agriculture

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Ommatissus lybicus Infestation in Relation to Spatial Characteristics of Date Palm Plantations in Oman

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Received: 29 January 2019; Accepted: 5 March 2019; Published: 8 March 2019

Abstract: The agricultural ecosystem and its interaction with the outside environment plays a major role in the population of herbivores. The infestation of the Dubas bug, *Ommatissus lybicus*, has shown a spatial and temporal variation among different date palm plantations in Oman. This study focused on the relationship of infestation with date palm cultivation environments. The infestation and some selected environmental factors were evaluated in 20 locations for four consecutive infestation seasons over two years. Ordinary least squares (OLS) regression was used to identify the significant factors and the global relationship. Geographically weighted regression (GWR) was used to determine the spatial relationship. The results showed that GWR had better prediction than OLS. The model explained 61% of the infestation variation in the studied locations. The most significant coefficient was the tree planting pattern, the trees planted in uneven rows and columns (irregular pattern) had a positive effect; the infestation increased as the irregularity increased due to an increase in tree density. This reduced the interaction of harsh outside weather with the date palm plantation microclimate. The proportion of side growing area had a negative effect on insect population; as the percentage of side growing area increased as the infestation decreased, assuming the side growing crops hosted natural enemies. The study concluded that the variation of spatial and temporal infestation was primarily due to the variation of the cultural practices and spatial environment of the date palm plantations.

Keywords: *Ommatissus lybicus*; date palm; environment; date palm habitat

1. Introduction

The Dubas bug *Ommatissus lybicus* de Bergevin (Hemiptera: Tropiduchidae) is a highly destructive pest in date palm *Phoenix dactylifera* Linnaeus plantations in Oman and many countries in the Middle East and North Africa. In addition to Oman, *O. lybicus* is listed as a serious pest in five other countries and recorded in 14 other countries [1]. *O. lybicus* has an incomplete metamorphosis life cycle, and life-cycle longevity varies between the two seasons (autumn and spring) and gender. The female adult's lifespan is 17–95 days (mean = 49.7 ± 3.5) in the spring season and 14–117 days (mean = 53.7 ± 5.8) in the autumn season. The male adult's life span is 21–102 days (mean = 56.5 ± 4.3) and 19–133 days (mean = 66.8 ± 5.3) in these seasons, respectively. A difference in the egg oviposition numbers was reported between the seasons, 17–205 eggs (mean = 98.5 ± 9.9) in spring and 11–216 eggs (mean = 128.1 ± 15.4) in autumn [2]. The eggs hatch in 39 days at the optimal growth temperature (25–27.5 °C), and the duration increases as the temperature increases or decreases from the optimal. The nymphs complete five instars before reaching the mature stage, extending from 34 to 95 days depending on the temperature. The total average development time from egg to adult is 84 days at 27.5 °C [3].

Both immature and mature stages cause direct damage to the date palm by feeding on the nutrient sap, and necrotic spots result from the eggs' oviposition events. Honeydew is accumulated on the leaves' surfaces due to the feeding process of the insect, and sooty mold fungus grows on the leaves, consequently blocking stomata openings and reducing photosynthesis [4]. The leaves lose their green color in a few months in severe infestation conditions [5]. Heavy infestation reduces the quality and quantity of the fruits [6], and an extremely heavy infestation can kill the date palm trees [7]. *O. lybicus* is controlled by the use of very expensive chemical pesticides; a total of 523 tons of pesticides were applied in Oman from 1993 to 2010 at a cost of approximately $23 million [1]. In addition to its cost, pesticide application has many negative impacts and is expected to pose considerable problems to the environment and humans as a result of the chemical application, such as disruption of natural enemies of the *O. lybicus*, impacts on other beneficial insects such honey bees, human health and environment [8].

The environmental variations of both abiotic and biotic characteristics have a significant impact on the insect population [9]. Pest population variations can be the result of the destruction of natural habitation, climate variation and chemical application in the agricultural environment [10,11]. Researchers have conducted many studies to understand how pest infestations interact with the agro-ecosystem to mitigate the effects of pests on crops and thereby lower the financial losses and avoid environmental hazards. Monocultural practices provide a fertile environment for insect pest outbreaks [12] compared to polyculture that plays a vital role in reducing pest infestation [11]. In addition, scientists have investigated various crop ecosystems that may affect pest population, such as the effect of tree size [13], tree-planting patterns [14], habitat characteristics, such as host plants presence, phenology, landform index and chemical applications [15], crop ages [16,17] and field size. The behaviour of insect infestation has been found to vary spatially within the same field. For instance, some insect species have the tendency to aggregate at the edge of the field such as pear midge *Contarinia pyrifvora* Riley [18], the *Aphis fabae* Scopoli infestation [19] and the cabbage butterfly *Pieris rapae* Linnaeus [20]. The tendency of insects to aggregate at the edge is mainly influenced by abiotic factors [21].

Limited studies exist on the effect of the date palm plantation agro-ecosystem on the *O. lybicus* population. A clear understanding of date palm plantation habitat variations and their interactions with *O. lybicus* behaviour, population and spatial and temporal variance is expected to provide better opportunities for management strategy planning and resource saving. An earlier investigation on the relationship of environmental factors and *O. lybicus* was undertaken by Al-Kindi et al. [22]. The authors found significant relationships among elevation, slope, geology, soil type, water type and distance to streams with the distribution of *O. lybicus* infestation along with many other factors. The authors explained the reason for high infestation in the area near to valleys in the elevation between 251–750 m and fresh water was due to high uptake of fresh water by trees from loam soil which makes the date palms trees produce more nutrient sap that is more suitable to *O. lybicus*. In addition, the direct sun-facing of date palm plantation (slope) lowers *O. lybicus* infestation. Mahmoudi et al. [23] reported a positive relationship of infestation with different management and cultural practices with a good prediction model (75%) in Iran. In addition, [23], Al-Kindi et al. [24] investigated the relationship of *O. lybicus* infestation with many farming practices and found that the ordinary least squares (OLS) regression model of different farming practices explains 70% of the infestation. The high-density trees and intercropping provide a good microclimate for insect increases and good fertilizer application provides more nutrients to the plants which is a preference of insects. Moreover, other studies have explored the relationship of *O. lybicus* infestation with different abiotic factors, solar radiation [25], tree density [26] and temperature and humidity [27]. High solar radiation with high temperature increases the body thermal accumulation, increasing metabolic activity which disrupts insect physiology [28];

however, high tree density reduces the interaction of outside weather, which increases the insect population [26].

Earlier studies of the relationship of *O. lybicus* infestation with different environmental factors did not consider the interaction of those factors with the date palm habitat/ecosystem. This study was planned to be a complementary study to cover other environment factors not included in earlier studies that focused mainly on plantation environment interactions with different infestation levels. The study includes general factors, such as field size area, field land structure (landform index), planting pattern and the distance of the field from the nearest date palm plantation. Additionally, a few focal parameters of tree plantations were assessed, such as the distance of sampled trees from plantation edges, irrigation intervals and height of nearest trees in four directions (indicator of shading). The study hypothesises that certain agricultural factors, such as the large field size, high tree aggregation (non-systemic planting/overlapped rows and columns) and the distance of trees from the outside environment will promote the infestation of *O. lybicus*. The objective of the study was to explore the effects of date palm agricultural environment characteristics and their relationship with infestation intensity.

2. Materials and Methods

2.1. Study Area

The data was collected from 20 villages in three Omani governorates—Muscat, Ad Dakhliyah and Al Batinah South (Figure 1). These 20 locations were selected to satisfy the factors that needed to be included in the current study, such as the variation in date palm plantation area size, different land topography (terrace cultivation, flat land or different slopes), variation in the presence of side cultivated land and variation in planting patterns. The locations were in various areas from a modern city (Barka) to some of Oman's oldest villages (Samil and Staal). The study area extended from lowland land 24 m above sea level to mountain ranges 801 m above sea level. Most of the 20 locations are isolated villages where the cultivated land is confined to one area, except for a few locations which are urbanized due to population growth. The major cultivated crop in all these locations is the date palm. In some cases, other fruit trees are grown in small numbers as intercropping between date palm trees. In addition, farmers usually plant fodder crops beneath or between date palm trees to maximize the benefit of land and water resources.

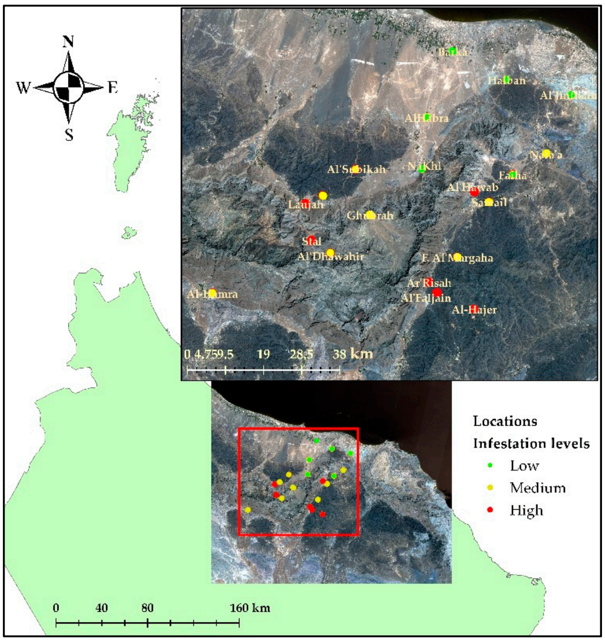


Figure 1. Map of north Oman showing the study area within Oman, the point of each field and the average infestation levels over four seasons.

The date palm trees are grown in regular rows and columns in modern farms, however, the land shape, availability and water irrigation system control the date palm planting pattern in traditional agricultural fields that are often found in irregular rows and columns. This results in a high density of date palm trees per unit area. In addition, the presence of intercropping, especially folder crop, controls the irrigation application intervals, especially in traditional plantation which is not very common in modern farms. The main control method of *O. lybicus* is insecticide spraying by aerial application during the spring season.

2.2. Infestation Data

The infestation readings were collected from 20 trees in each field for four consecutive seasons (autumn 2016, spring 2017, autumn 2017 and spring 2018). The number of nymphs and adults were counted from 20 leaflets from two fronds (one facing north and one facing south) from 10 trees; another 10 trees at each location were evaluated by the honeydew droplet method using water-sensitive paper [29]. Water-sensitive papers (26 mm width and 76 mm length) were placed underneath each selected palm tree, 1–1.5 m from the trunk in each direction (North, West, East and South) for two hours (from 8 AM to 10 AM) and the number of honeydew drops were counted. The 20 leaflets were marked to be used for insects counting in all the four seasons. In a few cases, different fronds were chosen because of the age of the fronds or tree service practices by selecting other fronds from the same trees. The same tree was used for honeydew evaluation in all seasons. The data was collected at the peak of infestation (middle of the season). The total number of insects per total number of leaflets and the total number of honeydew droplets per one centimeter (of water-sensitive paper) were the infestation reading for each tree. The coordinate location of each selected tree was recorded.

2.3. Factor Data

The studied parameter/factors were collected from a ground survey conducted by the Ministry of Agriculture, Oman or computed through remote-sensing procedures from Sentinel satellite images using ArcGIS 10.4.1 (ESRI, Redlands, CA, USA). Google Earth (Google, Menlo Park, CA, USA) was used to grid the date palm planting patterns and the proportion of side growing area to the date palm tree area. Field observation was utilized to confirm the grading (scale). The normalized difference vegetation index (NDVI) was computed from the satellite image and used to extract the agricultural area size and the distance of each field to the nearest date palm plantation. The date palm trees that had been evaluated for infestation in the field were exported as a point layer, which was used to measure the distance of each tree to the edge of the same field (the field's polygon layer). Digital elevation models (DEMs) were used to calculate the landform index. The height of the trees nearest to the tree which had a field reading were graded as follows: short, stem less than an average human's height; medium, stem more than an average human's height and less than 3 m; and high, more than 3 m in height. Next, the heights were scored as follows: 0, when none of the surrounding trees were graded as high; 1, when at least one of the surrounding trees was graded as high; 2, when two of the surrounding trees were graded as high and one as medium; 3, when three of the surrounding trees were graded as high or when two were graded as high and two as medium; 4, when all four of the surrounding trees were graded as high (Table 1).

Table 1. Environmental factors included in the study and the scale of each factor.

Serial Number	Factors	Description
1	Planting pattern	Regular = 1, semi-regular = 2 and random = 3.
2	Irrigation Interval	Number of days between irrigation cycles.
3	Landform index	Increases as the slope increases.
4	Side growing area	Presence of side growing area (0 = nil, 1 = minor area, 2 = clearly distinguishable area form the image, 3 = almost 20% of total area, 4 = almost 40% of total area and 5 = nearly 50% of total area.
5	Location area	In square meters
6	Distance to nearest date palm plantation	In meters
7	Tree distance to edge of field	In meters
8	Surrounding tree height	Graded as 0, when none of the surrounding trees were graded as high; 1, when at least one of the surrounding trees was graded as high; 2, when two of the surrounding trees were graded as high and one as medium; 3, when three of the surrounding trees were graded as high or when two were graded as high and two as medium; 4, when all four of the surrounding trees were graded as high.

2.4. Data Analysis

Spatial analysis was run to determine the relationship between the infestation and the various factors. First, the OLS model was run to find the significant factors that best fitted the model and to determine the global relationship. Then, geographically weighted regression (GWR) was run to find the spatial relationship using only the significant factors. GWR is a strong statistical regression approach that is used to build a correlation of different factors spatially; it is more advantageous than OLS in overcoming the non-stationary heterogeneity [30,31]. Moreover, GWR considers the spatial weight matrix when it construct the relationship between different variables; therefore, it is considered an accurate estimation for the spatial data modelling [32,33]. The infestation was used as the dependent variable, and the scales of each factor were included as the predictor variable. OLS and GWR were run three times—the average of four seasons' data, as well as the average of autumn and the average of spring, individually.

3. Results

3.1. Infestation

The average infestation of each field is presented in Figure 2. In general, the infestation during the autumn season was lower than during the spring season. Only one field showed medium infestation level, more than 2 insects/leaflet, in autumn; compared to six locations in spring. The infestation of the 2016 autumn season was higher than that of the 2017 autumn season with an average infestation 0.33 insects/leaflet and 0.24 insects/leaflet, respectively, for all locations. The 2017 spring season (1.27 insects/leaflet) infestation was higher than that of the 2018 spring season (0.29 insects/leaflet): 2 locations showed a high infestation level (more than 5 insects/leaflet), and 4 locations showed a medium infestation (more than 2 and lower than 5) in the 2017 spring season. However, only one location showed medium infestation and none of the locations showed high-level infestation in the spring of 2018. There was an obvious difference in the infestation between the two spring seasons but not between the two autumn seasons.

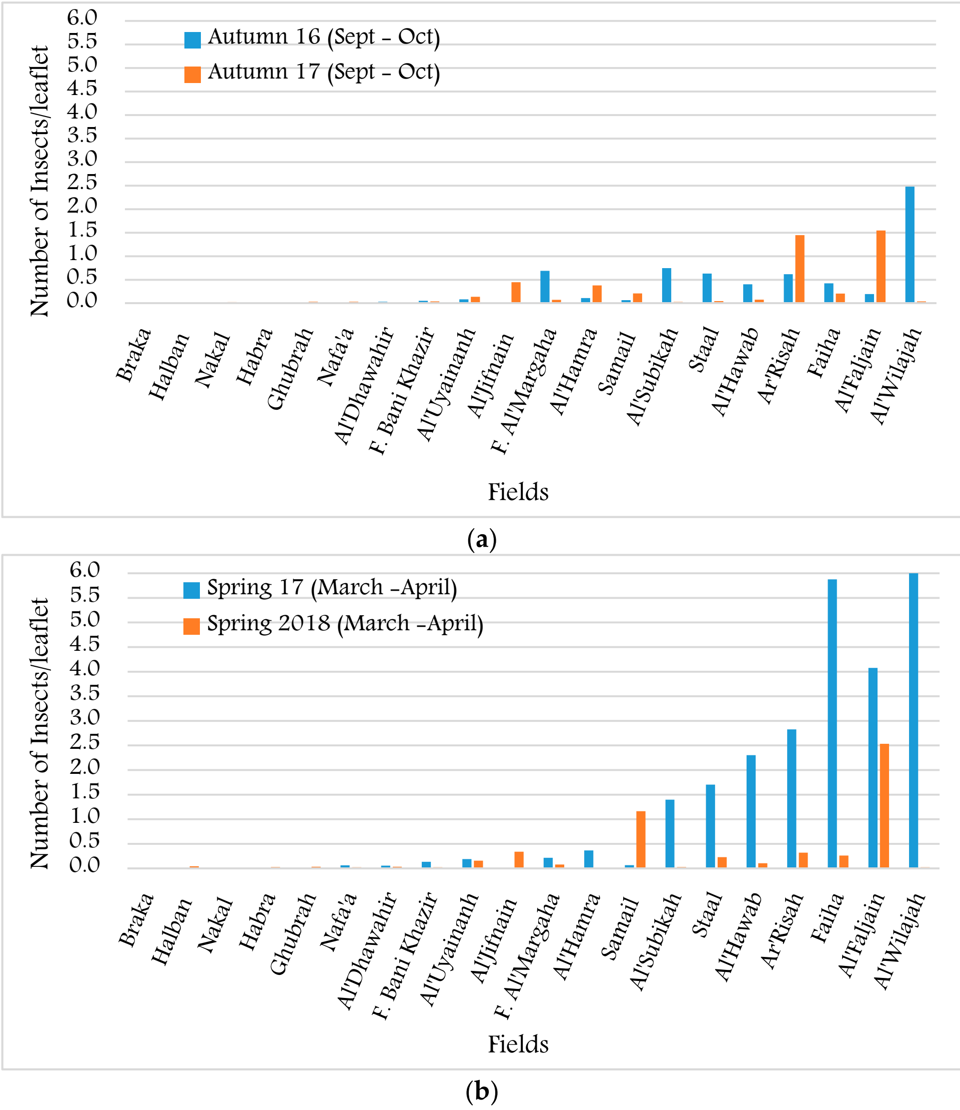


Figure 2. Average number of *O. lybicus*, infestations in each field for the autumns of 2016 and 2017 (**a**) and springs of 2017 and 2018 (**b**).

3.2. Results of Ordinary Least Squares (OLS) Regression

The OLS of pooled data showed that all tested factors had a significant relationship with the infestation. The tree distance to the edge of the field and tree height were insignificant for the autumn average infestation, and the irrigation interval and landform index were insignificant for spring infestation. The highest coefficient was found with planting patterns: 0.46, 0.31 and 1.19 for the four seasons', autumn and spring means, respectively. The variance inflation factor (VIF) value was less than 7.5, indicating no redundancy/correlation among the tested factors. The side growing area, location area and nearest village were the only three factors that showed a negative relationship with infestation; the other five factors were positive factors (Table 2). The coefficient of determination was R^2 = 0.50 mean infestation for all four seasons, and R^2 = 0.42 for both the autumn and spring seasons (Table 3, Figure 3).

Table 2. Coefficient and variance inflation factors (VIF) of pooled four seasons, autumn and spring means infestation with different environmental factors.

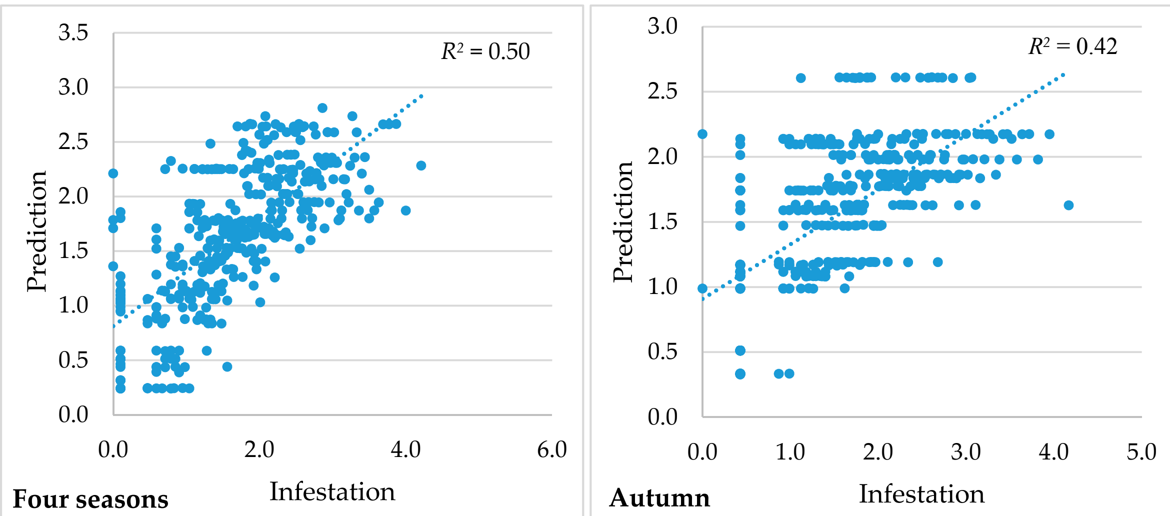
Variable	Four Seasons		Autumn		Spring	
	Coefficient	VIF	Coefficient	VIF	Coefficient	VIF
Intercept	0.617 *	—	0.415 **	—-	1.827 **	—-
Planting pattern	0.462 *	1.40	0.311 **	1.40	1.187 **	1.40
Irrigation Interval	0.055 *	1.62	0.061 **	1.76	0.025	1.76
Landform index	0.092 *	1.40	0.266 **	1.40	0.044	1.40
Side growing area	−0.226 *	1.20	−0.166 **	1.21	−0.512 **	1.21
Field area	−0.000 *	1.46	−0.000 **	1.46	−0.000 **	1.46
Near village	−0.000 *	1.26	−0.000 *	1.35	−0.000 **	1.35
Near edge	0.000 *	1.10	0.000	1.12	0.000 **	1.12
Near trees height	0.074 *	1.13	0.014	1.16	0.284 **	1.16

* Significance difference at p-value ≤ 0.05; ** Significance difference at p-value ≤ 0.001.

Table 3. Results of OLS (ordinary least regression) regression of pooled four seasons, autumn and spring means infestation with different environmental factors.

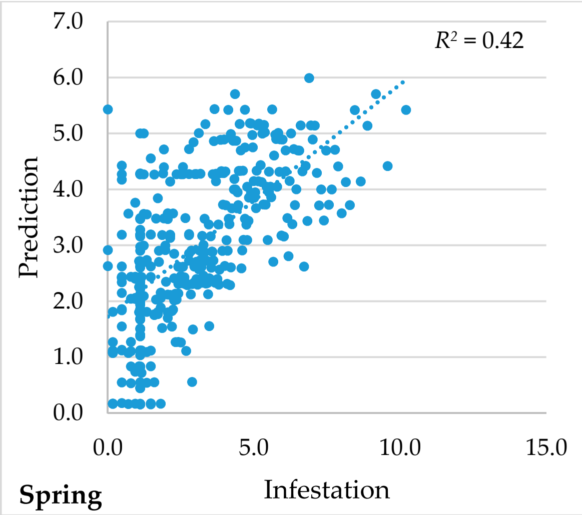
Parameter	Four Seasons	Autumn	Spring
Number of observations	399	399	399
Multiple R^2	0.50	0.42	0.42
Joint F-statistic	48.79	31.34	31.82
Joint Wald statistic	808.29	753.41	588.52
Koenker (BP *) statistic	32.93	42.80	73.38
Jarque-Bera statistic	6.42	4.16	14.64
Akaike information criterion (AICc)	790.72	828.72	1527.62

* BP is Bruesch-Pagan statistic, a test to determine if the independent (explanatory) variables in the model have a constant relationship to the dependent variable.



(**a**) (**b**)

Figure 3. *Cont.*



(**c**)

Figure 3. Scatter plot for the OLS (ordinary least regression) regression model of the significant environmental factors for four seasons (**a**), autumn (**b**) and spring means (**c**).

3.3. Results of Geographically Weighted Regression (GWR)

The factors that showed a significant difference were used to run the GWR model. The coefficient of determination for the four season data was higher than the mean of each season's infestation (R^2 = 0.61), and the spring coefficient of determination was higher than the autumn coefficient (R^2 = 0.58 and R^2 = 0.52, respectively). The lowest residual squares was with pooled seasons' data, followed by autumn and spring. The lowest difference in the prediction coefficient of determination (R^2) between the OLS and GWR was with the autumn data, which had the lowest effective number (14.06). Sigma is the square root of the normalized residual sum of squares, and it is used to calculate the AICc that is used to compare the efficiency of different models' fitness. The lowest sigma value and AICc value were found with a four-season mean to be 0.58 and 706.86, respectively, and showed a higher coefficient of determination R^2 = 0.61 (Table 4, Figure 4).

Table 4. Results of GWR (geographically weighted regression) of pooled four seasons, autumn and spring means infestation with different environmental factors.

Variable Name	Four Seasons	Autumn	Spring
Bandwidth	36,035.46	35,012.06	20,004.21
Residual squares	126.50	145.94	735.11
Effective number	17.41	14.06	23.89
Sigma	0.58	0.62	1.40
AICc	706.86	758.00	1421.77
R^2	0.61	0.52	0.58
R^2 adjusted	0.59	0.50	0.56

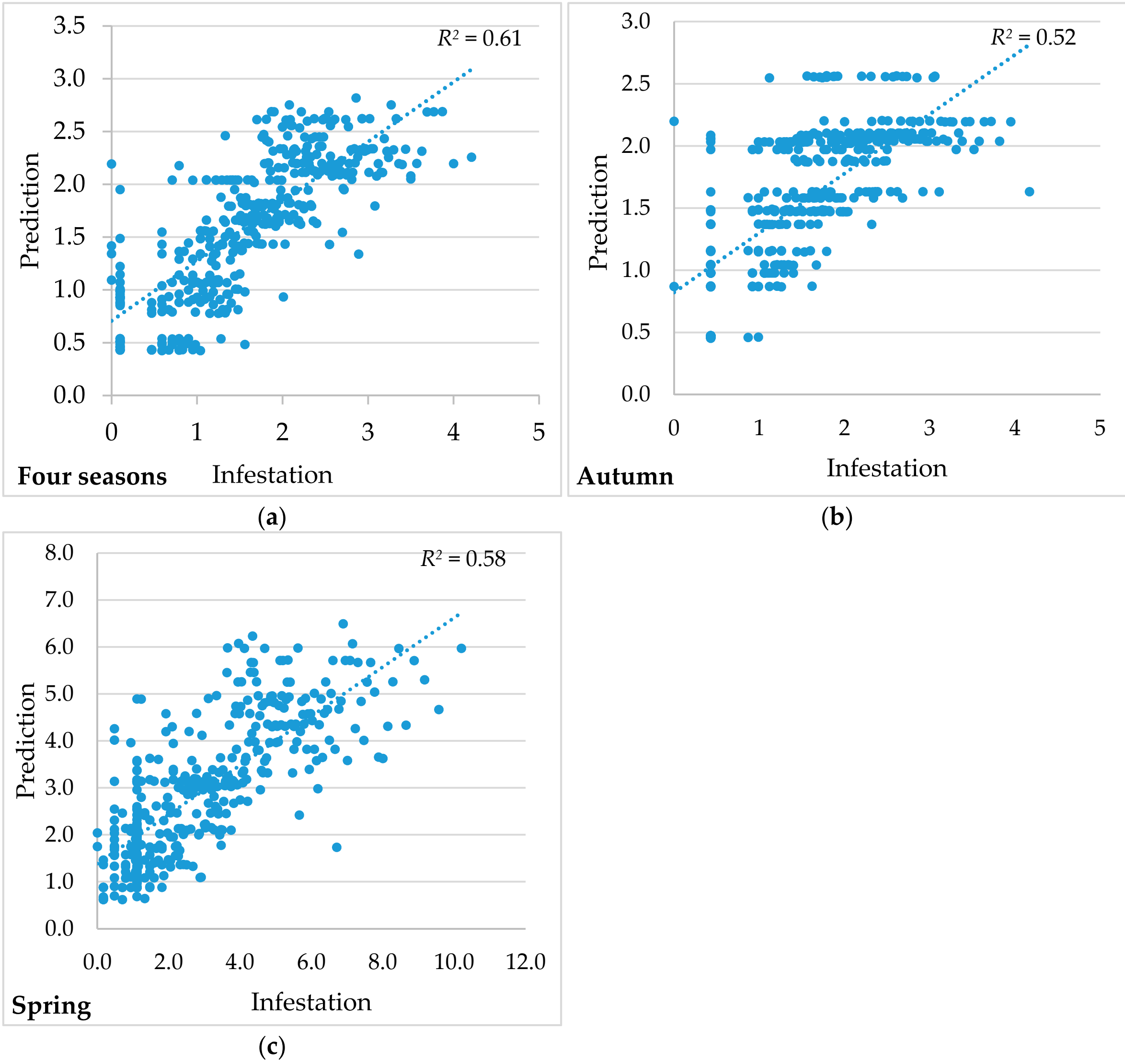


Figure 4. Scatter plot for GWR (geographically weighted regression) model of significant environmental factors for four seasons (**a**), autumn (**b**) and spring means (**c**).

4. Discussion

The results showed variance of infestation between the autumn and spring seasons, and in the same season during different years. This is a clear indication of temporal variation among the locations. The seasonal variation was attributed to the variance in climate or biotic factors. A high infestation during the spring season was explained in earlier studies by high temperature during the off-season period between spring and autumn, above the high lethal temperature (34.5 °C) [3], the female lays more eggs during autumn than spring [2] and a short egg-hatching period in spring and temperature [1].

The results showed an insignificant relationship between the infestation and the distance of trees from the edge and the presence of high trees (shading) in the autumn season. This could be attributed to high temperatures and high solar radiation during the autumn season [25] which made the impact of shading or the microclimate between date palm trees low and the opposite in spring season where tall trees created lower interaction between outside temperature and solar radiation and provided a suitable microclimate for insect multiplications. In contrast, there was an insignificant relationship with irrigation period and landform index during the spring season. This can be attributed to low temperatures and, consequently, the water stress in the plant is low.

The GWR showed better prediction for pooled data, autumn and spring (R^2 = 0.61, R^2 = 0.52 and R^2 = 0.58) than OLS (R^2 = 0.50, R^2 = 0.42 and R^2 = 0.42), respectively. At the same time, the Akaike information criterion (AICc) values were reduced from 790.72, 828.72 and 1527.62, respectively, with OLS to 706.86, 758.00 and 1421.77 with GWR. This confirmed the presence of a spatial relationship between infestation and the studied environmental factors and showed that the GWR model was much better for predicting the relationship than the OLS model. The results showed that the relationships between the infestation and side growing area, the size of field area and the distance to the nearest date palm field were negatively correlated and that all the other factors were positively correlated with both pooled data and the autumn season.

The infestation was reduced significantly with the increase of the side growing area, the size of field and the distance to the nearest date palm plantation. The side growing crop can be a source of natural enemies which influence the population of *O. lybicus*. The most common crop grown in the side growing area were fodder and/or field crops such as alfalfa, sorghum, corn, barley and oats. Fodder crops including alfalfa are a good source of general biological control agents such as the predators belonging to chrysopidae and coccinellidae families [34]. Few species of those two families species were reported as predators on *O. lybicus* in Oman [35]. In most cases, the literature reported that the negative or positive relationships of various insects with side growing crops, nearness to pest outbreak, and/or the location size were due to the effect of natural enemies. This mainly depends on the interaction between natural enemies and pests. A positive relationship was found when the dispersal of pests was longer than that of their predators and negative when there was an opposite pattern [36]. A significantly lower infestation for the fruit borer, *Leucinodes orbonalis* Guenée, was found for eggplant crops when maize crops were grown in the border [37]. In addition, the results showed that the infestation decreased as the distance to the nearest date palm plantation increased. The infestations of the woodwasp *S. noctilio* on *Pinus ponderosa* Douglas ex C. Lawson were found to be correlated negatively with the nearest infested field [38]. Also, it was found that a large area field may influence the richness/diversity of beneficial arthropods [39]. In contrast, a strong relationship between infestation and small area plantations was found [40].

The irregular planting pattern of date trees results in high tree density per unit area, and higher density was reported to have a positive relationship with *O. lybicus* infestation [26]. Latifian et al. [41] reported that the intensity of other pest species on date palm plantation was significantly higher when there are shorter distances between date palm trees. This confirmed the current study results of a positive relation between the infestation and planting pattern.

The current results showed that, as the irrigation interval increased, the infestation increased. Phytophagous insect populations are influenced by the plant water contact [42]. When the water level inside the plant increases, the insect survival and fertility increase [43,44]; however, the defense mechanism in the plant drops down when the crops are under water stress [45]. The current results agree with those reported in other studies [46] that found a positive relationship with different pest species as the water stress increases, as indicated by our irrigation interval results. Han [42] categorized the relationships between plants and herbivorous insects into five categories. Its seems that *O. lybicus* falls into the category known as the 'pulsed stress hypothesis', where the insect sap feeder performs well under a medium level of drought [47]. This fact and the current results agree that the relationship of *O. lybicus* is within the stress group.

The positive relationship of infestation and the landform index agree with the previous results that found a positive relationship of *O. lybicus* infestation with slope [22] and a positive relationship of the landform index with other insect species infestation, such as the European gypsy moth *Lymantria dispar* Linnaeus [15] and the infestation of Woodwasp *S. noctilio* on *P. ponderosa* [38]. The traditional method, using handheld clinometers to study the relation of *Adelges tsugae* Annand and the landform index, did not show a significant relationship [48].

A positive significant relation was reported between tree height and *O. lybicus* infestation in Iran date palm. Shah et al. [49] reported that a high number of *O. lybicus* eggs are laid in the date palm parts that are under shade. A positive relationship was found between the infestation of other insect species and the height and/or size of trees [50,51].

The current results show a positive relationship between infestation and the distance from the edge. This agrees with the findings of other studies of other insects species [52]. They attributed this to a high number of natural enemies' movement from the wild plant to main crop. However, other studies disagree with the current results, such as those concerning the infestation of galling insects on *Styrax pohlii* Fritsch [39] and the infestation of *Fagus orientalis* Lipsky [53]. The authors explain the preference of insects to attack stressed plants at the edge were due to climate stress. The pattern could vary with the infestation severity. The infestation of the weevil, *Ceuthorhynchus assimilis* Payk, on oil-seed rape was found to occur more at the edge in low infestations and the opposite in high infestations [54]. Indeed, the spatial variation (edge to centre) for the same insect species, the adults of the beetle *Brassicogethes* spp. (synonym *Meligethes* spp.), was found more at the edge of the crop than inside the field and the opposite for the larval stage and their main parasitoid, *Tersilochus heterocerus* Thomson [55].

It is critical to understand the direct and indirect interactions of organisms within the agro-ecosystem in order to achieve good management strategy planning [56] or prediction of attack risk [38]. The insect and disease susceptibility and attractiveness are reduced with good planned cultural practices, such as location preparation, planting distance, planting method, hygiene application, and control and thinning practices [57]. The current results of the data analysis show that infestation is associated with highly irregular planting patterns and that such locations should be the target of control practices and resources. In addition, they indicate that there are great opportunities for conservation and biological control practices in the field with a high proportion side growing area. Thus, further study is required to increase our understanding of the role of each of these factors and how they can be integrated into a management strategy.

5. Conclusions

The study found that environmental factors have significant effects on *O. lybicus* infestation. The GWR prediction model showed that integrating different environmental factors was explained with the pooled, autumn and spring data (61%, 52% and 58%, respectively). The OLS model showed the trend of the relationships of infestation and different environmental factors. The tree planting system, irrigation, landform index, nearness of trees to the location edge and increase of the shading around the trees have positive effects, and the size of the date plantation, side growing area and the distance to the nearest date palm plantation have negative effects. In addition, the study indicates that temporal and spatial variations are due to variances in different date palm tree plantation habitat in different locations. The most significant factors that influence this variance are the tree planting pattern and side growing area/crops.

Author Contributions: R.H.A.S. and L.K. devised the experiment; R.H.A.S. performed the experiment and analysis under the guidance of L.K.; S.A.H.A.-K. and N.A.A.-A. helped with fieldwork and data collection.

Funding: This research was funded by The Research Council, Oman, grant number A13/3383.

Acknowledgments: Thanks to The Research Council, Oman, for funding this research work and Directorate General of Agriculture and Livestock Research, Ministry of Agriculture and Fisheries, Oman, for facilitating the field work and the Oman and National Survey Authority for providing the DEM data. Many thanks for all staff and technicians of Plant Protection Research Centre, Directorate General of Agriculture and Livestock Research, who helped in field data collection.

Conflicts of Interest: The authors declare no conflict of interest.

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