

# Microclimatic conditions drive summer flight phenology of *Platypus cylindrus* in managed cork oak stands

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## Abstract

The oak pinhole borer, *Platypus cylindrus* F., mainly colonizes oaks (*Quercus* sp.), and it is considered among the most serious pests of cork oak (*Quercus suber* L.). Despite being traditionally considered as a secondary pest in thermophilic oak woodlands, outbreaks seem to be more frequent throughout the Mediterranean Basin thus becoming a growing forest health concern. In the Iberian Peninsula, this insect mainly attacks cork oaks (*Q. suber*) causing intense stress to mature trees specially after cork harvesting season. In this study, we investigated the summer flight phenology of *P. cylindrus* in six stands located in north-eastern Spain. We recorded the number of insects trapped in pheromone-baited traps from late April to early September of 2021, and computed sex ratio, average date of flight and season flight curve in each plot. We fitted a GAM model to evaluate how population dynamics are driven by date and climatic factors. A total of 1795 insects were collected during the sampling period. Population peaks occurred from late May to mid-August. The fitted GAM predicted changes in the number of captures throughout the summer varying with microclimatic conditions. In addition, diversity of trapped non-target Curculionidae resulted moderate with low evenness including either ambrosia or bark beetles. This study represents the first attempt at modelling *P. cylindrus* flight, thus providing insights into the association between climate, pests and forestry.

## KEYWORDS

ambrosia beetles, cork harvesting, GAM model, non-target bark beetles, oak pinhole borer, *Quercus suber*

## 1 | INTRODUCTION

Beetles, and more specifically, bark and ambrosia beetles (Coleoptera; Curculionidae: Scolytinae and Platypodinae) are considered among the most important forest pests both in coniferous and broad-leaved woodlands. These insect guilds are commonly considered as primary, species able to colonize healthy trees, or secondary pests, those that usually attack stressed or dying hosts affected by other abiotic or biotic agents such as drought (Kelsey

et al., 2014), windstorms (Hroššo et al., 2020) or pathogens (i.e. nematodes, fungi or bacteria), which could, in turn, be vectorized by bark and ambrosia beetles (Fernández-Fernández et al., 2019; Santini & Faccoli, 2014). Their role as primary or secondary pests should, nevertheless, not be understood as static since several species exhibit both behaviours depending on environmental conditions or biological stage [e.g. *Tomicus piniperda* L. (Scolytinae) is considered as a secondary pest in trunk infestation but primary in twigs (Lieutier et al., 2015)].

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Insects' lifecycle is also expected to become adapted to the future climate conditions. In this context, climate-influenced phenomena such as synchrony between host phenology and insect development (Foster et al., 2013; Watt & McFarlane, 2002), pest-predator/parasitoid interactions, colonization of new habitats, outbreaks severity or voltinism could be altered in the medium term because of changes in climate regimes (Harrington, 2002; Logan et al., 2003). For instance, outbreaks of the spruce bark beetle (*Ips typographus* L.; Scolytinae) are thought to become more frequent in Central Europe (Sommerfeld et al., 2021). In parallel, more restrictive conditions caused by global warming could reduce optimum habitat range of hosts (López-Tirado & Hidalgo, 2016), thus favouring stress episodes in poorer quality stands that would increase the susceptibility of trees [e.g. higher mortality associated to infestations of so-called secondary borers after drought periods (Siitonen, 2014)]. These future scenarios highlight the need for better understanding the ecology of pests to develop effective management and adaptation strategies.

The oak pinhole borer (*Platypus cylindrus* F.; Platypodinae; from here on referred as "OPB") is widely distributed throughout the Mediterranean Basin. This xylomycetophagous (ambrosia) beetle mainly colonizes oaks (*Quercus* sp.) and is considered among the most relevant pests of cork oak (*Quercus suber* L.). OPB exhibits a lifecycle with several generations coexisting in a single gallery system therefore causing multiple emergence peaks along the year. Sousa and Inácio (2005) summarized the flight period as follows: adults from the first generation fly from May to autumn-winter with no emergences between February and April, next generation starts to fly in the following spring. These authors also reported differences in adult emergence patterns between latitudes with delayed summer flight in northern locations. In the Iberian Peninsula, little is known about OPB's flight phenology (Catry et al., 2017); hence, more research is needed to clarify environmental conditions that affect the flight period during endemic population level.

*Platypus cylindrus* has been traditionally considered as a secondary trunk colonizer in Europe and some regions of northern Africa; nevertheless, its capacity to attack healthy hosts and quickly kill weakened trees (i.e. 3–18 months) has been reported (Sousa & Inácio, 2005). In addition, the occurrence of severe outbreaks is becoming more frequent in Algeria, the Iberian Peninsula, and Morocco in the last decades (Bellahirech et al., 2015). In this regard, intense damage on mature cork oaks caused by massive entry is especially visible after debarking in *Q. suber* productive stands. Cork planks are removed every 9–14 years from mature trees [–20–35 (40 years old) generating an important economic revenue in several regions of the Mediterranean Basin (mainly Portugal and Spain, which together grow >80% of global cork production; Sierra-Pérez et al., 2015). Consequently, OPB is considered as an important threat for this renewable non-wood forest product in the medium term since infestations tend to be more intense in debarked trees (Belhoucine & Bouhraoua, 2012; Sousa & Inácio, 2005). Besides, *P. cylindrus* proliferation reduces the vigour of the trees, favours proliferation of fungal diseases (i.e. it carries propagules of pathogens such as *Biscogniauxia* spp. and *Botryosphaeria* spp.) and kills mature oaks (Inácio et al., 2011; Tiberi et al., 2016).

TABLE 1 Description of sampled plots

Plot	County	Location	UTM coordinates	Area (ha)	Height (m. a. s. l.)	Cork oak diameter (cm)	Cn	V
1	La Selva	Mas Feliu	41.850730 N 2.834706 E	36.26	134	31.70 ± 4.48	1.38 ± 0.47 a	61.04 ± 5.73 abc
2	La Selva	Can Mau	41.926775 N 2.631814 E	26.54	372	34.00 ± 4.09	19.11 ± 4.23 b	66.85 ± 1.37 a
3	La Selva	Can Huix	41.879136 N 2.600310 E	29.61	349	19.99 ± 3.26	2.22 ± 1.16 a	39.55 ± 3.83 d
4	La Selva	Can Massaguer	41.829946 N 2.572938 E	20.25	583	35.27 ± 3.51	36.16 ± 10.09 b	58.00 ± 0.92 b
5	La Selva	Can Albò	41.902445 N 2.599218 E	21.32	517	38.52 ± 3.49	6.38 ± 2.75 a	66.18 ± 1.82 a
6	Vallès Oriental	Ca l'Aràbia d'Olzinelles	41.658137 N 2.537927 E	30.00	443	36.16 ± 2.61	32.63 ± 5.84 b	71.66 ± 0.99 c

Note: Cn, Number of *Platypus cylindrus* captured per sampling event in each plot. V, average date of flight (expressed in Julian date). Small letters (a–e) denote significant differences (p-value < 0.05) according to Dunn's (Cn) and Welch's (V) tests. Mean values and standard error are shown.



FIGURE 1 Dorsal view of *Platypus cylindrus*. Black rectangles represent 1 mm [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

Population dynamics of insects during the dispersion period usually exhibits fluctuations (e.g. population peaks caused by overlapping generations) that complicate making a prediction using linear models. In this regard, generalized additive models (GAMs) address non-linearity of data using smooth functions for predictor variables (Pedersen et al., 2019). GAMs are gaining interest in insect ecology since variation in the number of flying adults can be modelled considering environmental variables (Munro et al., 2021; Pawson et al., 2020). In this study, we hypothesized that summer flight phenology of *P. cylindrus* could vary among locations and be related to microclimatic conditions. In consequence, the aims of this study were (i) to characterize the summer flight period of *P. cylindrus* with special focus on cork debarking period and (ii) to identify climate factors that could drive population dynamics during the season.

## 2 | MATERIAL AND METHODS

### 2.1 | Field sampling and insect identification

We chose the La Selva county (Catalonia, north-eastern Spain; Table 1), one of the core cork-producing counties in the NE cork growing region of Spain, to monitor the summer flight of OPB also including the cork harvest period in the area (from 15<sup>th</sup> June to 15<sup>th</sup> July, approximately). We selected stands that fulfilled the following criteria for the study: (i) mature *Q. suber* stands, (ii) minimum required area: 20 ha and (iii) last cork harvest season: 2020. We identified 5 stands that fit the criteria and we set a study plot in each of them. An additional plot was set in Vallès Oriental county (eastern Catalonia) where previous infestations caused by OPB had been reported (Regional Government Forest Services, unpublished data). This additional plot did not fit criterion (iii) because it was debarked for the last time in 2018 (Table 1). The mean distance between plots was  $16.98 \pm 2.57$  km being the shortest distance between plots 2.58 km (i.e. plots 3 and 5). Two Theysohn® slot traps (Theysohn) were set in each plot on 28<sup>th</sup> April 2021. Each trap was set at 1.60-m height, separated approximately 100 m from each other and were

baited with *P. cylindrus* pheromone [Cilindriwit®, Blend composition: ( $\pm$ ) 6-methyl-5-hepten-2-ol 0.052 g; 6-methyl-5-hepten-2-one 0.026 g; 1-hexanol 0.052 g and ethanol 1.270 g] (Catry et al., 2017; Pacheco, 2013). Traps were supported by two metallic 2-m-tall bars covered with odourless petroleum jelly (Fagron Ibérica) in the first 30–40 cm above ground to prevent predation by ants inside the trap. Synthetic pheromone was periodically replaced according to manufacturer's recommendations (60 days of expected duration), and expired lures were not removed from the traps.

Sampling plots were characterized by measuring diameters at 1.30-m height of five randomly selected cork oaks located between each pair of traps (Table 1), as well as by stand description according to thirteen geographical and forestry variables (i.e. location, elevation, forest structure, tree species composition, canopy cover, shrub density and composition, and health status. Appendix S1). In addition, climatic variables (i.e. temperature and relative air humidity) were recorded every hour by an ELUSB-2 data logger (Lascar Electronics) placed in a shaded and well-ventilated location between the two traps in each plot. Any measurement gap because of datalogger failure was estimated using the hourly records from the two nearby meteorological stations (Servei Meteorològic de Catalunya; <https://www.meteo.cat/>).

Insects trapped in each plot were collected every 7–10 days between 3<sup>th</sup> May and 1<sup>st</sup> September 2021. Specimens of the two traps in each plot were stored together in sterile 50-ml plastic tubes and sent to Forest Pathology Laboratory of the University of Lleida. There, insects were stored at 7°C until being processed. Each adult was identified as male or female according to sexual dimorphisms features (i.e. unequal well-developed teeth at elytral declivity in males, more apparent mycangia in the female's notum) under Leica ZOOM™ 2000 binocular lens (Leica; Figure 1; Sousa & Inácio, 2005).

### 2.2 | Flight period characterization

For each sampling date, we measured the total number of captures and the sex ratio (Sr: number of males/number of females).

The variation in the number of *P. cylindrus* trapped in each sampling event (i.e. trap monitoring day) among plots was evaluated using Kruskal–Wallis rank sum test in R programming environment (R Core Team, 2021). Dunn's test was used as post hoc analysis using the package 'rstatix' (Kassambara, 2021). On the other hand, variations in the average date of flight (i.e. theoretical date corresponding to mean of captures in each plot, namely V) between plots was determined as described by Murtaugh et al. (2012) for comparing observed times in stage. Firstly, pairwise comparisons of V between plots were performed using Welch's test in R. Later, the Fisher's meta-analysis test for *p*-values obtained from Welch's tests was performed in R using the package 'metap' (Dewey, 2020) to determine significance of global variability between plots.

Generalized additive models (GAMs) were computed using the package 'mgcv' (Wood, 2021) for characterizing OPB's flight phenology. Each model was fitted for the number of captures per sampling period (regardless of sex) as response variable (C; Table 2). The date of sampling expressed as Julian date (i.e. correlative numbering from 28<sup>th</sup> April as day 1 to 1st September as day 127) was evaluated as explicative variable. Microclimatic conditions were evaluated in the GAMs by considering mean, maximum and minimum records of relative air humidity and temperature between consecutive sampling events. Mean temperature and relative air humidity (TMean and HMean, respectively) were used for model fitting since the corresponding maximum and minimum records were strongly correlated with these two variables. Correlation between climate variables was analysed through correlogram computation using the package 'corrplot' in R (Wei & Simko, 2021). Models were fitted using 'gam' function and Poisson error distribution (link function: log). Plot was included in four of fitted models as independent factor. Julian date was included in all models as explicative smooth variable (i.e. low rank isotropic smoother), although four GAMs considered Julian as smooth variable separated by plot. Climate variables Tmean and Hmean were included in all models as smooth predictors or tensor product smooths (Table 2). After model fitting, the maximum and minimum values of Tmean and Hmean corresponding to the higher

values of smooth predictor (i.e.  $\geq 6$ ) were selected to identify the most suitable climatic conditions for flight (optimal microclimatic window).

The most explicative model for the dataset was selected according to Akaike's information criteria (AIC), besides the percentage of explained deviance of each fitted model was used as a complementary selection indicator. The two most parsimonious fitted models were compared using the  $\chi^2$  test. Model fitness and predictor functions were visualized using the package 'gratia' (Simpson, 2021). Graphical material was drawn with 'ggplot2' package in R (Wickham, 2016), SigmaPlot© 12.0 (SYSTAT Software Inc.) and Surfer© 22.0 (Golden Software, LLC.).

### 2.3 | Identification of non-target bark and ambrosia beetles

All non-target beetles belonging to subfamily Scolytinae that were trapped during sampling period were identified morphologically (Balachowsky, 1949; Gil & Pajares, 1986; J.M. Riba-Flinch, pers. comm.). Species composition (i.e. observed richness S), Shannon diversity index ( $H'$ ), Camargo's dominance index (species *j* is considered dominant if  $p_j > 1/S$ ; being  $p_j$  = number of individuals of *j*/ number of non-target beetles trapped) and community evenness (E) were calculated (Camargo, 1993; Zak & Willing, 2004). Ecological indices were calculated using records of all plots in the whole sampling period to characterize the specificity of the lure used.

## 3 | RESULTS

### 3.1 | Insect sampling and characterization of flight period

A total of 1795 adults of *P. cylindrus* (56.43% ♀♀ and 43.57% ♂♂) were captured during the 127-day sampling period. The number of trapped insects per sampling event differed among sampled

TABLE 2 Generalized additive model (GAM) selection

Model	Description	R <sup>2</sup>	Explained deviance (%)	AIC	ΔAIC
<b>m1</b>	<b>C~s(Julian; by plot) + te(TMean x Hmean)</b>	0.99	<b>99</b>	<b>492.74</b>	-
m2	C~s(Julian; by plot) + s(TMean) + s(HMean)	0.99	98.6	497.03	4.29
m3	C~s(Julian; by plot) + s(HMean)	0.98	98	502.25	9.51
m4	C~s(Julian; by plot) + s(TMean)	0.97	97.2	514.37	21.63
m5	C~plot + s(Julian) + te(TMean x HMean)	0.89	90.5	717.42	224.68
m6	C~plot + s(Julian) + s(TMean) + s(HMean)	0.82	87.7	794.46	301.71
m7	C~plot + s(Julian) + s(TMean)	0.81	86.2	831.35	338.61
m8	C~plot + s(Julian) + s(HMean)	0.82	83.7	912.76	420.02

Note: C, captures of *Platypus cylindrus* per sampling period; Julian, Julian date; TMean/HMean, Mean temperature/relative air humidity recorded between sampling events in each plot, respectively; s, Low rank isotropic smoother; te, Tensor product smooths and interaction. Selected model in bold.

Abbreviation: AIC, Akaike's information criteria.

areas ( $p$ -value  $< 0.01$ ) pointing at two different clusters of plots, one including those plots with higher captures (i.e. plots 2, 4 and 6;  $p$ -value  $> 0.43$  among them in pairwise comparisons according to Dunn's test) and another with plots with lower captures (i.e. plots 1, 3 and 5;  $p$ -value  $> 0.38$  in each comparison; Table 1). More specifically, plot 4 yielded the highest number of trapped insects during the study ( $n = 651$ , 52.38% ♀♀, 47.62% ♂♂) followed by plot 6 where 620 adults were trapped (56.29% ♀♀ and 43.71% ♂♂), and 2 with 344 individuals (58.43% ♀♀ and 41.57% ♂♂). The plots with lower number of captures were 5 ( $n = 115$ , 66.09% ♀♀ and 33.91% ♂♂), 3 ( $n = 40$ , 67.50% ♀♀ and 32.50% ♂♂) and 1 where the lowest number of adults were trapped ( $n = 25$ , 76% ♀♀ and 24% ♂♂).

Overall sex ratio revealed female-biased capture rate (Sr: 1:1.3). However, this indicator fluctuated over the summer. Males were more abundant than females in our traps in the first weeks of sampling. More specifically, sex ratio became  $> 1$  in three periods in plot 2 (June, July, and August), during June and July in plot 4, at the end of July in plot 5 and in August in plot 6 (Appendix S2). Both plots 1 and 3 always yielded  $< 1$  sex ratio (males over females) denoting dominance of females in the traps.

Regarding summer flight phenology, the dates corresponding to mean value of captures ( $V$ ) significantly varied among plots (Fisher's meta-analysis test,  $p$ -value  $< 0.01$ ). Pairwise comparison according to Welch's tests showed significant differences between plot 3 and the other plots (Table 1) being the date of mean of captures earlier than in other locations (i.e. 39.55 in Julian date, 4–5<sup>th</sup> June approx.;  $p$ -value  $< 0.01$  in all pairwise comparisons). Plots 2 and 5 yielded similar  $V$  (i.e. 2nd–3rd July approx.;  $p$ -value = 0.76) with a later mean capture date than in the plots 1 and 4 (~27<sup>th</sup> and ~24<sup>th</sup> June, respectively), which did not differ significantly between them ( $p$ -value = 0.60). The location with latest  $V$  was plot 6 where the date of mean capture corresponded to 7<sup>th</sup> July (approx.) being significantly different from plots 2–5 ( $p$ -value  $< 0.01$  in all cases; Table 1). These differences in phenology resulted also noticeable in the computed flight curve where 1–4 populations peaks could be found during the summer depending on the plot (Figure 2).

### 3.2 | Summer flight model

The GAM selected as most explicative for the dataset (i.e. m1) included the number of captures ( $C$ ) per sampling event as response variable and the corresponding Julian date (separated by plot) as smooth predictor. Microclimatic factors (i.e. HMean and TMean) were also included as tensor product smooth variable. Model 'm1' provided a notably lower AIC value than the other fitted models ( $\Delta AIC > 4$  in all cases) as well as higher explained deviance (Table 2). The selected GAM was also significantly different from the closest model 'm2' according to  $\chi^2$  test ( $p$ -value = 0.01).

The fitted model 'm1' considered the variability of Julian date by plot yielding better fitness to our dataset than other computed models including the plot as factor (i.e. m5–m8). Variations of smooth function for Julian date showed different optimum dates for

predicted captures by plot: negative values of predictor were detected until the end of May ( $< 25$  in Julian date; Figure 3) for the plots 2, 4 and 6, whereas additional negative curve development were found in the plots 1 and 3 in mid-summer. Plots 1, 3 and 5 showed negative development of the smooth curve at the end of the study period (Figure 3).

The inclusion of mean temperature and relative air humidity records per sampling period improved the fitness of the corresponding GAMs in respect of the use of those variables separately (e.g. m1 or m2 against m3 and m4), despite their observed correlation ( $\varphi = 0.80$ ; Appendix S3). In this regard, variations of both climatic factors had significant effect in the number of fitted captures in 'm1' (Table 3) and the inclusion of tensor product of TMean and HMean highlighted a microclimatic narrow window (i.e. mean temperature: 13.21–20.99°C; mean relative air humidity: 56.86%–70.22%; average range:  $17.35 \pm 0.14^\circ\text{C}$  and  $65.28 \pm 1.08\%$ ) that produced a noticeable positive effect of smooth predictor in the response variable (red-shaded areas in Figure 4) revealing microclimatic scenarios associated with higher number of predicted captures.

### 3.3 | Diversity of non-target bark beetles

A total of 201 Scolytinae belonging to 7 taxa were detected in OPB pheromone-baited traps (Table 4). More specifically, 4 taxa of bark beetles (i.e. *Hylurgus micklitzi* Wachtl, *Orthotomicus erosus* Wollaston, *Ips sexdentatus* Börner and *Pityophthorus* sp.) and 3 species of ambrosia beetles (i.e. *Xylosandrus germanus* Blandford, *Xyleborus monographus* F. and *Xyleborinus saxesenii* Ratzeburg) were identified by morphological traits. The Shannon diversity index was 1.39, while the evenness was 0.71.

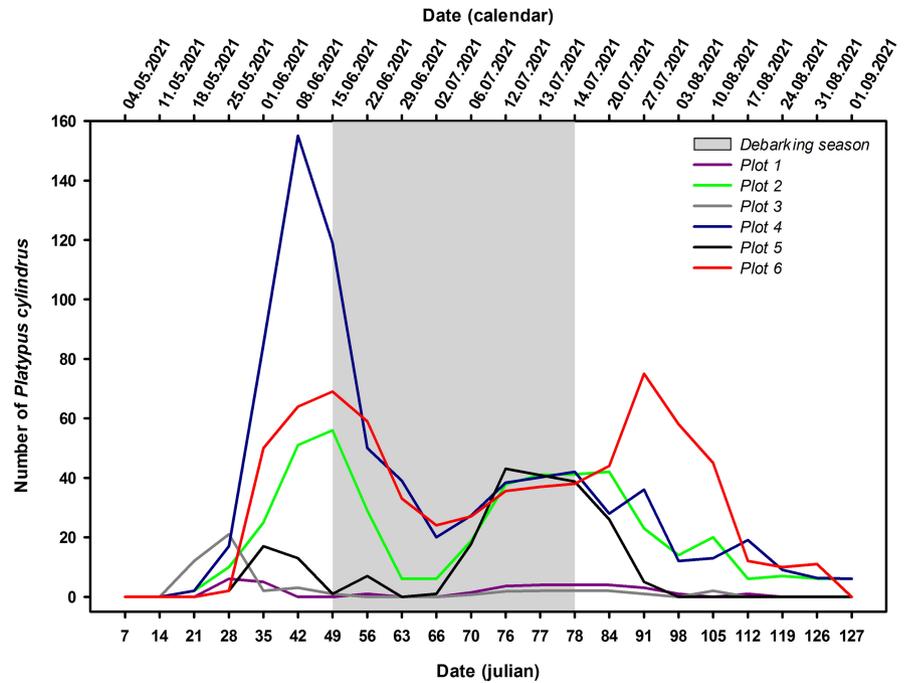
### 3.4 | Climate description of plots

Climatic characterization of sampled plots revealed slight differences in overall climate factors. Mean temperature in May was around 15.5°C ranging from 21°C to 23°C for the rest of the sampling period in all plots. Maximum temperatures during the summer rarely surpassed 40°C (i.e. plot 3 and 4, at particular moments of midday in July and August). Minimum temperatures were recorded in May ranging between 5.5°C and 9°C in all plots. Mean air humidity remained over 60% in all sampling plots during the study period with minimum summer records of 24%, 15%, 13%, 17%, 16% and 22.5% in the plots 1–6, respectively (all these minimum values were recorded in July).

## 4 | DISCUSSION

In this study, we investigated the phenology of OPB's summer flight in six locations of north-eastern Iberian Peninsula. Emergence patterns (i.e. average date of flight and population peaks) differed among

**FIGURE 2** Flight curve of *Platypus cylindrus* per sampling plot between 28<sup>th</sup> April and 1st September 2021. Grey shaded area represents cork harvesting season (from 15<sup>th</sup> June to 15<sup>th</sup> July, approx.) [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



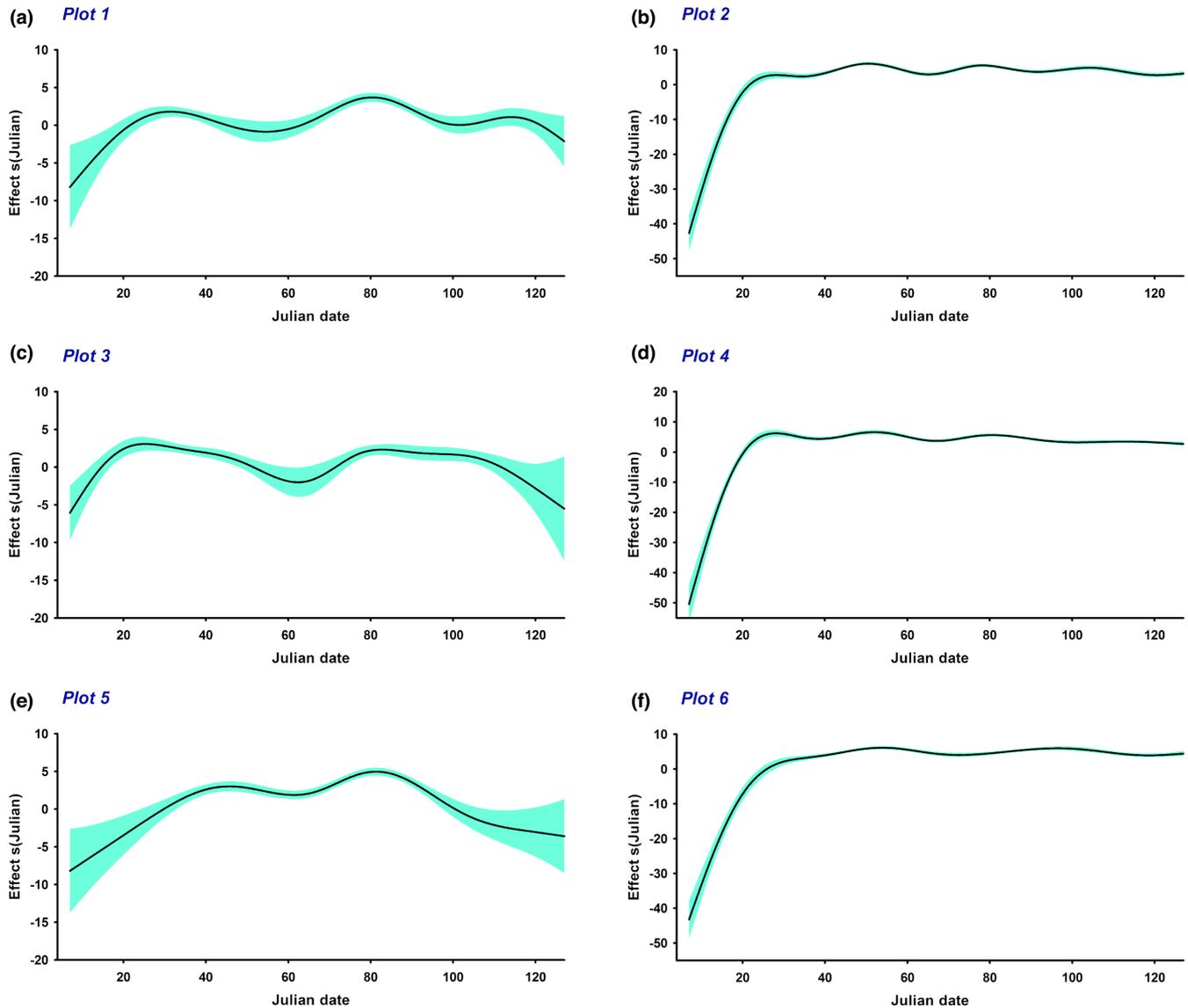
locations; nevertheless, a general pattern in our sampling areas could be summarized as follows: (i) adults of *P. cylindrus* emerge in later May and the population markedly increases during June. Then, (ii) flying population decreases until early July when a secondary increase occurs causing a more attenuated population peak in mid-July. Finally, (iii) populations fluctuate without reaching high densities (with exceptions, i.e. plot 6) until the end of summer, thus pointing a two-wave development of the flight curve (Figure 2) also reported in other Iberian regions (see below). Although lower emission rate of lures could interfere in curve interpretation in mid-summer, we considered the reported wide oviposition period of this species (i.e. from the end of summer until winter; Sousa & Inácio, 2005) as the most plausible explanation of the observed dynamics. Consequently, the bimodal pattern of flight curve described here matches the expected dynamics of sister generations with staggered emergence.

Our results also revealed that the flight period spans the whole cork harvest season (i.e. from 21 days before the first debarking working day to the end of the harvesting period). Hence, OPB mainly colonizes cork oaks with unaltered phellem being the symptoms observed from mid-summer onwards (proliferation of holes and sawdust accumulation, among others) caused by both early established individuals, and by adults from the second population peak which penetrate in trees during cork harvesting season.

Flight phenology of OPB in western Mediterranean Basin seems to follow an almost homogeneous pattern with early emergence in May–June in Algeria, Morocco, Portugal (Belhoucine et al., 2011; Sousa & Inácio, 2005) and north-eastern Spain. More specifically, Pacheco (2013) and Catry et al. (2017) studied flight period in Portugal and reported marked increases in captures in later May, June and mid-July that agree with our observations (Figure 2). Population dynamics of *P. cylindrus* has been scarcely studied in Spain until now, even though a previous report showed absence of

peaks in June with later intense population increases either in August or September in a Mediterranean stand located further south than those sampled in our study (Castellón province) (Pérez-Sánchez et al., 2018). In this regard, long-term survey programmes would be informative to characterize whole-year flight phenology of OPB in eastern Iberian Peninsula since autumn population peaks have been documented in Portugal (Catry et al., 2017; Pacheco, 2013).

*Platypus cylindrus* tends to colonize trees with higher diameters (Belhoucine & Bouhraoua, 2012; Bellahirech et al., 2019) and debarked *Q. suber* seem to be more prone to be infested than unstripped ones (Bellahirech et al., 2015). The intensity of debarking in previous years was not evaluated here as a possible driving factor; nevertheless, previous studies did not find a significant effect of this stand variable in the abundance of *P. cylindrus* (Bellahirech et al., 2015). The exploratory analysis of captures as well as the fitted GAM revealed significant differences in the number of trapped OPB per plot through the study period. All sampled plots showed rather similar diameters (>30 cm, except on the plot 3, see below), and they were not debarked during the study period. Consequently, we tend to think of stand structure rather than diameter as possible driver of the observed differences. Plot 1 provided the lowest number of captures; nevertheless, cork oaks in this area were irregularly distributed in a savannah-like stand where trees were isolated or clustered with pines (*Pinus* spp.; Appendix S1). On the other hand, plot 3 also exhibited a low number of captures during the whole study despite *Q. suber* being the main canopy species. In this case, the lower diameter of the trees surrounding traps could explain, at least in part, the lower number of insects trapped in the plot as proposed by Bellahirech et al. (2019). The rest of the sampled areas exhibited in greater or lesser extent, higher abundance of OPB showing all of them *Q. suber* as dominant canopy species with canopy cover



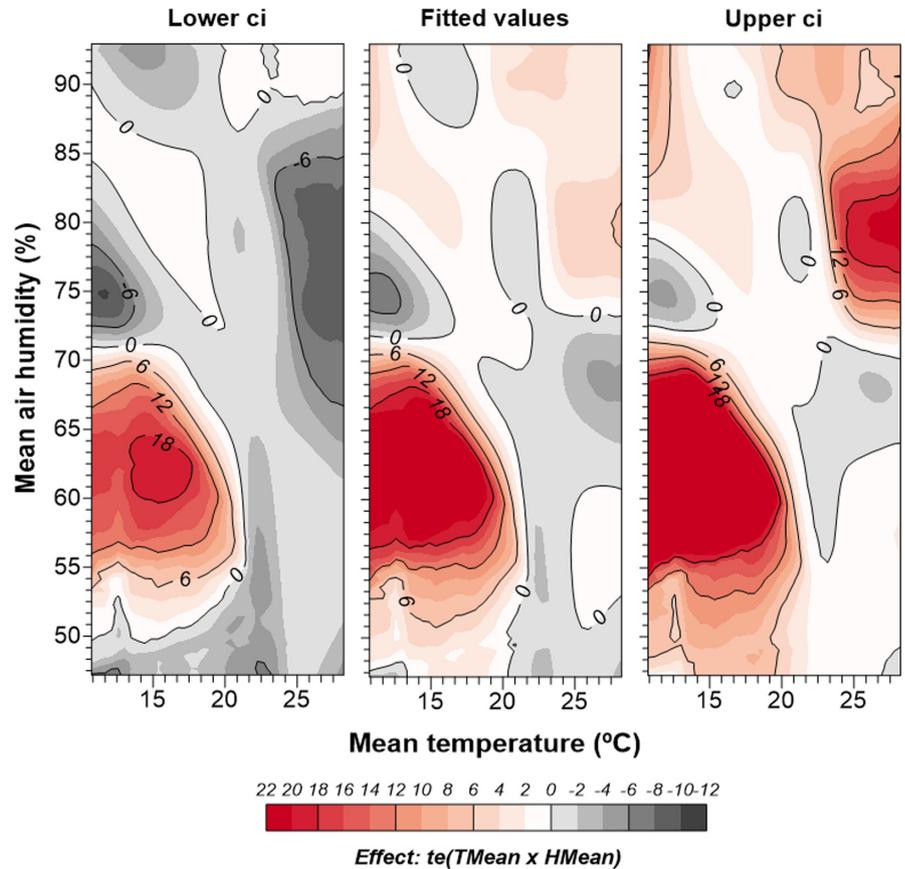
**FIGURE 3** Estimated effect of smooth coefficient function of Julian date by experimental plot per sampling period over the number of trapped *Platypus cylindrus* (a-f). Shaded areas represent 95% confidence intervals. Positive values of predictor effect indicate positive effects of the corresponding smooth variable in the number of captured *P. cylindrus* per sampling period [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Response variable	Predictors			
	Smooth terms	Edf	$\chi^2$	p-value
C (n = 109)	Julian (plot 1)	7.60	26.24	<0.01
	Julian (plot 2)	9	132.24	<0.01
	Julian (plot 3)	7.56	19.92	0.02
	Julian (plot 4)	9	116.69	<0.01
	Julian (plot 5)	5.96	115.34	<0.01
	Julian (plot 6)	9	131.77	<0.01
	TMeanxHMean	21.47	61.98	<0.01

**TABLE 3** Summary of GAM fitted for *Platypus cylindrus* trapping (m1)

Note: C, Captures of *P. cylindrus* per sampling period; Julian, Julian date; TMean/HMean, Mean temperature/relative air humidity recorded between sampling events in each plot, respectively. Abbreviation: Edf, effective degrees of freedom.

**FIGURE 4** Estimated effect of tensor product of mean relative air humidity and temperature per sampling period over the number of trapped *Platypus cylindrus*. Lower ci/upper ci: 95% lower/upper confidence interval for fitted values, respectively. Positive values of predictor effect indicate positive effects of the corresponding tensor variable in the number of captured *P. cylindrus* per sampling period. Isolines represent constant values of tensor variable. Interpolation method used for the plot: point kriging [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**TABLE 4** Non-target ambrosia and bark beetles (Coleoptera, Scolytinae) found in the study

Taxon	Plot						Total	Relative abundance (%)	Dominance
	1	2	3	4	5	6			
<i>Hylurgus micklitzi</i>	5	2	0	0	0	2	9	4.47	Non-dominant
<i>Ips sexdentatus</i>	0	0	1	0	0	0	1	0.49	Non-dominant
<i>Orthotomicus erosus</i>	0	0	0	0	0	4	4	1.99	Non-dominant
<i>Pityophthorus</i> sp.	0	13	1	0	0	30	44	21.89	Dominant
<i>Xyleborinus saxesenii</i>	7	6	0	1	2	54	70	34.82	Dominant
<i>Xyleborus monographus</i>	9	14	5	7	4	30	69	34.32	Dominant
<i>Xylosandrus germanus</i>	0	4	0	0	0	0	4	1.99	Non-dominant

Note: Dominance according to Camargo's index (Camargo, 1993).

ranging from moderate to high. Additionally, holm oak [*Quercus ilex* subsp. *ballota* (Desf.) Samp.] was a secondary canopy species in the stands 4–6, while sweet chestnut (*Castanea sativa* Mill.) was locally abundant in the stand 2. These tree species have been cited as alternative hosts of *P. cylindrus* (Sousa & Inácio, 2005) that could positively contribute to the observed high population. In consequence, the effect of forest structure in OPB's dynamics deserves more research (e.g. age of the stand, number of dead and weakened trees per hectare, or canopy cover), since it has been found as a relevant factor in other ambrosia and bark beetles (Holuša et al., 2021; Stereńczak et al., 2020).

Climate variables are key factors in subcortical insect's dispersion; thereby, their effects should be better understood to foresee future scenarios caused by climate change. Mean annual

temperature has been reported as a relevant factor in *P. cylindrus* proliferation (Bellahirech et al., 2019). In that study, the authors found a noticeably higher proportion of *Q. suber* infested by OPB when annual mean temperature surpassed 15–20°C. We used microclimatic records instead annual data for fitting GAM 'm1'; nevertheless, our results agree with that reported tendency since a higher number of captures were predicted after periods of mean temperature between 13.21 and 20.99°C (Figure 4). The use of microclimatic data revealed homogeneous summer climate in the studied area despite the distance between plots reached up to 30km of rugged landscapes. In addition, the availability of local records allowed us to fit a model based on the actual environmental conditions affecting the studied insect populations. The effect of temperature has been studied in other members of

Platypodinae. Nam and Choi (2014) found adults of *Platypus koryoensis* Murayama flying when temperature reached 16°C (dawn and early morning), with an optimum thermal range between 20 and 27°C for this ambrosia beetle. The fitted GAM did not reveal clear upper threshold of temperature and the observed flight curve suggests *P. cylindrus* flies during the whole summer. These results agree with those expected since this species is distributed along the Mediterranean Basin and high temperature is not considered to be a major limiting factor for its dispersion.

The effect of air humidity in dispersion fitness has been less studied because of its synergistic effect with temperature (Jones et al., 2019). The GAM 'm1' showed positive effect of captures when humidity was moderate to high (i.e. 56.86%–70.22%; central chart of Figure 4). Wet conditions are considered positive for ambrosia beetles since they rely on fungal growth for developing (Holuša et al., 2021); nevertheless, little is known about the actual effect of humidity in their flight phenology. Interestingly, Nam and Choi (2014) reported lack of captures of *P. koryoensis* during rainfall episodes although temperature was adequate for adults' flight. A similar effect was also observed in *Pityophthorus juglandis* Blackman (Scolytinae), plausibly due to the higher metabolic cost in terms of wing-beat in humid environments (Chen et al., 2020). The tensor predictor for mean air relative humidity and mean temperature used here also showed a negative effect of those variables when humidity reached >70%–80% keeping stable the mentioned range of temperature (Figure 4). This negative effect could be caused by rainfall episodes between sampling events since precipitation is thought to disorient the flight of insects to the baited traps (Moser & Dell, 1979). Our model also predicts higher captures after wetter periods (right-upper part of Figure 4, central and right charts). This increase of captures could be caused by adults emerged during adverse conditions (rainfall or high humidity without precipitation), which started to disperse together when weather became favourable, as proposed by Moser and Dell (1979).

Our trapping method used lures formulated with specific pheromones of the target ambrosia beetle. Females seemed to be more attracted by the lure than males according to the overall female-biased sex ratio found here, and also reported before (Catry et al., 2017). Regarding selectivity of the used lure, *P. cylindrus* represented 71.57% of trapped beetles (90.37% of total trapped arthropods, data not shown). Curculionidae represented a moderately diverse subcommunity where 8.01% of trapped beetles corresponded to Scolytinae species. The presence of *H. micklitzi*, *I. sexdentatus*, *O. erosus* and *Pityophthorus* sp. could be easily explained by the presence of *Pinus pinea* L. and *Pinus pinaster* Aiton as main canopy species in the stand, randomly distributed in the plot or as plantations near sampling areas since these bark beetles are considered polyphagous coniferous borers (Balachowsky, 1949). On the other hand, the ambrosia beetles *X. monographus* and *X. saxesenii* were rather abundant among trapped Scolytinae. These two species usually co-occur with *P. cylindrus* since they also colonize weakened cork oaks, even

infesting the same host (Catry et al., 2017). Special interest deserves the black timber bark beetle (*X. germanus*) since it is considered as an invasive species in Europe (included in the A2 list of EPPO) with more than 200 documented hosts around the world (Dzurenko et al., 2021; EPPO, 2021). This insect has been previously cited in Spain (López et al., 2007) although it has not been detected before in the sampled area. Its relative abundance in the plot 2 was rather low (i.e. three individuals in mid-May; one in late July), where high diversity of potential tree and shrub hosts could embody a suitable habitat for this exotic species (J.M. Riba-Flinch et al., in prep.).

In conclusion, our study revealed continuous summer flight of OPB in north-eastern Spain including the whole cork harvesting season, which would favour OPB colonization of current-year stripped trees. Additionally, microclimatic conditions suitable for insect dispersion have been described. Consequently, intensive monitoring campaigns from mid-spring on are recommended to estimate the risk of colonization in cork productive stands. On the other hand, predictions of the GAM model suggest the use of weather forecasts as a complementary information source to identify favourable conditions for intense infestations (i.e. optimal microclimatic window and expected accumulation of captures after wet periods). This information could be used as a useful tool in forest management thus contributing to schedule and prioritize stands to be stripped according to the expected dynamics of OPB. Otherwise, future climate is expected to challenge the health status of forests; hence, phenology models as the one discussed here should be developed to get more accurate predictions about pest dissemination and population dynamics.

#### AUTHOR CONTRIBUTIONS

C.C. and E.J.M.-A. conceived the study, developed the methodology and wrote the article. J.A. performed laboratory tasks, collected and curated the data, and drafted preliminary reports. E.J.M.-A coordinated field surveys and performed the statistical analysis. All authors reviewed and approved the final manuscript.

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## CONFLICT OF INTEREST

The authors declared that they have no conflict of interest.

## DATA AVAILABILITY STATEMENT

The datasets generated during and/or analysed during the current study are available in a public repository (<https://doi.org/10.34810/data162>).

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