

Original Article

Monitoring of infestation percentages of the invasive red palm weevil, *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae), and management tactics: a six-year study

Monitoramento das porcentagens de infestação do gorgulho-vermelho invasor, *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) e táticas de manejo: um estudo de seis anos

N. F. Abdel-Baky^{a,b*} , M. A. Aldeghairi^a , M. I. Motawei^{a,c} , L. A. M. Al-Shuraym^d , A. A. S. Al-Nujiban^e , M. T. M. Alharbi^f  and M. Rehan^{a,g} 

^aQassim University, College of Agriculture and Veterinary Medicine, Department of Plant Production and Protection, Buraydah, Saudi Arabia

^bMansoura University, Faculty of Agriculture, Economic Entomology Department, Mansoura, Egypt

^cAlexandria University, College of Agriculture, Department of Crop Science, Alexandria, Egypt

^dPrincess Nourah Bint Abdulrahman University, College of Science, Department of Biology, Riyadh, Saudi Arabia

^eQassim University, College of Science and Arts, Department of Biology, Unaizah, Saudi Arabia

^fMinistry of Environment, Water, and Agriculture, Red Palm Weevil Control Program, Qassim, Saudi Arabia

^gKafrelsheikh University, Department of Genetics, College of Agriculture, Kafr El-Sheikh, Egypt

Abstract

Red palm weevil (RPW), *Rhynchophorus ferrugineus* (Olivier) (Coleoptera, Curculionidae), is a devastating invasive pest, that invaded Saudi Arabia's date palms in 1987. Evaluation of the infestations and the efficacy of both preventative and control treatments have been studied from 2015- 2020 in Qassim. The results indicated that the number of infested date palms varied according to the years and locations. The infested date palm trees percentage was relatively high in 2016 (2.24%) and 2017 (3.19%), then gradually decreased to reach its lowest in 2020 (0.73%) due to the management protocol applied by the Ministry of Environment, Water, and Agriculture. Furthermore, the infested palm trees' percentage varied among the eight study locations, reaching the highest percentage in location G (SA7) with a general average of 4.31%. While in the other locations, the general infested percentage average was very low when compared to location G (SA7) with 1.21 and 0.47% in locations A (SA1) and H (SA8), respectively. The effectiveness of control methods increased sharply from 52.141% in 2015 to 90.0% in 2020 with a general average of 72.73%. The quarantine and management protocols of *R. ferrugineus* applied in Qassim decreased the number of palm infestations. Contrary, the intensive use of insecticide in the last two decades promoted genetic mutations within the *Rhynchophorus*, which led to the emergence of a new species *R. bilineatus*. This leads to increase pesticide pollution, and control costs and the insect becomes more resistant to pesticides.

Keywords: *Rhynchophorus ferrugineus*, *R. bilineatus*, invasive species, palm weevils, RPW infestation, monitoring, IPM.

Resumo

O bicudo-vermelho-das-palmeiras (RPW), *Rhynchophorus ferrugineus* (Olivier) (Coleoptera, Curculionidae), é uma praga invasora devastadora, que invadiu as tamareiras da Arábia Saudita em 1987. A avaliação das infestações e a eficácia dos tratamentos preventivos e de controle foram estudadas a partir de 2015-2020 em Qassim. Os resultados indicaram que o número de tamareiras infestadas variou de acordo com os anos e localidades. A porcentagem de tamareiras infestadas foi relativamente alta em 2016 (2,24%) e 2017 (3,19%), depois diminuiu gradativamente até atingir seu menor valor em 2020 (0,73%), devido ao protocolo de gestão aplicado pelo Ministério do Meio Ambiente, Água e Agricultura. Além disso, o percentual de palmeiras infestadas variou entre os oito locais de estudo, atingindo o maior percentual no local G (SA7), com média geral de 4,31%. Enquanto nas demais localidades, a média geral do percentual infestado foi muito baixa quando comparada à localidade G (SA7) com 1,21% e 0,47% nas localidades A (SA1) e H (SA8), respectivamente. A eficácia dos métodos de controle aumentou acentuadamente de 52,141% em 2015 para 90,0% em 2020, com média geral de 72,73%. Os protocolos de quarentena e manejo de *R. ferrugineus* aplicados em Qassim diminuíram o número de infestações de palmeiras. Ao contrário, o uso intensivo de inseticidas nas últimas duas décadas promoveu mutações genéticas dentro do *Rhynchophorus*, o que levou ao surgimento de uma nova espécie *R. bilineatus*. Isso leva ao aumento da poluição por agrotóxicos, além de controlar os custos, e o inseto se torna mais resistente aos agrotóxicos.

Palavras-chave: *Rhynchophorus ferrugineus*, *R. bilineatus*, espécies invasoras, bicudo-vermelho-das-palmeiras, infestação de RPW, monitoramento, IPM.

*e-mail: nafabdel2005@yahoo.com

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1. Introduction

The date palm, *Phoenix dactylifera* L. (family, Arecaceae), is considered one of the most important and oldest fruit trees in the Arabian Peninsula, and Middle East (Krueger, 2021). *P. dactylifera* is a keystone tree species in many parts of arid and semi-arid regions of the world, where date palm trees have inhabited those areas thousands of years ago (Tengberg, 2012). In the literature, about 132 insects and mites species are reported to attack date palm trees and are associated with it worldwide, including 22 species attacking stored dates (Wakil et al., 2015, 2018; Elshafie et al., 2017). Red Palm Weevil (RPW), *Rhynchophorus ferrugineus* (Olivier) (Coleoptera, Curculionidae), is the most important stem and trunk borers of the palm trees over the world. RPW larvae are feeding internally on the trunk soft tissue, destroying and killing the trees from within (Al-Dosary et al., 2016). Recently, *R. ferrugineus* ranked 1st place among date palm key pests as the most destructive pest of palm trees, worldwide (FAO, 2017; El-Shafie and Faleiro, 2020).

Due to the global seriousness and importance of *R. ferrugineus*, FAO in its 'Rome Declaration' called, in March 2017, for the urgent need to suppress RPW distributions and damage by unifying the efforts of date palm farmers and the agricultural organizations in various countries interested in palm cultivation (FAO, 2017; El-Shafie and Faleiro, 2020). Since mid of the 1980s, *R. ferrugineus* has spread widely within the different geographical regions of the world. Consequently, RPW emerged as a major invasive date palm pest in Saudi Arabia and became a key pest within a short period from its introduction (Abdel-Baky et al., 2021, 2022). In the diverse agroecosystems over the world, *R. ferrugineus* is defined as invasive species based on its ability to invade, colonize and adapt to new agricultural areas and new Palmaceae hosts, being reported from new countries almost every year (Wang et al., 2015). In addition, the increase in commercial activity led to a progressive distribution of RPW which was previously confined to specific regions like India and Southern Asia (Dembilio and Jaques, 2015; Al-Dosary et al., 2016; Knutelski et al., 2021; Abdel-Baky et al., 2022). Investigating the physiological changes that occur within RPW-infested palms may be useful in establishing a new control strategy that helps in RPW early detection (Harith-Fadzilah et al., 2020).

RPW damage estimated at least 15% of the global coconut growing countries and about 50% of the date palm growing countries, which are exposed to the RPW destruction risk, that may cause huge losses of palm production and the based industries (Murphy and Briscoe, 1999; Elshafie et al., 2017). RPW is considered an epidemic pest against the plants of the Palmaceae family, attacking up to 40 palm species (Cangelosi et al., 2016; Elshafie et al., 2017), causing massive economic losses, worldwide. Globally, date palm farmers are facing increasing difficulty to manage their farms due to several undesirable biotic and abiotic factors, particularly *R. ferrugineus* and its associated control measures (El-Juhany, 2010; Wakil et al., 2015).

R. ferrugineus has a cryptic nature and mostly prefers palm trees younger than 20 years old in which the crown, trunk, and bole are the perfect parts for feeding and damage

(El-Shafie and Faleiro, 2020). Globally, 30% of losses in date palm production are due to a wide range of pests, as well as, RPW activities (FAO, 2017). In the Gulf countries, the annual loss of RPW infestation and due to the eradication of severely infested palms, are estimated to be from 1.74 to 8.69 million USD at 1 and 5% infestation, respectively (El-Sabea et al., 2009). Thus, indicating the seriousness of RPW due to its high rate of infestation concerning the economic importance of the date palm (Abdel-Baky et al., 2022). *R. ferrugineus* is the most harmful insect during its larval stage. The eggs hatch inside the fissures of the palm's soft tissues (Rochat et al., 2017). From there, larvae chew and feed on the soft tissues using their strong mandibles in mouthparts, gradually creating deep tunnels inside the tree trunk. It is difficult to identify infested palm trees in palm plantations due to the absence of clear symptoms of infestation, especially in the early stage of infestation (Kontodimas et al., 2017).

Date palm growth (e.i. plant height, the circumference of leaves, and chlorophyll content) had not a significantly different between infested and non-infested trees, so, utilization of date palm photosynthesis activity as a signal for detecting RPW infestation at the early infestation stage could be useful in IPM programs (Harith-Fadzilah et al., 2020).

Over recent decades, the high prevalence and dominance of *R. ferrugineus*, in Saudi Arabia in general and the Qassim region in particular, can be attributed to several factors in combination that led to insufficient eradication and containment of RPW (Abdel-Baky et al., 2022). Factors like the lack of effective methods for early detection and date palms transfer from infested to non-infested farms had a significant impact (Balijepalli and Faleiro, 2019). The phenotypes and genetic variations among *R. ferrugineus* are emerging as considerable factors as recently documented (Abdel-Baky et al., 2022). The seriousness of RPW may be due to one or more of the following factors, such as **1**) the absence of RPW natural enemies in the new infested areas, as well as, **2**) the ineffectiveness of these natural enemies if any, and **3**) the fact that most of RPW life stages are hidden inside the palm tree trunk. Therefore, the only means available to manage RPW populations by farmers and decision-makers are early detections and the use of chemical pesticides (El-Shafie and Faleiro, 2020). In area-wide IPM, El-Shafie et al. (2011) used pheromone traps to monitor and mass-collect RPW. A bait-free method to 'attract and kill' RPW adults, Hook™ RPW, has been recently developed for weevil control in date palm. The efficiency of four pheromone trap densities viz., 1, 2, 4, and 8 traps/4 ha, were evaluated in Saudi Arabia. The treatment with 1 trap/4ha captured an average of 10.0 weevils as compared to 61.5 weevils in 8 traps/4 ha, in Al Hassa while in Al Qatif, the average was 5.0 and 49.8 weevils in 1 trap and 8 traps/4 ha, respectively in 10 weeks indicating the superiority of high-density trapping (Vidyasagar et al., 2016).

To control RPW, synthetic chemical insecticides and fumigants have been the mainstay of date palm growers since their discovery for decades. However, chemical insecticides are challenging due to RPW's cryptic nature. Moreover, the injudicious use of chemical insecticides has

exerted negative effects on the environment and human health. In addition, RPW management by these traditional control methods is considered costly besides being harmful to the environment and human beings (socio-economic impacts) (Wakil et al., 2018). Additionally, traditional control methods helped in the emergence of new genetic structures (mutations) among RPW individuals, which led to the emergence of new species of *Rhynchophorus* and/or haplotypes of the two species recorded at Qassim (Abdel-Baky et al., 2022). As a result, RPW has developed resistance against many of these chemicals, which enabled RPW, to overcome all resistant measures and helped exacerbate the crisis in date palm cultivation and the industries based on it (Faleiro, 2006).

Once established in any agricultural area, the success of RPW in reproducing and spreading is governed by a complex range of intrinsic population factors (e.g. longevity, host-searching behavior) and extrinsic environmental and anthropogenic parameters (e.g. climate, human population movements, travel, and trade). These factors may affect the interactions between RPW and its' plant hosts in a composite task.

In this study, a field investigation was carried out to monitor RPW infestation, and control treatments in 8 locations in Qassim province for 6 years from 2015-2020. As well as, shedding the light on combat efforts and fieldwork, which lasted for six years from 2015 to 2020 in different regions in Qassim province, Saudi Arabia. Therefore, this study aims to establish IPM control strategies against RPW based on the infestations and control tactics of the past six successive years from 2015 to 2020 that can be useful to develop a comprehensive strategy in the future to decrease RPW damage while preserving the environment and human health through eliminating the use of harmful chemical pesticide.

2. Materials and Methods

2.1. Description of the study area

Qassim province is located in the center of Saudi Arabia approximately 400 km (250 ml) northwest of the capital city, Riyadh (Figure 1). Qassim province is famous for its agricultural value to Saudi Arabia. Due to its fertile agricultural soil, it is referred to as the “food basket” of Saudi Arabia, which cultivates about 8 million date palm trees of different varieties (according to the official 2020 census). Of those 8 million, more than 5 million date palm trees are considered fruitful trees with 71.5% of the total production. Date palm farm locations and GPS information is shown in Table 1.

2.2. Study sites

This study was carried out at eight-date palm locations in Qassim, as shown in Table 1 and Figure 2. All palm trees (about 8 million) {Nabtet Ali, Shakrah, Red Sukary, Um Kobar, Saghy, Barhi, Khalas, Rashodia, Nabtet Sultan, Yellow Sokkari, and fohool (males)} were subject to detect *R. ferrugineus* infestation. The area of each palm orchard in the eight study locations varied from one orchard to another, as well as the number of trees in each orchard.

2.3. Monitoring program of the epidemic *R. ferrugineus*

Since the monitoring procedure is a system of comprehensive periodic detection for RPW infestations and damage in each of the study areas, a direct visual examination to search for the presence of RPW symptoms was applied. Early detection of RPW maybe led to limit insect reproduction, and spread, as well as, reducing its infestations.

Due to the seriousness and economic importance of the Red Palm weevil, *R. ferrugineus*, the Ministry of

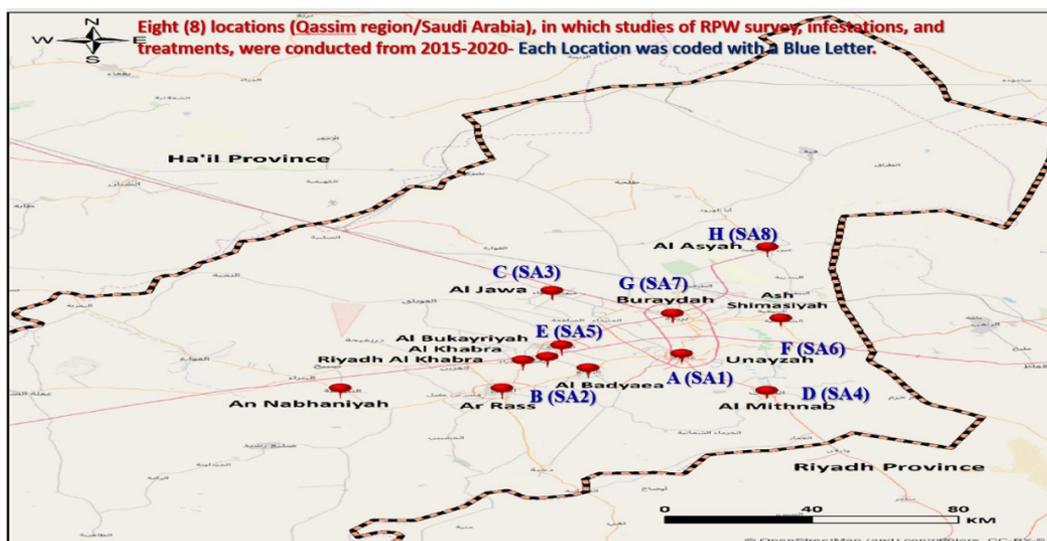


Figure 1. Map of Qassim province showing the 8 locations of study. In the eight locations (Qassim/Saudi Arabia) in which a survey of RPW studies was conducted from 2015-2020 - Each Location was coded with a Blue Letter.

Table 1. Date palm farm locations, PGS Coordinations, and code numbers.

Locations		Locations	
Code Letter/Map (Figure 2)	Coordinations GPS	Code Letter/Map (Figure 2)	Coordinations GPS
A (SA1)	N 25.971937 ; E 43.768341; N 25.953041; E 43.769447; N 25.965752; E 43.737438	E (SA5)	N 26.10394; E 43.41341; N 26.13431671; E 43.35529247; N 26.16396; E 43.29463; N 26.21441; E 43.34315; N 26.25280; E 43.30125
B (SA2)	N 26.553359; E 43.6583912; N 26.5038679; E 43.6905432; N 26.5229389; E 43.6784632; N 26.5715508; E 43.6384591; N 26.547889; E 43.652322	F (SA6)	N 26.122641; E 43.899953; N 26.87598; E 43.880859; N 26.130083°; E 43.925633°
C (SA3)	N 26.5806297; E 43.5062228; N 26.507208; E 43.659465; N 26.525307; E 43.599949; N 26.508451; E 43.628249; N 26.5068418; E 43.5599163	G (SA7)	N 26.15161; E 43.56325; N 26.2399032; E 43.8417568; N 26.2509943; E 43.9152718; N 27.174961; E 43.651234; N 27.155226; E 43.627216
D (SA4)	N 25.52591; E 44.04166; N 25.51301; E 44.09264; N 25.855526; E 44.229214; N 25.857210; E 44.229572; N 25.51469; E 44.14014; N 25.50499; E 44.13322	H (SA8)	N 26.712198; E 44.221534; N 26.688963; E 44.205548

Environment, Water and Agriculture (MEWA) in Saudi Arabia has categorized RPW as a quarantine pest that affected date palm trees and restricted the transporting of offshoots and whole date palm parts between all agricultural regions within KSA. The visual samples and the external symptoms of RPW infestation in date palm orchards were applied, as well as, the aggregation pheromone traps from 2015-2020. Monitoring RPW presence, infestations, and damage in the eight-date palm locations have been biweekly scheduled using aggregation pheromone baited traps.

2.4. Date palm trees examination

A field study was conducted in cooperation with the MEWA, Qassim branch, to survey RPW infestations and damage among eight-date palm locations in Qassim province. A monthly periodic examination was done in each location separately. A scientifically trained team performed a monthly survey at each location. Data of RPW infestation and damage were taken randomly in each location according to the status of RPW infestation and the conditions of each farm. Evidence and data were collected with the help of teamwork from the Palm Weevil Control Center in Qassim. This study was conducted for six successive years from 2015 to 2020.

2.5. Determine palm trees damage

The survey procedures followed by the Palm Weevil Control Center in Qassim affiliated with the MEWA were applied such as the visual examination methods as well as, the aggregation pheromone traps (15; 16). RPW adult preference was evaluated in 11 date palm cultivars under



Figure 2. The injection device recommended by MEWA, Saudi Arabia to control *R. ferrugineus*.

free-choice conditions in 79 date orchards farms at Qassim, Saudi Arabia. Visual examination was carried out with aid of the damage symptoms of RPW.

RPW symptoms damage were summarized by Abraham et al. (1998) as; the presence of a tunnel attack on the trunk and the base of the leaf petiole; oozing out

a thick brown liquid from the tunnels; the appearance of chewed plant tissues; with a typical fermented odor around the tunnel opening; the appearance of a dry branch mostly those emerging from the bases of the leaves; chewing sounds by larvae; trunk breaking and empty pupal cocoons. Visual inspection of date palm trees was conducted, particularly careful inspection of the base of date palm trunk, to determine the infested trees through recognizable damage signs. RPW infestation degree was assessed according to Facylate's (1971) equation and Abdel-Baky et al. (2022), which infestation degree was calculated from Equation 1:

$$(A) = (n / N) \times 100 \quad (1)$$

where: **A** = The infestation incidence percentage; **n** = Number of infested samples; **N** = Total number of samples (uninfested + infested) taken on each inspection date.

The damage scales were classified into three categories according to their percent of infestation as follows:

- Percentage of RPW infestation (all trees that are infested by RPW and/or symptoms of damage).
- Percentage of treated trees (mechanical treatment by cleaning the damaged part and removing the larvae) without using insecticides (Low infestation = 1 -25% damage.).
- Percentage of removed trees (Heavy infestation = more than 50% damage)
- Percentage of insecticide sprayed to the infested palm trees) (Medium infestation = 25 -50% damage).
- Cutting and removing severely infested palm trees
- Transferring severely infected palm trees after cutting and removal from the field
- Chopping severely affected palm trees after removal from the field
- Backfilling and burying severely infected palm trees with dirt after removing them from the field and cutting them down into small pieces.

2.6. Removal of heavily infested date palm trees:

In case of heavy infestations in which RPW destroyed the internal trunk, the tree was not able to stand and tolerate the outside pressure and the heavy crown. So, it is important for the immediate disposal of heavily infested palm trees. Therefore, a quick decision must be taken to remove and dispose of them safely.

Automatically cut the infested palm trunk into small parts not exceeding 2 meters in length by a cutting machine to eliminate the stages of RPW alive inside the trunk. The second option for the safe disposal of infested parts from the palm in case of the chopping process is not possible. Infested parts of the tree trunk are placed in a deep trench and then covered with soil at a depth not less than 2 meters to ensure the killing of RPW life stages and RPW adults not being able to come out.

2.7. Treatment/or injection

It is to inject a specific amount of pesticide solution directly inside the palm trunk close to the area of the infestation using specialized injection devices Figure 2.

Thus, giving a greater chance of the pesticide reaching the insect inside the trunk, which is difficult to reach by applying insecticide directly. The advantages of the direct injection process are that the entire amount of the pesticide can reach the palm trunk and kill all RPW stages, ease of application, less economic cost, less damage to the environment, as well as fewer weather factors effect.

2.8. Insecticides treatments

Control practices authorized by the MEWA were based on the following insecticide (Fipronil, Deltamethrin 2.5%EC, Imidacloprid 35%, and Deciban,) either used alone/ or with others during the period of study, as well as, fumigation using aluminum phosphide (implemented in the last two years).

2.9. Data analysis

Analysis of variance (ANOVA) was performed using JMP Ver. 11 (SAS Institute, 2013) and only significant results are presented). Furthermore, Tukey's HSD at $P < 0.05$ was chosen to conduct pairwise comparisons for each significant factor in analyses. When significant interactions occurred, contrasts to determine the effects of interacting variables were conducted at the 0.05 level of significance.

3. Results

3.1. Infested, treated, and removed date palm trees from 2015-2020

Table 2 and 5 shows the average percentage of red palm weevil infestation in 8 locations in Qassim province from 2015 to 2020. Location SA7 (G) recorded the highest rates of palm weevil infestation, as it started relatively low in 2015 (2.15%), then gradually increased in 2016 (2.45%) and reached its highest rate (19.76%) in 2017. This was followed by a sharp decline in the infestations rates in 2018, 2019, and 2020, with 0.64%, 0.56%, and 0.30%, respectively (Table 2).

The general averages of RPW infestation percentage in eight locations were 0.77, 2.24, 3.19, 0.96, 1.00, and 0.73% for the years 2015, 2016, 2017, 2018, 2019, and 2020 respectively (Figure 3). Also, from Table 2 and Figure 3, it could be seen that the highest rates of infestation were in 2017 as a general average percentage of infestation (3.19%), while the lowest infection percentage was recorded in 2020 (0.73%). The data in Table 2 and Figure 4 showed the general average RPW infestation percentage in the eight locations during the six years of study.

The highest RPW infestation percentages were observed in location SA7 (G), followed by the location SA6 (F), then location SA1 (A) with an average of 4.31%, 2.74%, and 1.21%, respectively. For the rest locations, RPW infestation percentages ranged between 0.62% in location SA2 (B) and 0.98% in location SA5 (E). In regards to treated palm trees infested by RPW, the results showed that the response rates of palm trees to treatment were positive, whether over the years of the study or within the locations (Table 3).

The rate of the date palm tree's recovery from RPW infestations increased after cleaning the weevil life stages

Table 2. Percentages of *R. ferrugineus* infested date palm trees from 2015 to 2020 in Qassim Province, Saudi Arabia.

Locations of the Date palm farms	Years of study						General Average
	2015	2016	2017	2018	2019	2020	
A (SA1)	0.94	1.12	0.44	2.71	1.89	0.16	1.21
B (SA2)	0.44	0.43	0.02	0.56	1.28	0.96	0.62
C (SA3)	0.02	0.02	1.26	0.19	1.53	1.48	0.75
D (SA4)	1.03	0.09	1.17	0.57	0.94	0.87	0.78
E (SA5)	0.10	0.10	2.51	2.12	0.95	0.09	0.98
F (SA6)	1.30	13.61	0.24	0.76	0.21	0.34	2.74
G (SA7)	2.15	2.45	19.76	0.64	0.56	0.30	4.31
H (SA8)	0.20	0.13	0.12	0.16	0.61	1.62	0.47
Average	0.77	2.24	3.19	0.96	1.00	0.73	1.48

Table 3. Percentages of the treated date palm trees infested by *R. ferrugineus* from 2015 to 2020 in Qassim, Saudi Arabia.

Locations of the Date palm farms	Years of study						General Average
	2015	2016	2017	2018	2019	2020	
B (SA1)	60.27	60.56	67.26	77.88	83.19	93.74	73.82
B (SA2)	57.52	62.12	76.56	75.23	86.17	97.89	75.92
C (SA3)	43.33	60.90	78.27	78.21	84.87	85.84	71.90
D (SA4)	51.64	64.03	72.99	74.46	88.19	90.77	73.68
E (SA5)	56.39	57.89	66.35	78.64	90.54	92.63	73.74
F (SA6)	60.19	61.61	71.69	72.40	80.68	85.65	72.04
G (SA7)	42.46	51.89	71.74	74.57	80.35	84.15	67.53
H (SA8)	47.46	50.85	59.32	75.14	87.07	95.54	69.23
Average	52.41	58.73	70.52	75.82	85.13	90.78	72.23

from the infested area in the tree trunk. It is clear from Tables 3 and 5 and Figure 3 that the control efforts to treat the infested palm trees were initiated at a low rate in 2015. Then gradually increased until they reached the highest effectiveness rates in 2020. The successfully treated palm trees percentages reached 52.41, 58.73, 70.52, 75.82, 85.13, and 90.78% for the years 2015, 2016, 2017, 2018, 2019, and 2020, respectively. As for the locations, the general average percentage of achieved treated palm trees reached for location SA2 (B) at 75.92%, location SA1 (A) at 73.82%, location SA5 (E) at 73.74%, location SA4 (D) at 73.68%, location SA6 (G) at 72.04%, location SA3 (C) at 71.90%, location SA8 (E) at 69.23 and location SA7 (H) at 67.53% in descending pattern.

Concerning the removed trees that were infested by RPW, the highest number of removed trees was from location G (SA7) with a general average of 0.83 while the highest number of removed trees according to the year of study was in 2017 with an average of 0.76 (Table 4).

It should be noted here that the treated palm trees are those trees in which infestation percentage does not exceed 25%, can tolerant RPW damage, and even recover and continue developing after the control program is implemented and followed up by the competent authorities.

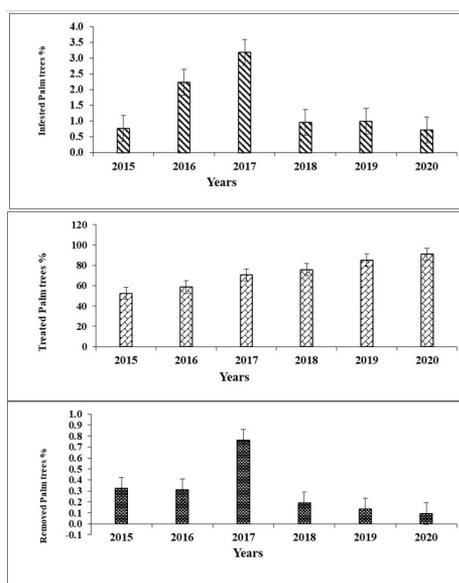
**Figure 3.** The yearly average of infested, treated & removed date palm trees affected by *R. ferrugineus* from 2015 to 2020, Qassim Province, Saudi Arabia.

Table 4. Percentages of removed date palm trees infested by *R. ferrugineus* from 2015 to 2020 in Qassim, Saudi Arabia

Locations of the Date palm farms	Years of study						General Average
	2015	2016	2017	2018	2019	2020	
B (SA1)	0.74	0.80	0.14	0.37	0.14	0.07	0.38
B (SA2)	0.18	0.16	0.03	0.04	0.03	0.02	0.07
C (SA3)	0.02	0.02	1.08	0.09	0.36	0.36	0.32
D (SA4)	0.26	0.03	0.55	0.23	0.04	0.12	0.20
E (SA5)	0.18	0.18	1.08	0.49	0.11	0.00	0.34
F (SA6)	0.26	0.26	0.32	0.19	0.12	0.00	0.19
G (SA7)	0.82	0.94	2.80	0.10	0.21	0.11	0.83
H (SA8)	0.12	0.08	0.07	0.04	0.07	0.07	0.08
Average	0.32	0.31	0.76	0.19	0.13	0.09	0.30

3.2. Regressions analysis of the relationships between the infested and treated date palm trees

Through the field study that was carried out from 2015 to 2020 in 8 date palm locations in the Qassim region, it became clear that there is a positive relationship (positive correlation) between the percentage of infested date palm trees and the percentage of the treated trees. Simple linear regression between the percentage of treated trees and the percentage of infested trees was studied. The results in Table 6 showed that the relationship between these two variables was positively intermediate (R^2 values ranging from .04552 to 0.5949) for the six years of study and the general average (Table 6, Figure 5).

3.3. Regressions analysis of the relationships between the infested and removed date palm trees

Data in Table 7 showed a clear positive relationship (positive correlation) between the percentage of infested date palm trees and the percentage of removed trees from 2015 to 2020. Simple linear regression between the percentage of treated trees and the percentage of infested trees revealed that the relationship was positively weak (R^2 values 0.3919, 0.8363, 0.5359, 0.4167, 0.4471, and 0.6396 for 2015, 2016, 2017, 2018, 2019, and 2020, respectively). While the R^2 value for the general average between the two abovementioned variables was 0.4159 (Table 7, Figure 5).

4. Discussion

The red palm weevil, *Rhynchophorus ferrugineus*, is a serious invasive palm pest that originated in Southeastern Asia (Murphy and Briscoe, 1999). *R. ferrugineus* has recently been widely introduced to several new areas, including the Middle East, Mediterranean countries (Bozbuga and Hazir, 2008), North Africa, Europe, the Caribbean, Oceania, North America (Fiaboe et al., 2012), and southern China (Wang et al., 2015). Many of the literature reviews revealed that populations of the RPW had a drastic increase and rapid spread (Azmi et al., 2017). In Malaysia, RPW was detected for the first time in 2007 and then the insect

Table 5. General average percentages of infested, treated, and removed date palm trees affected by *R. ferrugineus*, from 2015 to 2020 in Qassim, Saudi Arabia.

Locations of the Date palm farms	Therapeutic operations carried out on date palm trees		
	% Infested	% Treated	Removed %
B (SA1)	1.21	73.82	0.38
B (SA2)	0.62	75.92	0.07
C (SA3)	0.75	71.90	0.32
D (SA4)	0.78	73.68	0.20
E (SA5)	0.98	73.74	0.34
F (SA6)	2.74	72.04	0.19
G (SA7)	4.31	67.53	0.83
H (SA8)	0.47	69.23	0.08
Average	1.48	72.23	0.30

spread to 58 localities in all seven districts of Terengganu (Azmi et al., 2017). However, the number of infestation sites in the Terengganu district has increased significantly to 858 localities in 2011 (Azmi et al., 2017). A wide range of climates, coupled with intensive modernized date palm farming, has provided the pest with an ideal ecological habitat (Manzoor et al., 2020). *R. ferrugineus* expansion has been largely due to the widespread palm tree shipping between different territories (Ávalos et al., 2014). Besides human activity, RPW usually spread through the flying of adults searching for new habitats, food sources, and oviposition sites (Hussain et al., 2013).

In Qassim province, Abdel-Baky et al. (2022) reported a crucial difference in RPW infestation percentage in 2019 and 2020, which reached 1.14% as the highest percentage of infestation in 2019, while this ratio decreased to 0.8 in 2020. Additionally, they found that the percentage of RPW infested treated trees was very high, exceeding an average of 70% in two successive years. This may be due to palm varieties, palm trees' age, and irrigation systems (Aldryhim and Al-Bukiri, 2003). The dominance from

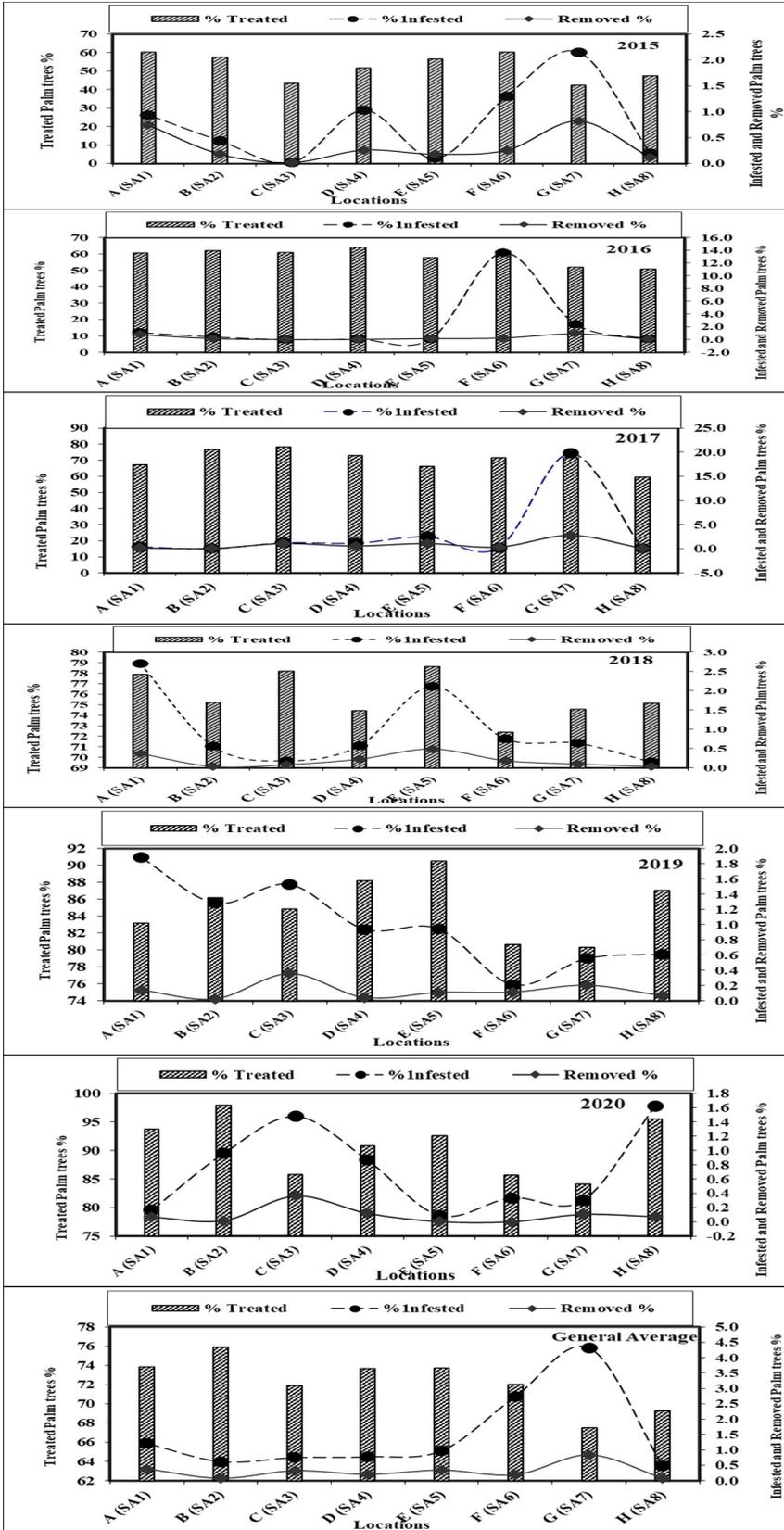


Figure 4. Percentages of infested, treated & removed palm trees affected by *R. ferrugineus*, in 8 date palm locations in Qassim Province from 2015 to 2020, Saudi Arabia.

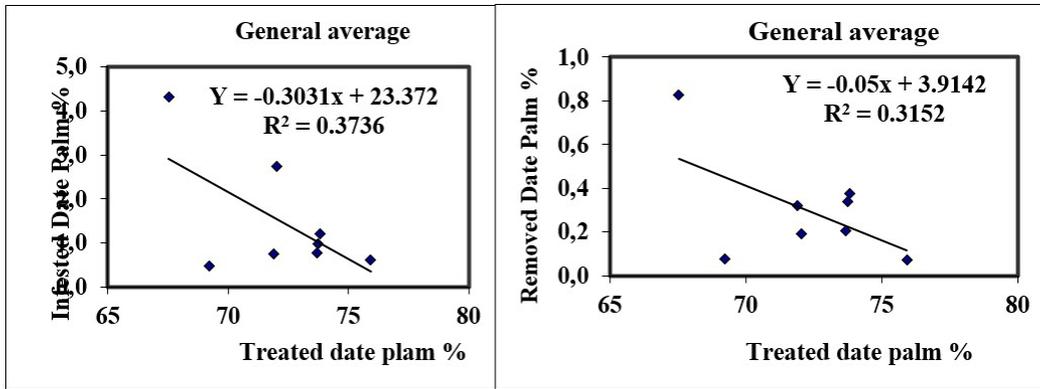


Figure 5. The relationship between the percentage of infested to treated and infested to removed date palm trees affected by *R. ferrugineus*, from 2015 to 2020 (Regression equations and R² values).

Table 6. The relationship between the percentage of infested and treated date palm trees affected by *R. ferrugineus* from 2015 to 2020.

Year	Regression Equation parameters			
	X	Y	Equation	R ²
2015	Treated date palm %	Infested date Palm %	Y = -0.0774x + 4.8263	0.5949
2016			Y = -0.7247x + 44.804	0.5701
2017			Y = -0.8425x + 62.603	0.5768
2018			Y = -0.2903x + 22.969	0.4669
2019			Y = -0.1035x + 9.8102	0.4552
2020			Y = -0.0842x + 8.3699	0.5116
Average			Y = -0.4056x + 30.781	0.4928

Table 7. The relationship between the percentage of removed and treated date palm trees affected by *R. ferrugineus* from 2015 to 2020.

Year	Regression Equation parameters			
	X	Y	Equation	R ²
2015	Treated date palm %	Removed date Palm %	Y = -0.0252x + 1.6451	0.3919
2016			Y = -0.0675x + 4.2704	0.8363
2017			Y = -0.1116x + 8.6263	0.5359
2018			Y = -0.048x + 3.8314	0.4167
2019			Y = -0.0201x + 1.8417	0.4471
2020			Y = -0.0185x + 1.7759	0.6396
Average			Y = -0.0571x + 4.4232	0.4157

which population densities and distributions were in the favor of *R. ferrugineus* (80.0%). Due to the convergence in many of the genetic factors between those two species. Accordingly, it will be expected, that the emergence of more new haplotypes could happen if interbreeding (crossing mate) between them occurs.

The results of RPW infestation rates indicated that the eradication efforts conducted by the MEWA, Qassim branch, through treating, removal, chopping, burning,

and burying palm trees of the first infested patch of RPW did not prevent the insect spreading to other date palm trees or from locations to another in Qassim date palm farms. However, their effort helped in the decline of the infestation percentage curve which was higher in 2016 (2.24%) and 2017 (3.19%) and decreased to 0.73% in 2020. The findings also indicated a continued infestation of date palm trees in the region due to the infestations of the neighboring date palm farms (El-Mergawy and Al-Ajlan,

2011; Alderawii et al., 2020). Furthermore, the promising results obtained in this study indicated that the constant quarantine and development of an IPM program for RPW minimized the infested palms in the six successive years led to recording the lowest infestation percentage in 2020

Moreover, the total removal percentage of severely infested palm trees was very low during the six years of study in all locations of the study, with an average of 0.30%. This is due to the efforts of the early detection teams, intensive training on the latest developments in insect detection programs, and the application of the plant quarantine system between regions (Dembilio and Jaques, 2012; Al-Shawaf et al., 2013; Alderawii et al., 2020)

The applied control programs to eliminate RPW infestations and treat the infested palm trees were excellent, as they gradually increased from 52.42% in 2015 to reach the highest treatment percentage of 90.87% in 2020 (Table 2). This is maybe due to the highly qualified training programs and the cumulative experience of the work team, as well as, the use of the latest methods concerning control procedures and detection within IPM programs.

5. Conclusion

5.1. 36 years since the introduction of RPW to Saudi Arabia, the question remains

Is RPW still a potential threat to the date palm-based industries?

The answer: Red palm weevil nowadays is a serious pest of date palm trees. However, with rapid commercialization, RPW build-up and dramatically increased its population, and it's rapidly spreading within the Gulf country and Mediterranean Basin. A monitoring study conducted from 2015 to 2020 showed that RPW was highly abundant and distributed within date palm plantations in Saudi Arabia. Through this study, Data revealed that the date palm trees varied in their response to the highest growth rate in which the RPW larval stage duration could be shortened. This weevil is presumed to be one of the most aggressive pests that may threaten the existence of date palms, which represent the backbone commodity of agricultural production in Saudi Arabia. Qassim province has about 8 million trees of date palms that provide a stable source of income to many small farmers as well as large farms in Saudi Arabia. Therefore, urgent action is crucially required from MEWA, Saudi Arabia, to avoid any significant economic yield losses in the future. So, for RPW management sustainability, more comprehensive and effective control measures of the RPW must be required seriously. Effective control measures such as implementing an effective IPM program, as well the early detection and monitoring are also essential. Consequently, the next studies must focus on new technologies or innovations in the development of early detection techniques. Besides, the improvement of the trapping systems and effective delivery methods of the chemicals should be emphasized. A proper quarantine protocol at the national and international levels is most needed, as there is still an urgent need for an effective national program to control the ongoing expansion of RPW.

Finally, the quarantine and management protocol of RPW applied in Qassim province decreased the population of the invasive pest. On the contrary, intensive insecticide use in the last two decades initiated genetic mutations in the species of *Rhynchophorus ferrugineus*, which led to the emergence of new haplotypes of *R. ferrugineus* that may pose major obstacles to date palm farmers in the future.

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