



Modelling pest dynamics under uncertainty in pest detection: the case of the red palm weevil

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Abstract A common complication in invasive pest management is that the infectious state of the host can be wrongly assessed, leading to biases in the estimation of the prevalence of the pest and on the efficacy of mitigation actions. We designed a multievent model that accommodates uncertainty on host state to investigate the dynamics of the infestation of *Phoenix canariensis* by the invasive *Rhynchophorus ferrugineus*. Since 2011, the council of Palma city (Mallorca Island, Spain) applied preventive, curative and destructive treatments to public *Phoenix* palms. A year later awareness campaigns focused on every palm owner in an attempt to control the plague. We estimated the probability of infestation and assessed the efficiency of mitigation measures, awareness campaigns and palm-dependent covariates. Our results show that infestation probabilities were higher for palms infested in the previous year than for healthy palms and it decreased substantially over time as a

results of mitigation measures and awareness campaigns. Palms surrounded by treated palms had a lower probability of being infested than palms surrounded by untreated palms, i.e. private palms before awareness campaigns implementation. Our results highlight the key role of awareness campaigns and public participation for invasive species control.

Keywords Biological control · Epidemiological models · Invasive pest management · Monitoring · Multievent capture-recapture · *Rhynchophorus ferrugineus*

Introduction

Human-introduced species are listed among the most important threats to the maintenance of local ecosystem services (Vilà and Hulme 2017). The eradication of those new species that generate important economic losses (i.e. pests) relies on early detection and fast responses (Rejmánek and Pitcairn 2002; Lockwood et al. 2007). When this is not possible, pest management should aim to identify, assess and improve mitigation measures. In insect-plant interactions, pest management assessment is complicated by the fact that monitoring cannot always be exhaustive (i.e. partial monitoring) and that plant infectious state can be uncertain, i.e. false negatives due to detection failure. Both problems lead to underestimate pest

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prevalence and its dynamics, yielding to potentially erroneous conclusions on the effectiveness of mitigation measures. We propose a multievent analytical framework (Pradel 2005) to investigate the dynamic of pest species and to assess the efficiency of mitigation actions, accounting for an imperfect detection on the infectious state of the host. We applied this approach to the management of an insect-plant interaction, the weevil-palm system, within the municipality of Palma city, Mallorca Island (Balearic archipelago, Spain).

The red palm weevil (RPW) *Rhynchophorus ferrugineus* (Olivier 1790) is an insect native to Southeast Asia and Melanesia (Faleiro 2006) that has expanded its distribution worldwide, facilitated by the global plant trade (Milosavljević et al. 2019). The larvae of RPW develop inside palm trees and feed on the host internal tissues ultimately leading to the death of the plant. The species presents a high reproductive potential, being able to complete several generations in a single year (Nirula 1956; Dembilio and Jacas 2011), which can promote its invasion success and outbreaks that generate important economic losses worldwide (Faleiro 2006; El-Sabea et al. 2009; Al-Dosary et al. 2016). It has recently been declared as the most destructive insect of palm tree plantations worldwide (Al-Dosary et al. 2016). Although the species is able to move large distances, most individuals are short-distance flyers covering < 500 m (Ávalos et al. 2014, 2016). This could explain the appearance of aggregation hotspots or contagious spatial distribution patterns (Faleiro et al. 2002). The cryptic larval stage makes its detection especially difficult (Faleiro 2006; Milosavljević et al. 2019). Given the abovementioned ecological characteristics, the control/eradication of RPW is complicated and requires an integrated pest management strategy (IPM) including intense and continuous monitoring, trapping and insecticide applications (Abraham et al. 1998; Murphy and Briscoe 1999; Faleiro 2006; El-Sabea et al. 2009). The complete eradication of RPW was achieved for the first time on the Canary Islands, Spain, where the species disappeared in 2016, 11 years after it was first detected, thanks to the exhaustive monitoring, extensive awareness campaigns and treatments (<http://www.picudorojocanarias.es/>). Islands can be considered as a good laboratory to study potential mitigation/eradication methods because continuous colonization by new individuals is less likely to occur than in the

mainland. Mallorca Island, the largest island of the Balearic archipelago (western Mediterranean, Spain) was first colonized by the RPW in 2007. A year later the insect was first observed in the main city of Palma, where public authorities began to apply preventive treatments on *Phoenix canariensis* and *P. dactylifera* with entomopathogenic nematodes (*Steinernema carpocapsae*). Since 2011, as a response to an increasing infestation, authorities launched an extensive monitoring of public palms, together with preventive treatments with chemical insecticides, and, when necessary, curative or destructive treatments, i.e. partial or total destruction of the palm tree. However, most palms within the municipality were private and, as such, outside the council remit. As a consequence, treatments covered only a small proportion (~ 15%) of potential hosts. In 2012 the pest was declared out of control and an Integrated Pest Management (IPM) was implemented, which included the geolocation of every palm tree within the municipality together with awareness campaigns targeting all palm owners (details in <https://www.palma.cat/portal/PALMA/>). The problem in assessing the temporal dynamics of the pest and the efficacy of management, i.e. awareness campaigns and effect of treatments, is that the detection of the infectious state of the palm was imperfect. In particular, a healthy-looking plant could in reality be hosting RPW larvae at its first stage of development, i.e. false negative.

The aim of this study was to develop a multievent model to investigate pest dynamics and to assess the efficiency of management actions. The multievent model is similar to a classical epidemiological model, but have the advantage to frame imperfect monitoring (i.e. missing data) and assessment of the infectious state of the host (i.e. insect detection) (Pradel 2005; Conn and Cooch 2009; Santoro et al. 2014; Benhaïem et al. 2018; Simon et al. 2018). In addition, the flexibility of multievent models allows assessing the influence of external variables or individual covariates as predictors of model parameters. It has similarities with dynamics site-occupancy models (MacKenzie et al. 2003) but it includes misdiagnose of the infectious state. Here, we investigated if the density of preferred hosts (*P. canariensis* and *P. dactylifera*) around each public Canary Island date palm and their ownership (public or private owned) influenced the temporal probabilities of infestation by RPW. We made the hypothesis that (1) the destruction, pruning

and insecticide treatments applied to public palms should reduce the population of red palm weevils at a local scale and (2) palms surrounded by treated palms should show lower probabilities of infestation and (3) palms surrounded by numerous private palms (many of them untreated) should have higher probability of being infested. Finally, we assessed whether the probability of palm infestation by RPW decreased after the implementation of the IPM campaign from 2012.

Materials and methods

Pest management actions

Preventive, curative and destructive treatments were applied to public palms by the Palma city council. Preventive treatments focused on detection and preventive chemical control. Six visual surveys were carried out annually (in March, May, June, July or August, September and November) by trained personnel at ground level and at the level of the fronds. Preventive chemical treatments were applied on all palms alternating sprays of ImidaclopridTM (0.075%) with sprays of ChlorpyrifosTM (0.2%). Curative treatments on partially affected palms were applied during the 48 h following weevil detection. First, mechanical sanitations (pruning) of infested palm tissues were carried out followed by monthly chemical treatments with ImidaclopridTM and ChlorpyrifosTM during the subsequent 10 months. Destructive treatments were applied to those palms presenting high levels of infestation and when curative treatments evidenced a degradation of the apical meristem. All palms cut and tissues from pruning were covered during transport and destroyed by incineration. This service was also provided at no cost to those particulars that delivered the infested tissues of palms. Pruning on apparently healthy palms was only allowed during winter (December to February) and never on green fronds. Finally, since late 2012, awareness campaigns (informal talks) and documents with recommendations for the control of the RPW were elaborated and distributed to particulars and both public and private entities, i.e. schools, banks, hospitals, etc. Furthermore, information related to the RPW control was sent to press agencies and regional TVs

and newspapers to increase presence of the species in the media.

Data codification

We collected data on 657 Canary Island date palms *P. canariensis* located in public gardens within Palma city monitored between 2011 and 2017. During this period, 197 (28%) public Canary palms infested by reds palm weevils were cut and destroyed. To study the dynamics of plant–insect interaction we coded yearly observations on each palm into individual histories using the four following codes:

- 1 = palm tree apparently healthy (i.e. with no signs of weevil infestation).
- 2 = palm tree infested by red palm weevil and treated with a partial pruning (i.e. curative treatment)
- 3 = palm tree infested by red palm weevil and treated with a total cut (i.e. destructive treatment).
- 0 = palm tree that no longer exist due to a destructive treatment applied the previous year.

Statistical methods

We analyzed the dynamics of RPW infestation by means of multievent capture-recapture models implemented in the software E-SURGE (Pradel 2005; Choquet et al. 2009). Multievent models relate the real and unknown sanitary state of the palm ('state', hereafter) to the field observations ('events', hereafter; Fig. 1) through conditional probabilistic processes. We considered four different states of the palm:

- H a healthy palm tree (i.e. not infested by RPW)
- I a palm tree infested by the red palm weevil
- D a dead palm tree removed due to destructive treatment (i.e. just dead)
- R a palm tree removed after a destructive treatment on precedent years (i.e. dead for a long time)

Multievent models contemplate three sets of parameters: the initial state probabilities (i.e. the proportion of individuals at each state at the initial occasion), the transition probabilities (i.e. the probabilities of moving among states between time $t - 1$ and t), and the event probabilities (i.e. the probabilities of observe/code a particular event conditional on the underlying state of the individual) (Choquet et al.

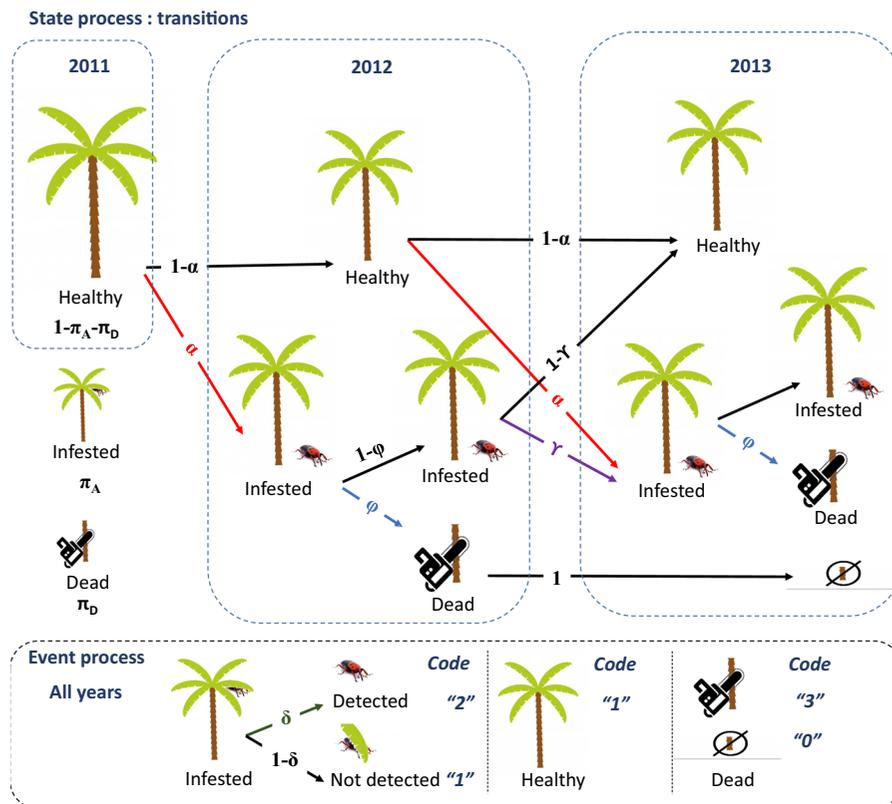


Fig. 1 Diagram showing between state transitions (i.e. the probabilities of infestation of public Canary Island date palm trees by red palm weevils α and γ and the probabilities of palm tree destruction ϕ) during the first 3 years of monitoring. The

diagram shows the example for trees not infested during the first year (i.e. sane). The event process account for red palm weevil detectability (δ)

2009; Pradel 2005). The different parameters (i.e. probabilities) are presented in matrices with states at $t - 1$ in rows (departures) and arrival states at t in columns (see specific matrices below). We briefly describe the model below and refer the readers for more details to the original work by Pradel (2005).

The first set of parameters in the multievent model is the initial state vector containing the initial proportion of healthy ($1 - \pi_I - \pi_D$), infested (π_I) and dead (π_D) palm trees:

$$\text{Initial state} = \begin{pmatrix} H & I & D \\ 1 - \pi_I - \pi_D & \pi_I & \pi_D \end{pmatrix}$$

Note that initial state vectors (by software specifications) include the total number of states minus one because multievent models were initially developed to estimate animal survival probabilities from individual encounter histories and animals found dead at the first encounter are not usually considered. However, in our

case palms might have seen infected and destroyed at their first observation. To include this, we considered a ‘recently dead’ state, D (included into the model) and an additional ‘long dead’ state, which does not appear into the initial state vector (see also Lebreton et al. 1999).

The second set contains the parameters that specify the probabilities of transitions among states over time. Here, in order to test separately the effect of individual covariates on infestation probabilities (see biological hypotheses below) we decompose between state transitions into two processes. The first process, Matrix 1, accounts for the probability, α , of a palm moving from a healthy state to an infested state between year $t - 1$ and t (row 1 in Matrix 1) and the probability, γ , of remaining infested or being re-infested (row 2 in Matrix 1). Note that the probability of a dead palm removed “D” to move to a state “R” (i.e. a palm tree removed after a destructive treatment

on precedent years) is 1 (row 3 in Matrix 1), which is a permanent state (row 4 in Matrix 1).

$$Matrix1 = \begin{matrix} & H & I & D & R \\ \begin{matrix} H \\ I \\ D \\ R \end{matrix} & \begin{pmatrix} 1-\alpha & \alpha & 0 & 0 \\ 1-\gamma & \gamma & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{matrix}$$

Given the infestation state, which probabilities are specified in Matrix 1, we consider the conditional probability, φ , of a palm to be destroyed. This appears in Matrix 2 as the transition probability from state “I” to state “D” (row 2 in Matrix 2). Note that here individuals in state “D” and “R” remain in their state because the transition from these states has already been considered in Matrix 1.

$$Matrix2 = \begin{matrix} & H & I & D & R \\ \begin{matrix} H \\ I \\ D \\ R \end{matrix} & \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-\varphi & \varphi & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{matrix}$$

The matrices above described the real state of the palm. The last set of parameters (Matrix 3) describes the probabilities, conditional on the state of the individual (rows), to observe a particular event (columns).

$$Matrix3 = \begin{matrix} & (0) & (1) & (2) & (3) \\ \begin{matrix} H \\ I \\ D \\ R \end{matrix} & \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 1-\delta & \delta & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{pmatrix} \end{matrix}$$

Matrix 3 links the observations (events) to the real state of the palm (i.e. healthy, infested, just dead and removed on precedent years). Here, we model the probability of RPW detection, δ , on infested palms (row 2 in Matrix 3). The probability of misdiagnose an infested palm is $1 - \delta$. The detection probability was considered to be constant over time for all the different models tested (see below). The model is made by the multiplications of the three matrices. In summary, the multievent model is a compartmental model used in

discrete time with state vector $X(t)$, initial conditions $X(0)$, and state transition matrices T1 and T2 (that can also be merged). The difference equations that describe the infestation dynamics are given by $X(t) = T2 * T1 * X(t - 1)$, whereas the observations are given by $O(t) = D * X(t)$, with D being the observation probability matrix 3. The resulting model is similar to a dynamic site-occupancy models (MacKenzie et al. 2003), but it has been extended to incorporate uncertainty in assigning the infectious state of the palm (Matrix 3). Note that matrix 3 accounts for false negatives, i.e. a misdiagnose of the health state of the palm, but does not account for false positives, i.e. a misdiagnose of the infested state of the palm. False positives are common in several epidemiological studies. They occur, for example, when signs of infestation can be originated by other causes. This misdiagnose probability can be incorporated into Matrix 3 as an additional parameter but here we assumed that a palm recorded as infested is correctly diagnosed. The E-SURGE software delivers parameter estimates by maximum likelihood procedure (Choquet et al. 2009).

Testing biological hypotheses

We used model information theory to contrast hypotheses on palm susceptibility. Model selection was based on Akaike’s Information criterion, corrected for sample size (QAICc) (Burnham and Anderson 2002). Models with a $\Delta QAICc \leq 2$ were considered equivalent (Burnham and Anderson 2002). We began model selection with a general model in which the probabilities of infestation, re-infestation and palm destruction (α , Υ and φ , respectively) varied over time (Model 8, Table 1). We first assessed if probabilities of infestation (α) were equivalent to the re-infestation probability (Υ ; Model 4 vs. Model 8, Table 1). Subsequently, we test whether these two probabilities varied in parallel over time or independently (Models 3 and 4, respectively, Table 1), were constant through time (Model 7, Table 1) or changed as a consequence of awareness campaigns immediately after year 2012 (Models 5 and 6, Table 1) or after 1-year lag (Models 1 and 2, Table 1). Once we detected the best structure for α and Υ , we assessed whether the probabilities, φ , of destroying an infested palm tree varied over time (Model 1, Table 1) or not (Model 9 Table 1). Subsequently we investigated the

Table 1 Modelling the infestation dynamics (i.e. the probabilities of infestation of previously healthy α and previously infested trees Υ and the probabilities of tree destruction ϕ) of *P. canariensis* by *R. ferrugineus*

Model	α/Υ	ϕ	np	Dev	AICc	Δ AICc
1	$(\alpha \neq \Upsilon) + (2011-14;2014-17)$	Year	12	2754.84	2778.92	0.00
2	$(\alpha \neq \Upsilon) * (2011-14;2014-17)$	Year	13	2754.82	2780.92	2.00
3	$(\alpha \neq \Upsilon) + \text{year}$	Year	16	2751.95	2784.09	5.17
4	$(\alpha \neq \Upsilon) * \text{year}$	Year	21	2747.51	2789.75	10.83
5	$(\alpha \neq \Upsilon) + (2011-13;2013-17)$	Year	12	2768.39	2792.47	13.55
6	$(\alpha \neq \Upsilon) * (2011-13;2013-17)$	Year	13	2768.26	2794.35	15.43
7	$(\alpha \neq \Upsilon)$	Year	11	2835.08	2857.14	78.22
8	$(\alpha = \Upsilon) * \text{year}$	Year	14	2845.37	2873.48	94.56
9	$(\alpha \neq \Upsilon) + (2011-14;2014-17)$	Constant	7	2867.33	2881.36	102.44

np = number of estimable parameters, Dev = relative deviance of each model, AICc = Akaike's information criterion adjusted for small sample size (c), Δ AICc = difference between current model and the model with the lowest AICc, + = indicates an additive relationship between the effects, * = indicates the statistical interaction between the effects

role of individual covariates as linear predictors of infestation probabilities, α and Υ (Table 3). In order to test a possible effect of host density around the focal plant and a potential protective effect of preventive treatments (insecticides) applied to surrounding palms, we considered as an individual covariate the number of palms (*P. canariensis* and *P. dactylifera*) within a 500 m radius from each palm monitored. This radius was set following the evidence on flying distances reported by Ávalos et al. (2014, 2016). Data on individual covariates were obtained in year 2012 following a complete census and geolocation of every palm tree within Palma municipality. Because in the early years only public palms within council remit were recurrently treated (IG and OM own observation), we sorted palms into public (“public”, i.e. those directly managed by the city council) and private (“priv”), differentiating in this last case between palms under the responsibility of other governmental entities (e.g. schools, namely “ent”) and those belonging to particular owners in private areas (e.g. hotels or other private gardens, namely “part”) (Table 3). We made the hypothesis that the number of palms and their ownership (potentially reflecting differences in the implementation of preventive treatments) surrounding each focal palm may influence its probability of becoming infested. Moreover, we also hypothesized that the implementation of the IPM campaign may influence the awareness of particular owners on the RPW invasion problem increasing the application of preventive treatments and thus

providing a protective effect on surrounding palms. In order to test these hypotheses, we compared multiple models (Table 3). We assessed whether the number of “total”, “public”, “priv”, “ent” and “part” palms around each focal plant influenced the probabilities of infestation and re-infestation (by comparing models with covariates in Table 3 with the best model selected in Table 1) and if their effect changed or not the after IPM campaign implementation by comparing additive models with models with interactions (Table 3). Moreover, and also by comparing additive and interaction models including different covariates we evaluated if the existence of surrounding palms of different ownership affected similarly the infestation probabilities of each focal palm or not (Table 3).

Results

Model selection clearly showed that plague dynamics (i.e. the probability of infestation) changed after 2013, the year after IPM campaign implementation (Fig. 2; Model 1, Tables 1 and 2). Models considering a constant, a temporal or an immediate effect of IPM in infestation probabilities showed a higher value of AIC (Δ AICc > 5), being clearly rejected. Estimates of Model 1 (Table 1) indicate that the probability of being infested dropped during the last 3 years of monitoring (from 2014 to 2017), especially for healthy palms (3%, 95%CI 1–8%; Fig. 2). The initial proportion of infested canary palms was 7% (of which 2%

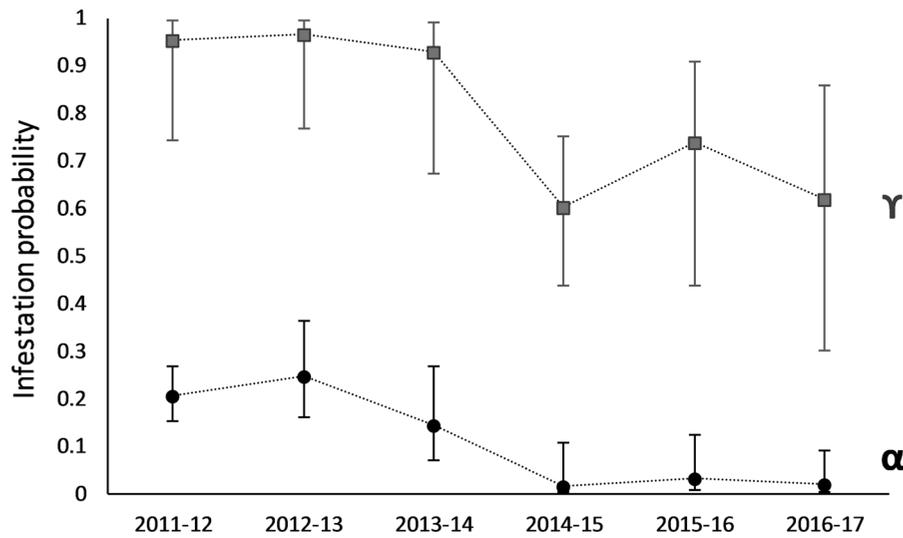


Fig. 2 Temporal estimates (and 95%CI) of the probabilities of infestation of healthy (α) and previously infested public canary palm trees by red palm weevils at Palma city between 2011 and 2017 (Model 3, Table 1)

Table 2 Estimates and 95% confidence intervals and SE of parameters (i.e. the initial proportions of infested and destroyed palms, the probabilities of infestation of previously healthy α and previously infested trees γ , the probabilities of tree destruction φ and the probabilities of red palm weevil detection δ) of model 1 of this table

Parameter	Year	Estimates	CI-	CI+	SE
π_A	2011	0.05	0.03	0.10	0.02
π_D	2011	0.02	0.01	0.03	0.01
α	2011–2014	0.20	0.17	0.24	0.02
γ	2011–2014	0.94	0.76	0.99	0.05
α	2014–2017	0.03	0.01	0.08	0.02
γ	2014–2017	0.63	0.51	0.73	0.06
φ	2012	0.57	0.44	0.69	0.06
φ	2013	0.16	0.10	0.23	0.03
φ	2014	0.07	0.04	0.12	0.02
φ	2015	0.19	0.12	0.29	0.04
φ	2016	0.29	0.17	0.44	0.07
φ	2017	0.18	0.08	0.34	0.07
δ	2011–2017	0.30	0.22	0.40	0.05

were destroyed; Table 2). Previously infested palms showed a higher probability of being infested the next year than healthy trees throughout the whole study period (Table 2, Fig. 2). The probabilities of infested palm destruction, φ , showed high temporal variation, ranging from 0.7 to 0.57 (Table 2). The detection probability of RPW on infested palms was 0.30 (95% CI 0.22–0.40, Model 1, Table 1), indicating that only a

third of infested palms are actually detected as infested.

The AICc value of ultrastructural models including individual covariates was much lower than the AICc value of the constant model (Table 3). The best model showed that the number of both public and private palm trees within a 500 m radius influenced the probability of infestation (Table 3, Fig. 3). However, the dynamics changed after 2013, as models with interaction effects including different slopes for the effect of covariates during the two periods considered (i.e. models with interactions) were preferred to additive models (Table 3). Estimates of the best model showed that during the first years of the study public Canary palms surrounded by numerous palms outside the city council remit had a much higher probability of infestation. The presence of palm trees treated by the city council showed the contrary effect acting as a buffer that reduced the infestation probability (Fig. 3). During the period 2014–2017 the presence of palm trees belonging to other entities and private owners provided a similar protective effect as those within the city council remit (Fig. 3).

Discussion

Given its ecological characteristics (e.g. high fecundity, high environmental tolerance and high mobility)

Table 3 Modelling the effect of the number of palms *P. canariensis* and *P. dactylifera* of public city council “Public” and other “Priv” (of particular private owners “Part” and of other public entities “Ent”) property on infestation probabilities (α and Υ) by *R. ferrugineus*

Infestation probability	np	Dev	AICc	Δ AICc
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Public} * \text{Priv})$	18	2634.97	2671.15	0
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Public} + \text{Part})$	16	2643.02	2675.16	4.01
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Public} + \text{Part} + \text{Ent})$	18	2639.92	2676.10	4.95
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Public} * \text{Priv})$	15	2660.45	2690.58	19.42
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Public} + \text{Ent})$	14	2664.53	2692.64	21.49
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Public} + \text{Part} + \text{Ent})$	15	2664.36	2694.36	23.34
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Public} * \text{Ent})$	18	2665.39	2701.56	30.41
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Public} * \text{Part})$	18	2670.49	2706.66	35.51
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Public} * \text{Ent})$	15	2679.53	2709.66	38.51
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Public} + \text{Ent})$	16	2691.54	2723.68	52.53
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Public} * \text{Part})$	15	2699.19	2729.32	58.17
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Public} + \text{Priv})$	14	2702.88	2730.99	59.84
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Ent} + \text{Part})$	16	2705.60	2737.74	66.59
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Public} + \text{Priv})$	16	2711.64	2743.78	72.63
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Public} + \text{Part})$	14	2717.78	2745.89	74.74
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Priv})$	14	2718.36	2746.47	75.32
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Ent})$	14	2718.88	2746.99	75.84
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Public})$	13	2723.48	2749.57	78.42
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Public})$	14	2723.46	2751.57	80.41
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Ent} + \text{Part})$	14	2726.83	2754.94	83.78
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Priv})$	13	2731.86	2757.96	86.80
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Ent})$	13	2736.74	2762.84	91.68
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{Part})$	14	2735.82	2763.93	92.78
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{Part})$	13	2741.88	2767.97	96.82
$(\alpha \neq \Upsilon) + (2011-14;2014-17) * (\text{total})$	14	2746.78	2774.89	103.74
$(\alpha \neq \Upsilon) + (2011-14;2014-17) + (\text{total})$	13	2752.43	2778.52	107.37
$(\alpha \neq \Upsilon) + (2011-14;2014-17)$	12	2754.84	2778.92	107.77

np = number of estimable parameters, Dev = relative deviance of each model, AICc = second order Akaike’s information criterion, Δ AICc = difference between current model and the model with the lowest AICc

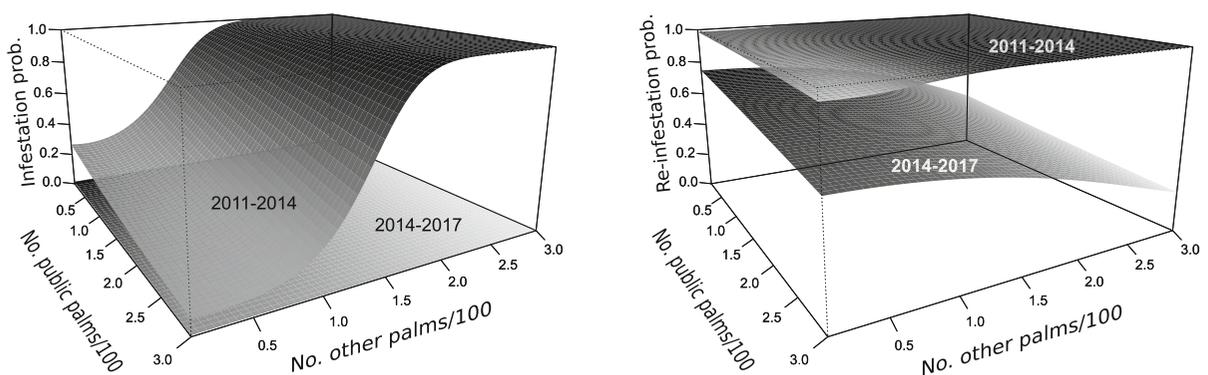


Fig. 3 Predictions (best model, Table 3) of infestation probabilities by *R. ferrugineus* of previously healthy α and previously infested Υ public *P. canariensis* at Palma city during 2011–2014 and 2014–2017, depending on the surrounding (500 m radio)

number of palms treated by the municipality (public) or by other entities and private owners (private). Dark cells correspond to higher infestation probabilities than light cells

and the anthropogenic factors mediating its introduction and spread, the RPW is a highly invasive species, extremely difficult to eradicate (Faleiro 2006; Milosavljević et al. 2019). Only two successful eradications of *Rinchochophorus sp* after invasion have been documented: at Canary Islands, Spain (total cost 12.000.000 €), and at Laguna Beach, California, USA (total cost 1.000.000 \$) (Hoddle et al. 2016). In both areas integrated pest management strategies (IPM) included the exhaustive visual sanitary evaluation of all private and public palms, application of regular pesticide treatments and the destruction of infested material. A problem in tracking the spread of pest species is the error in evaluating the infectious state of the host and the factors affecting the evolution of the infection. The multievent modelling approach developed here successfully framed the complexity of the insect–plant interaction at a local scale, accounting for the uncertainty of host infectious state. Results on the infestation dynamics of *P. canariensis* at public gardens of Palma municipality by RPW indicate that the pest species has not been eradicated but the severity of the pest has been largely reduced thanks to mitigation measures and awareness campaigns. The success of the IPM was not immediate but 1 year after its implementation the infestation probabilities decreased from 20 to 3% and from 94 to 63% for healthy and previously infested palms, respectively. However, to ensure the long-term effectiveness of management measures and to achieve a complete eradication, pest management measures should be implemented as a common strategy by all municipalities of the island, by public entities as well as private owners (Hoddle et al. 2016; Milosavljević et al. 2019). In fact, the proximity to treated and untreated palms (i.e. host abundance and connectivity) appeared as a critical factor influencing the infestation probability at a local scale (Senf et al. 2017; Wildemeersch et al. 2019). Although the species has high dispersal capabilities allowing the recolonization of not infested patches, individuals typically perform short-distance flights (Ávalos et al. 2014, 2016) explaining the existence of RPW infestation occurring in clusters (Faleiro et al. 2002; Al-Dosary et al. 2016). During the entire study period, the management measures implemented by the city council on public palms provided a protective effect on surrounding individuals, being less prone to be infected as well as the number of palms in the neighborhood was higher (i.e. a “mass

vaccination” effect). In fact, all public palms were recurrently treated with chemical insecticides to kill weevils (Hernandez-Marante et al. 2003). Moreover, the early detection of infestations at regularly monitored palms prevents adult emergence limiting the pest population growth (Al-Dosary et al. 2016). Contrarily, the presence of date palms belonging to private owners and other public entities on the neighborhood of favored the infestation of public *P. canariensis* during the first years of monitoring. At the initial steps of the invasion private owners (and other public entities) were reluctant to apply expensive treatments (IG and OM pers. obs.). However, as the species spread and numerous palms died, the problem became obvious. As a result of awareness campaigns, the implementation of preventive, curative and destructive treatments by other entities and private owners has improved. In the last years of the study the presence of public and private palms in the neighborhood decreased the infestation (and the re-infestation) probability of a given palm. Some trees previously infested by RPW have recovered after curative treatments, but our results show that previously infested individuals had a higher probability of been re-infested than healthy ones. The negative effects of this pest species at Palma city have been reduced but RPW has not been eradicated. Multiple environmental factors, landscape features, anthropogenic activities may modulate RPW dynamics at larger spatial scales (Raffa et al. 2008; Senf et al. 2017; Wildemeersch et al. 2019).

Multievent capture recapture models have been recently used to study of demographic parameters of animal populations (Frederiksen et al. 2014), including the epidemiological dynamics of animals in which the sanitary status of individuals cannot be assessed with total certitude (Conn and Cooch 2009; Santoro et al. 2014; Benhaim et al. 2018; Simon et al. 2018). Here, we show that multievent models can also be used to study the plant–insect interaction, analyzing the infestation data of the plant. Site occupancy models, framed into a multievent modelling to accommodate state assignment uncertainty, allow to assess multiple hypotheses on conditional processes and can be used, for example, to investigate the pattern of insect expansion (Tavecchia et al. 2017), the effect of species-specific life-history traits on site occupancy (Fernández-Chacón et al. 2013) or the influence of site-specific covariates (Sanz-Aguilar et al. 2018). Extensions of this model could also accommodate

partial monitoring of hosts in situations in which logistical or economical resources may constraint monitoring programs. In fact, capture-recapture models were specifically designed to deal with imperfect detection (i.e. recapture) of individuals (Lebreton et al. 1992). Consequently, monitoring probabilities can be easily accommodated in a multievent capture-recapture framework (Sanz-Aguilar et al. 2016, 2018). Moreover, the possibility to use covariates at individual as well as population level, open the possibility to assesses several hypotheses on the dynamic, prevalence and management of invasive plant pests.

In conclusion, our study highlights the important role of the spatial aggregation of hosts and the degree of preventive, curative and destructive treatments as predictor of the infestation probabilities of Canary Island date palms at a local scale. Palms surrounded by high densities of untreated conspecifics showed high probabilities of infestation/re-infestation by RPW. On the contrary, the existence of many surrounding treated individuals provided a protective effect. During de last years, the infestation probabilities of palms by RPW at Palma city have been low (3%), but re-infestation rates continued to be high (63%), highlighting the partial efficacy of curative treatments. Future studies should integrate information on local but also large scale process (Raffa et al. 2008) to improve the understanding of the RPW spatial temporal dynamics and optimize management strategies (Senf et al. 2017; Wildemeersch et al. 2019).

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Authors’ contribution ASA and GT conceived the analytical framework. IG and OM designed the field protocols and collected the data. IC, SG and ASA organized the data. ASA and GT analyzed data. ASA and GT wrote the first version of this manuscript and all authors contributed to and approved the present manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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