarhahama, Y., Noël, G., Bisimwa, E. B., Bugeme, D. M., Chuma, G. B., Ndeko, A. B., & Francis, F. (2020). Bioclimatic zonation and potential distribution of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in South Kivu Province, DR Congo. *BMC Ecology*, *20*(1), 1–13. https://doi.org/10.1186/S12898-020-00335-1/TABLES/2

Day, R., Abrahams, P., Bateman, M., Beale, T., Clottey, V., Cock, M., Colmenarez, Y., Corniani, N., Early, R., Godwin, J., Gomez, J., Moreno, P. G., & Murphy, S. T. (2017). Fall armyworm: impacts and implications for Africa. Outlooks on pest management. *Outlooks on Pest Management*, *28*(5), 196–201. https://doi.org/10.1564/v28

Díaz, B. M., & Blackburn, G. A. (2003). Remote sensing of mangrove biophysical properties: Evidence from a laboratory simulation of the possible effects of background variation on spectral vegetation indices. *International Journal of Remote Sensing*, *24*(1), 53–73. https://doi.org/10.1080/01431160305012

Dminić, I., Kozina, A., Bažok, R., & Barčić, J. I. (2010). Geographic information systems (GIS) and entomological research: A review. *Journal of Food, Agriculture and Environment*, *8*(2), 1193–1198.

Duarte, F., Calvo, M. V., Borges, A., & Scatoni, I. (2015a). Geostatistics applied to the study of the spatial distribution of insects and its use in integrated pest management. *Revista Agronómica Del Noroeste Argentino*, *35*(2), 9–20.

Duarte, F., Calvo, M. V., Borges, A., & Scatoni, I. B. (2015b). Geostatistics and geographic information systems to study the spatial distribution of *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) in peach fields. *Neotropical Entomology*, *44*(4), 319–327. https://doi.org/10.1007/s13744-015-0288-3

Early, R., González-Moreno, P., Murphy, S. T., & Day, R. (2018). Forecasting the global extent of invasion of the cereal pest *Spodoptera frugiperda*, the fall armyworm. *NeoBiota 40: 25-50*, *40*(40), 25–50. https://doi.org/10.3897/NEOBIOTA.40.28165

Ellsbury, M. M., Woodson, W. D., Clay, S. A., Malo, D., Schumacher, J., Clay, D. E., & Carlson, C. G. (1998). Geostatistical characterization of the spatial distribution of adult corn rootworm

(Coleoptera: Chrysomelidae) Emergence. *Environmental Entomology*, *27*(4), 910–917. https://doi.org/10.1093/EE/27.4.910

ESRI. (2016). *ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute*. https://www.esri.com

Farias, P. R. S., Barbosa, J. C., Busoli, A. C., Overal, W. L., Miranda, V. S., & Ribeiro, S. M. (2008). Spatial analysis of the distribution of *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) and losses in maize crop productivity using geostatistics. *Neotropical Entomology*, *37*(3), 321–327. https://doi.org/10.1590/S1519-566X2008000300012

Ge, S., Sun, X., He, W., Wyckhuys, K. A. G., He, L., Zhao, S., Zhang, H., & Wu, K. (2021). Potential trade-offs between reproduction and migratory flight in *Spodoptera frugiperda*. *Journal of Insect Physiology*, *132*, 1–7. https://doi.org/10.1016/J.JINSPHYS.2021.104248

Ginting, S., Zarkani, A., Wibowo, R. H., & Sipriyadi. (2020). New invasive pest, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) attacking corn in Bengkulu, Indonesia. *Serangga*, *25*(1), 105–117.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, *202*, 18–27. https://doi.org/10.1016/J.RSE.2017.06.031

Harrison, R. D., Thierfelder, C., Baudron, F., Chinwada, P., Midega, C., Schaffner, U., & van den Berg, J. (2019). Agro-ecological options for fall armyworm (*Spodoptera frugiperda* JE Smith) management: Providing low-cost, smallholder friendly solutions to an invasive pest. *Journal of Environmental Management*, *243*, 318–330. https://doi.org/10.1016/J.JENVMAN.2019.05.011

Herlinda, S., Suharjo, R., Sinaga, M. E., Fawwazi, F., & Suwandi, S. (2022). First report of occurrence of corn and rice strains of fall armyworm, *Spodoptera frugiperda* in South Sumatra, Indonesia and its damage in maize. *Journal of the Saudi Society of Agricultural Sciences*, *21*(6), 412–419. https://doi.org/10.1016/J.JSSAS.2021.11.003

Hernández-Mendoza, J. L., López-Barbosa, E. C., Garza-González, E., & Mayek-Pérez, N. (2008). Spatial distribution of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in maize landraces grown in Colima, Mexico. *International Journal of Tropical Insect Science*, *28*(3), 126–129. https://doi.org/10.1017/S1742758408096112

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, *83*(1–2), 195–213. https://doi.org/10.1016/S0034-4257(02)00096-2

Huete, A. R. (1988). A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment*, *25*(3), 295–309. https://doi.org/10.1016/0034-4257(88)90106-X

Hutasoit, R. T., Kalqutny, S. H., & Widiarta, I. N. (2020). Spatial distribution pattern, bionomic, and demographic parameters of a new invasive species of armyworm *Spodoptera frugiperda* (Lepidoptera; Noctuidae) in maize of South Sumatra, Indonesia. *Biodiversitas Journal of Biological Diversity*, *21*(8), 3576–3582. https://doi.org/10.13057/BIODIV/D210821

Jiang, C., Zhang, X., Xie, W., Wang, R., Feng, C., Ma, L., Li, Q., Yang, Q., & Wang, H. (2022). Predicting the potential distribution of the fall armyworm *Spodoptera frugiperda* (J.E. Smith) under climate change in China. *Global Ecology and Conservation*, *33*, e01994. https://doi.org/10.1016/J.GECCO.2021.E01994

Jonsson, M., Raphael, I. A., Ekbom, B., Kyamanywa, S., & Karungi, J. (2014). Contrasting effects of shade level and altitude on two important coffee pests. *Journal of Pest Science 2014 88:2*, *88*(2), 281–287. https://doi.org/10.1007/S10340-014-0615-1

Jordon, M. W., Hackett, T. D., Aboagye-Antwi, F., Eziah, V. Y., & Lewis, O. T. (2022). Effects of distance from semi-natural habitat on fall armyworm (*Spodoptera frugiperda*, J. E. Smith) and its potential natural enemies in Ghana. *Bulletin of Entomological Research*, *112*(3), 343–353. https://doi.org/10.1017/S0007485321000894

Kaufman, Y. J., & Tanré, D. (1992). Atmospherically Resistant Vegetation Index (ARVI) for EOS-MODIS. *IEEE Transactions on Geoscience and Remote Sensing*, *30*(2), 261–270. https://doi.org/10.1109/36.134076

Kumela, T., Simiyu, J., Sisay, B., Likhayo, P., Mendesil, E., Gohole, L., & Tefera, T. (2018). Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (*Spodoptera frugiperda*) in Ethiopia and Kenya. *International Journal of Pest Management* , *65*(1), 1–9. https://doi.org/10.1080/09670874.2017.1423129

Li, X., Xu, D., Jin, Y., Zhuo, Z., Yang, H., Hu, J., & Wang, R. (2021). Predicting the current and future distributions of *Brontispa longissima* (Coleoptera: Chrysomelidae) under climate change in China. *Global Ecology and Conservation*, *25*, e01444. https://doi.org/10.1016/J.GECCO.2020.E01444

Liebhold, A., Luzader, E., Reardon, R., Bullard, A., Roberts, A., Ravlin, W., Delost, S., & Spears, B. (1996). Use of a geographic information system to evaluate regional treatment effects in a gypsy moth (Lepidoptera: Lymantriidae) management program. *Journal of Economic Entomology*, *89*(5), 1192–1203. https://doi.org/10.1093/JEE/89.5.1192

Liebhold, A. M., Rossi, R. E., & Kemp, W. P. (1993). Geostatistics and geographic information systems in applied insect ecology. *Annual Review of Entomology*, *38*(1), 303–327. https://doi.org/10.1146/annurev.en.38.010193.001511

Lymburner, L., Beggs, P. J., & Jacobson, C. R. (2000). Estimation of Canopy-average surface-specific leaf area using landsat TM data. *Photogrammetric Engineering and Remote Sensing*, *66*(2), 183–191.

Major, D. J., Baret, F., & Guyot, G. (2007). A ratio vegetation index adjusted for soil brightness. *International Journal of Remote Sensing* , *11*(5), 727–740. https://doi.org/10.1080/01431169008955053

Mengesha, G. G., Salo, S. K., Fantaye, F. Y., & Mohammed, K. B. (2021). Geographic distribution, relative importance, and association of factors influencing fall armyworm [*Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae)] on maize (Zea mays L.) in Southern Ethiopia. *International Journal of Pest Management*, *67*, 1–15. https://doi.org/10.1080/09670874.2021.1917722

Midega, C. A. O., Jonsson, M., Khan, Z. R., & Ekbom, B. (2014). Effects of landscape complexity and habitat management on stemborer colonization, parasitism and damage to maize. *Agriculture, Ecosystems & Environment*, *188*, 289–293. https://doi.org/10.1016/J.AGEE.2014.02.028

Mngadi, M., Odindi, J., & Mutanga, O. (2021). The utility of sentinel-2 spectral data in quantifying above-ground carbon stock in an urban reforested landscape. *Remote Sensing 2021*, *Vol. 13*, *Page 4281*, *13*(21), 4281. https://doi.org/10.3390/RS13214281

Montezano, D. G., Specht, A., Sosa-Gómez, D. R., Roque-Specht, V. F., Sousa-Silva, J. C., Paula-Moraes, S. V., Peterson, J. A., & Hunt, T. E. (2018). Host plants of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the Americas. *African Entomology*, *26*(2), 286–300. https://doi.org/10.4001/003.026.0286

Poggetti, L., Raranciuc, S., Chiabà, C., Vischi, M., & Zandigiacomo, P. (2019). Altitude affects the distribution and abundance of two non-native insect pests of the common walnut. *Journal of Applied Entomology*, *143*(5), 527–534. https://doi.org/10.1111/JEN.12609

R Core Team. (2022). *R: A language and environment for statistical computing*. https://www.r-project.org/

Rios, É. S., Martins, I. C. F., Noronha, M. P. de, Silva, J. A. da, Silva, J. G. da, & Badji, C. A. (2014). Spatial distribution of *Spodoptera frugiperda* in the wasteland of southern Pernambuco state, Brazil. *Revista de Ciências Agrarias - Amazon Journal of Agricultural and Environmental Sciences*, *57*(3), 297–304. https://doi.org/10.4322/rca.ao1461

Rokni, K., & Musa, T. A. (2019). Normalized difference vegetation change index: A technique for detecting vegetation changes using Landsat imagery. *CATENA*, *178*, 59–63. https://doi.org/10.1016/J.CATENA.2019.03.007

Ruas, S., Kelly, R., Ahmed, K. S. D., Maher, S., O'hora, E., Volpato, A., Huallacháin, D. Ó., Gormally, M. J., Stout, J. C., Moran, J., & Castle, J. (2022). Does landscape structure affect the presence of woodland specialist pollinators in farmland? Implications for agri-environment scheme design. *Proceedings of the Royal Irish Academy*, *122*, 17–37.

Santoiemma, G., Mori, N., Tonina, L., & Marini, L. (2018). Semi-natural habitats boost

Drosophila suzukii populations and crop damage in sweet cherry. *Agriculture, Ecosystems & Environment*, *257*, 152–158. https://doi.org/10.1016/J.AGEE.2018.02.013

Sartiami, D., Dadang, Harahap, I. S., Kusumah, Y. M., & Anwar, R. (2020). First record of fall armyworm (Spodoptera frugiperda) in Indonesia and its occurence in three provinces. *IOP Conference Series: Earth and Environmental Science*, *468*(1), 012021. https://doi.org/10.1088/1755-1315/468/1/012021

Schell, S. P., & Lockwood, J. A. (1997). Spatial characteristics of rangeland grasshopper (Orthoptera: Acrididae) population dynamics in wyoming: Implications for pest management. *Environmental Entomology*, *26*(5), 1056–1065. https://doi.org/10.1093/EE/26.5.1056

Schirmel, J., Albrecht, M., Bauer, P. M., Sutter, L., Pfister, S. C., & Entling, M. H. (2018). Landscape complexity promotes hoverflies across different types of semi-natural habitats in farmland. *Journal of Applied Ecology*, *55*(4), 1747–1758. https://doi.org/10.1111/1365-2664.13095

Shylesha, A. N., Jalali, S. K., Gupta, A., Varshney, R., & Venkatesan, T. (2018). Studies on new invasive pest *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) and its natural enemies. *Journal of Biological Control*, *32*(3), 145–151. https://doi.org/10.18311/jbc/2018/21707

Sisay, B., Simiyu, J., Mendesil, E., Likhayo, P., Ayalew, G., Mohamed, S., Subramanian, S., & Tefera, T. (2019). Fall armyworm, *Spodoptera frugiperda* infestations in East Africa: assessment of damage and parasitism. *Insects*, *10*(7), 1–10. https://doi.org/10.3390/INSECTS10070195

Supartha, I. W., Susila, I. W., Sunari, A. A. A. A. S., Mahaputra, I. G. F., Yudha, I. K. W., & Wiradana, P. A. (2021). Damage characteristics and distribution patterns of invasive pest, *Spodoptera frugiperda* (J.E Smith) (Lepidoptera: Noctuidae) on maize crop in Bali, Indonesia. *Biodiversitas Journal of Biological Diversity*, *22*(6), 3378–3389. https://doi.org/10.13057/BIODIV/D220645

Tepa-Yotto, G., Winsou, J., Dahoueto, B., & Tamò, M. (2021). Assessing new scouting approaches for field sampling of *Spodoptera frugiperda* and its parasitoids. In N. G. Kavallieratos (Ed.), *The 1st International Electronic Conference on Entomology* (p. 10397). MDPI stays. https://doi.org/10.3390/iece-10397

Timilsena, B. P., Niassy, S., Kimathi, E., Abdel-Rahman, E. M., Seidl-Adams, I., Wamalwa, M., Tonnang, H. E. Z., Ekesi, S., Hughes, D. P., Rajotte, E. G., & Subramanian, S. (2022). Potential distribution of fall armyworm in Africa and beyond, considering climate change and irrigation patterns. *Scientific Reports* , *12*(1), 1–15. https://doi.org/10.1038/s41598-021-04369-3

Trisyono, Y. A., Suputa, S., Aryuwandari, V. E. F., Hartaman, M., & Jumari, J. (2019). Occurrence of heavy infestation by the fall armyworm *Spodoptera frugiperda*, a new alien invasive pest, in Corn Lampung Indonesia. *Jurnal Perlindungan Tanaman Indonesia*, *23*(1), 156–160. https://doi.org/10.22146/JPTI.46455

Tscharntke, T., Karp, D. S., Chaplin-Kramer, R., Batáry, P., DeClerck, F., Gratton, C., Hunt, L., Ives, A., Jonsson, M., Larsen, A., Martin, E. A., Martínez-Salinas, A., Meehan, T. D., O'Rourke, M., Poveda, K., Rosenheim, J. A., Rusch, A., Schellhorn, N., Wanger, T. C., … Zhang, W. (2016). When natural habitat fails to enhance biological pest control – Five hypotheses. *Biological Conservation*, *204*, 449–458. https://doi.org/10.1016/J.BIOCON.2016.10.001

Veres, A., Petit, S., Conord, C., & Lavigne, C. (2013). Does landscape composition affect pest abundance and their control by natural enemies? A review. *Agriculture, Ecosystems & Environment*, *166*, 110–117. https://doi.org/10.1016/J.AGEE.2011.05.027

Westbrook, J. K., Nagoshi, R. N., Meagher, R. L., Fleischer, S. J., & Jairam, S. (2015). Modeling seasonal migration of fall armyworm moths. *International Journal of Biometeorology* , *60*(2), 255–267. https://doi.org/10.1007/S00484-015-1022-X

Wright, R. J., Devries, T. A., Young, L. J., Jarvi, K. J., & Seymour, R. C. (2002). Geostatistical analysis of the small-scale distribution of European corn borer (Lepidoptera: Crambidae) larvae and damage in whorl stage corn. *Environmental Entomology*, *31*(1), 160–167. https://doi.org/10.1603/0046-225X-31.1.160

Wyckhuys, K. A. G., & O'Neil, R. (2007a). Influence of extra-field characteristics to abundance of key natural enemies of Spodoptera frugiperda Smith (Lepidoptera: Noctuidae) in subsistence maize production. *International Journal of Pest Management*, *53*(2), 89–99. https://doi.org/10.1080/09670870701245207

Wyckhuys, K. A. G., & O'Neil, R. J. (2006). Population dynamics of *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) and associated arthropod natural enemies in Honduran subsistence maize. *Crop Protection*, *25*(11), 1180–1190. https://doi.org/10.1016/J.CROPRO.2006.03.003

Wyckhuys, K. A. G., & O'Neil, R. J. (2007b). Local agro-ecological knowledge and its relationship to farmers' pest management decision making in rural Honduras. *Agriculture and Human Values*, *24*(3), 307–321. https://doi.org/10.1007/S10460-007-9068-Y

Zha, Y., Gao, J., & Ni, S. (2010). Use of normalized difference built-up index in automatically mapping urban areas from TM imagery. *International Journal of Remote Sensing* , *24*(3), 583–594. https://doi.org/10.1080/01431160304987.