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A multidimensional study on population size, deadwood relationship and allometric variation of *Lucanus cervus* through citizen science

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Abstract

1. The European stag beetle, *Lucanus cervus*, is the largest saproxylic beetle and a flagship species whose populations should be monitored according to the EU Habitats Directive. Different studies have addressed its abundance and phenology, its relationship with deadwood, or the allometry of males related to different reproductive strategies. While monitoring efforts are complicated by the limited phenological window of adults (active at dusk during a few weeks), different innovative strategies have been tested in the last few years, with a promising role of citizen science.
2. We tested the possibility of characterising key dimensions of a *L. cervus* population of an Italian Natural Park by involving a network of citizen scientists in a two-week sampling campaign along standardised sampling transects, using a capture-mark-recapture (CMR) approach. We investigated its relationship with deadwood at different sites, estimated population size with a Bayesian analysis and characterised the allometric variation by assembling a dataset of morphological traits.
3. With the participation of 41 volunteers, we collected and measured 651 individuals along four sampling transects. Our analyses uncovered a large *L. cervus* population (estimated to consist of almost 3400 individuals), characterising its relationship with deadwood availability in different areas, and the absence of the expected male allometry.
4. Our results suggest that even a woodland composed by relatively young trees can host a large *L. cervus* populations if cut deadwood of suitable size is available. The engagement of volunteers, to which the results were presented, proved crucial to cost-efficiently study different key ecological aspects of an insect species with a short phenology.

KEYWORDS
capture-mark-recapture (CMR), citizen science, Coleoptera, European stag beetle, forest management, linear morphometry, Lucanidae, saproxylic fauna

Daniele Giannetti and Enrico Schifani contributed equally.

INTRODUCTION

Saproxylic species, among which insects are vastly represented, depend on damaged or decaying woody material from weakened, living, or dead trees during at least part of their life cycle (Carpaneto et al., 2015; Stokland et al., 2012). They correspond up to a quarter of forest biodiversity (Campanaro et al., 2016; Siitonen, 2001), playing an essential role in decomposition processes and carbon and nutrient cycling (Bobiec et al., 2005; Graf et al., 2022; Harmon et al., 1986; Stokland et al., 2012). At the same time, saproxylic species are highly sensitive to forest management. Several species have become endangered due to management practises leading to a decrease in the volume of deadwood available in European forests that caused small and large-scale extinction of many taxa (e.g., Bobiec et al., 2005; Campanaro et al., 2016; Carpaneto et al., 2015; Grove, 2002; Hagge et al., 2021; Nieto & Alexander, 2010; Stokland et al., 2012; Seibold et al., 2015).

The Holarctic genus *Lucanus* (Coleoptera, Lucanidae) accounts for some 70 species, mostly distributed in Eurasia, ranging from the Iberian Peninsula to Japan and Indochina, and whose larvae develop in decaying wood. In Europe, five different species have so far been recorded: *Lucanus barbarossa* Fabricius, 1801, *Lucanus cervus* (Linnaeus, 1758), *Lucanus pontbrianti* Mulsant, 1839, *Lucanus tetraodon* Thunberg, 1806 and *Lucanus ibericus* Motschulsky, 1845 (Bardiani et al., 2017). *L. cervus* is the largest saproxylic beetle of the continent. It is considered a flagship species and it is a protected species under the European Habitats Directive, which asks Member States to monitor the conservation status of the species at national level (Council Directive 92/43/EEC of 21 May 1992, Bardiani et al., 2017; Campanaro et al., 2016; Harvey et al., 2011; Thomaes, 2008).

As it happens with other stag beetles (Kawano, 2000), *L. cervus* exhibits a strong sexual dimorphism: males have large ("exaggerated") mandibles, clearly surpassing the head length, while the opposite is observed in females (Clark, 1977). Males' mandibles represent a secondary sexual character, mainly used as weapons during intrasexual fights in which opponents fight each other on the logs and tree trunks for mating access (Romiti et al., 2016). However, besides sexual dimorphism, *L. cervus* is also characterised by a remarkable male inter- and intra-population polymorphism, whose study has attracted significant attention (Clark, 1977; Hardersen et al., 2011; Kawano, 2000; Romiti, De Zan, et al., 2017; Romiti et al., 2015, 2016). In particular, an 'exaggerated' allometric development of larger mandibles in larger males correlates with a better fighting success but requires their larvae to digest more or higher-quality food, and may facilitate predation by vertebrates during the adult stage (Hardersen et al., 2011; Knell et al., 2004; Songvorawit et al., 2022).

To explore different aspects, such as population size, habitat requirements or allometry, monitoring efforts focusing on this species have explored a variety of methods. These included observing or collecting remains of predations or living individuals along transects, using baited and aerial traps, and have recently started to rely on citizen science (Bardiani et al., 2017; Chiari et al., 2014; Romiti et al., 2016; Thomaes et al., 2021). The latter allows to obtain large data despite the difficulties related to the fact that the activity peak of the beetle is mostly restricted to a few weeks of June and July and the species is mostly active at dusk (Bardiani et al., 2017; Campanaro & Bardiani, 2012; Campanaro et al., 2011; Chiari et al., 2014; Della Rocca et al., 2020; Rink & Sinsch, 2007; Romiti, Bissattini, et al., 2017; Romiti, De Zan, et al., 2017; Thomaes et al., 2017, 2021; Tini, Bardiani, Campanaro, Chiari, et al., 2017).

In our study, we tested the viability of studying three key ecological aspects of a *L. cervus* population from an Italian Natural Park in a single two-weeks sampling campaign along standardised sampling transects. We employed a capture-mark-recapture (CMR) approach, and organised data collection based on the involvement of a network of citizen scientists with the following aims: (i) studying its relationship with deadwood availability and characteristics across different sites of the same woodland; (ii) estimating the population size through a Bayesian analysis; (iii) characterising the allometric variation of males and assemble a dataset of morphological traits.

MATERIALS AND METHODS

Study area

Our investigation focused on the woodland of the Regional Park 'Parco Regionale Boschi di Carrega' from Northern Italy (Emilia-Romagna, Parma Province), managed by the 'Managing Authority for the Parks and Biodiversity—Western Emilia'. The area is protected since 1982, with the establishment of the first Natural Park of the region and corresponds to a Special Area of Conservation (ZSC IT4020001) according to the EU Habitat Directive. It extends between the Taro River and the Baganza streams, over about 1270 ha which are mostly covered by a deciduous woodland, representing a significant forest fragment within the highly modified environment of the Po Plain in which agriculture is prevalent. Before becoming a protected area, the woodland has been coppiced for about a century. Inside the woodland, we selected four sites of 1 ha each characterised by deciduous oak forest dominated by *Quercus cerris* L. and *Q. robur* L.: site (a) Bosco della Capannella (44°43′59.8″N, 10°12′25.8″ E), site (b) Conecofor (44°43′11.6″N, 10°12′14.8″ E), site (c) Monte Castione (44°42′30.7″N, 10°11′36.1″ E), site (d) Piana Marchesi (44°42′44.3″N, 10°12′01.4″ E). The minimum distance between the areas was 655 m (Sites a–d), while the maximum was 3.1 km (Sites a–c; Figure 1). Each of these areas was characterised by forest paths with light conditions at twilight sufficient to spot the stag beetles (Campanaro & Bardiani, 2012; Campanaro et al., 2016). The age of trees across the areas is relatively young, as they are averagely 50–60 years old, while the four differed markedly in terms of deadwood availability based on a preliminary survey.

Volunteer engagement

Italian Natural Parks often engage in dissemination and educational activities building a network of citizens and associations as a part of

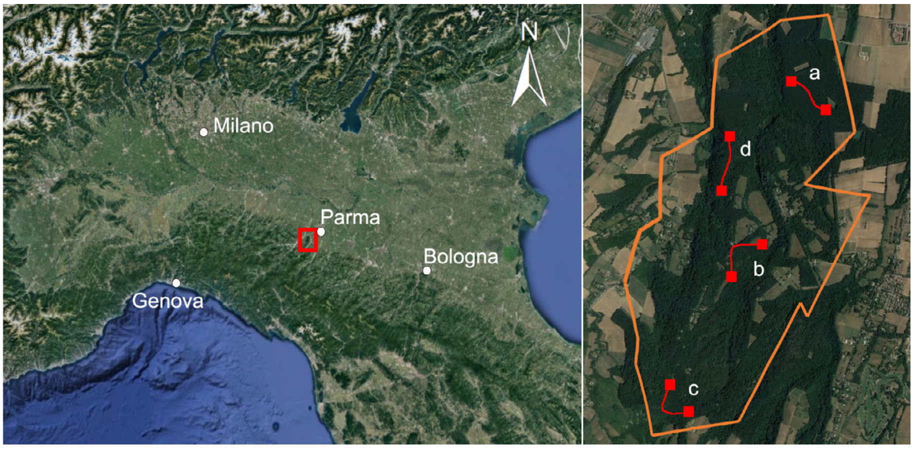

FIGURE 1 Study area in the Boschi di Carrega Natural Park (Emilia-Romagna, Italy). On the right, the four transects are indicated in red (site a, Bosco della Capannella; site b, Conecofor; site c, Monte Castione; site d Piana Marchesi).

their mission. The Regional Park "Parco Regionale Boschi di Carrega" recruited volunteers to raise citizens' awareness on the importance of the saproxylic fauna in woodland habitats and to monitor the *L. cervus* abundance in the park since 2018. We relied on this pre-existing network of volunteers as well as newcomers to conduct our monitoring activities. A total of 41 volunteers were involved, participating in preliminary training events dedicated to the general biology and ecology of *L. cervus* and to the CMR protocol. Lastly, researchers and volunteers met in a final meeting in which results were shared and discussed.

Sampling transects

We conducted our sampling following a standardised transect methodology (Bardiani et al., 2017; Campanaro et al., 2016). We identified four sites and one transect per site (sites a–d). Each transect was a 500 m long path, extending for 5 m on both sides of a linear trail (Figure 1). Each transect was divided into five sectors of 100 m each, and each sector was always inspected in approximately 6 min by a group of 2–4 volunteers (30 min for each transects). The group of volunteers shifted to different transect in different monitoring days. Transects were monitored every day from 13 July 2021 to 27 July 2021(14 days), starting 15 min before dusk time. Each volunteer group was equipped with an entomological net (circular frame Ø 50 cm) and a telescopic handle up to 2 m (following Romiti et al., 2016). The group of volunteers walked through the full transect three times, for a total of 90 min spent on every transect during each daily survey (all transects were investigated at the same time during each of the 14 sampling days). Every day, the starting point of the three walks alternated between the two ends of the transect. An expert was always present among the volunteers in all the transect during each sampling date, participating in data collection and taking care of data validation afterwards.

Capture-mark-recapture (CMR)

During each walk, volunteers carefully captured all seen *L. cervus* adults, with the exception of mating pairs, and placed them individually in breathable bags, which were labelled with a progressive number in addition to the following information: (i) specimen sex; (ii) transect of collection; (iii) position of collection (on the ground, on a tree, in flight >2 m high, in flight <2 m high; Figure 2).

After each sampling session, newly captured beetles (not already marked) were photographed with smartphones inside a 15 × 20 cm arena, using graph paper as a background to have a dimensional reference. Three pictures were taken: (i) whole insect in dorsal view; (ii) detail of the mandibles in dorsal view; (iii) whole insect in ventral view. This technique was used to reduce the sampling time (and consequent stress of the insects) compared to measuring with a calliper. Each beetle was then marked with a unique identification code using a non-toxic Pentel Paint-marker (Figure 2). The whole procedure of taking pictures and marking took approximately 1 min per specimen. Beetles that were already marked were not photographed if recaptured. All beetles were then released in the same section and transect of the original collection after 90 min at the base of different trees, to reduce the chances of contact.

Morphological data

We collected morphological data of the most widely used morphometric characters (Romiti, De Zan, et al., 2017) from all the captured beetles with the purpose of characterising male allometric variation of the population as well as producing a dataset available for future comparisons (Romiti, Bissattini, et al., 2017; Romiti, De Zan, et al., 2017; Romiti et al., 2015, 2016). Morphological observation was also key to confirm the species-rank identification of each specimen considering the possible presence of *L. tetraodon*, which has been reported in localised areas of northern Italy (Bardiani et al., 2017; Fabbri, 2009; Solano et al., 2016; Zilioli & Pittino, 2004).

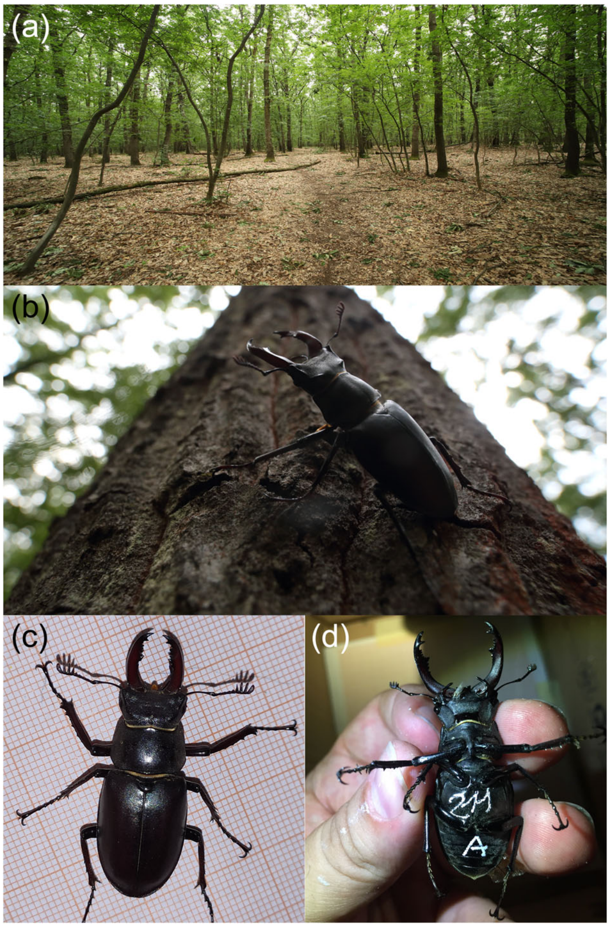

FIGURE 2 (a) sampling transect (site a); (b) a male *Lucanus cervus* on a tree trunk photographed before being captured; (c) a male of *L. cervus* photographed with smartphone using graph paper as a background to have a dimensional reference; (d) a male of *L. cervus* as it is marked before release.

TABLE 1 Number of *Lucanus cervus* individuals collected and recollected through the Capture-Mark-Recapture protocol divided per sex (site a, Bosco della Capannella; site b, Conecofor; site c, Monte Castione; site d Piana Marchesi).

	Captured	Recaptured once	Recaptured twice
Site (a)	288♂♂, 33♀♀	31♂♂, 4♀♀	2♂♂
Site (b)	169♂♂, 14♀♀	7♂♂, 1♀	–
Site (c)	48♂♂	–	–
Site (d)	82♂♂, 17♀♀	7♂♂, 1♀	–
Total	587♂♂, 64♀♀	45♂♂, 6♀♀	2♂♂

Photographed beetles were measured using the software ImageJ (Schneider et al., 2012) and the graph paper of each picture as a dimensional reference. Morphometric characters follow Romiti et al. (2015): Elytron length (EL), distance measured from the base of the scutellum to the apex of the elytra (i.e., including the scutellum size), across the suture; Elytron width (EW), EW: distance measured across the pronotal aspect of the elytra; Head length (HL), distance between

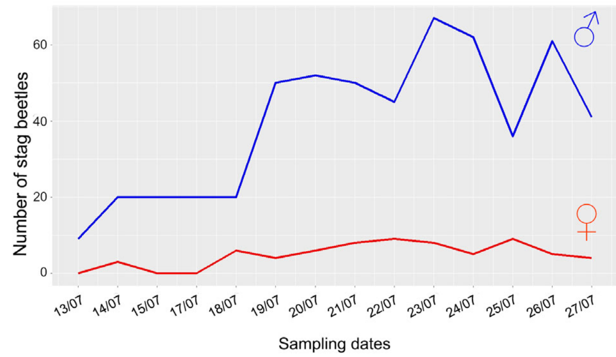

FIGURE 3 Number of *Lucanus cervus* individuals captured during each sampling date. Males are shown in blue and females in red.

the midpoint of the clypeus and the base of the head; Head width (HW), distance between the head ridges, measured above the eyes; Mandible length (ML), measured with sealed mandibles, distance from the clypeus to the distal tooth of the apical fork; Pronotum length (PL), distance measured across the midline. In addition, we annotated the following meristic characters: Number of mandibular dents (males only); Number of antennal articles.

Raw morphological data are available in the Table S1.

Deadwood estimate

To produce a precise quantification of deadwood availability at the four transects, around each transect, for 2.5 m on each side (total investigated area: 2500 m^2), we calculated the number of deadwood pieces on the ground according to the following three categories, which were adapted from those illustrated in the ForestBIOTA protocol by Travaglini et al. (2007): (i) small- to medium-sized branches (5 cm < Ø < 20 cm); (ii) large branches and tree trunks (Ø > 20 cm, generally dead trunks, often normally cut into shorter pieces); (iii) tree stumps. For each item, we measured its length and diameter (only considering the aboveground part for tree stumps), and we considered its volume as the product between the length and the circle area based on the diameter.

Statistical analyses

All statistical analyses were conducted using the software R 4.1.3 (R Core Team, 2021).

We analysed the relation between deadwood availability and the captures of *L. cervus* by running a multiple regression analysis with the R function glmer from the lme4 package (Bates et al., 2015). We used the number of individuals collected at each transect section as the dependent variable, and the number of deadwood items belonging to each of the three categories (tree stumps, large branches and tree trunks, small to medium-sized branches) as the independent variables, while treating the transect (A–D) as a random factor.

TABLE 2 Number of deadwood pieces and their volume measured in the four sampling sites (site a, Bosco della Capannella; site b, Conecofor; site c, Monte Castione; site d Piana Marchesi).

	Site (a)	Site (b)	Site (c)	Site (d)
Small- to medium-sized branches	$n = 235$, 1.75 m^3	$n = 187$, 1.30 m^3	$n = 238$, 1.36 m^3	$n = 217$, 0.95 m^3
Large branches and tree trunks	$n = 86$, 8.33 m^3	$n = 60$, 3.25 m^3	$n = 23$, 1.55 m^3	$n = 37$, 1.70 m^3
Tree stumps	$n = 59$, 0.71 m^3	$n = 50$, 0.25 m^3	$n = 40$, 0.29 m^3	$n = 20$, 0.30 m^3

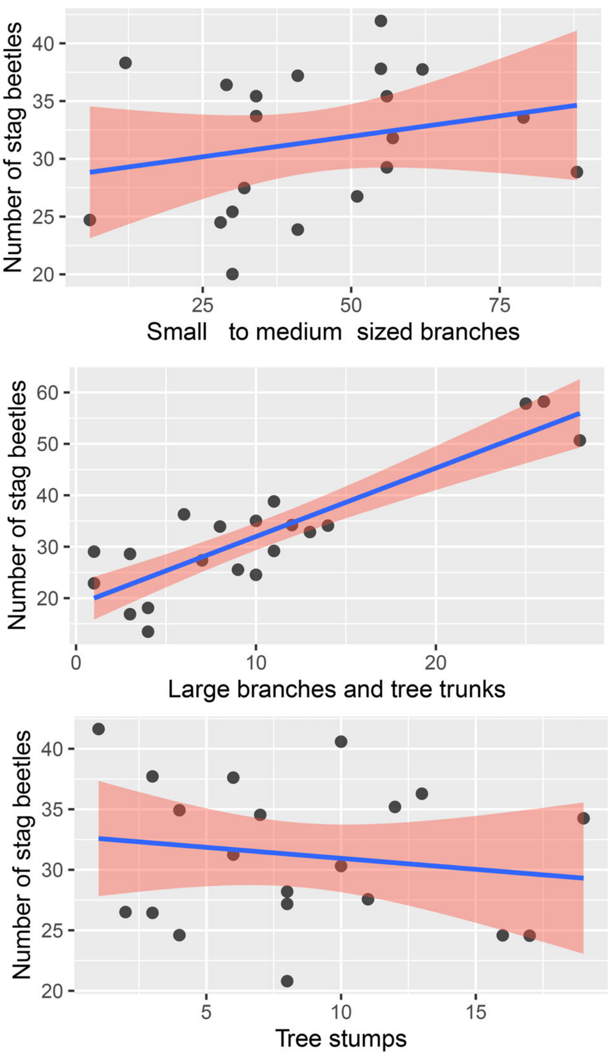

FIGURE 4 Result of the regression model illustrating the relationships between the number of *Lucanus cervus* individuals collected (Y-axis) and the number of deadwood pieces found in the same transect divided among the three categories (X-axis).

Male and female were analysed separately and population sizes for each sampling site were estimated by using a Bayesian approach according to Kéry & Schaub (2012, Chapter 6). Specifically, we fitted a model suited for closed populations, that is, assuming a sufficiently short sampling period such that populations are not affected by migration, immigration, births and deaths. The model allows for variation in time of detection probability, and it is known as 'M_t: Time Effects model' in Kéry and Schaub (2012). We used average daily temperature as a temporal covariate to model probability of capture. Daily temperature was first centred, subtracting the mean. Specifically, the model allowed for a variation in time of the intercept of capture probability (i.e., the capture probability when temperature was equal to the mean of all daily temperatures). The model changes the probability capture in a linear fashion depending on the daily temperature with a slope parameter estimated by the procedure. As suggested by Kéry and Schaub (2012), as a general procedure, we used the technique called *data augmentation* which basically converts the closed-population model into an occupancy model. Data augmentation does not have any effect on the estimates, but is more efficient (Kéry & Schaub, 2012). To do so we used R software with rstan version 2.26.9 and Stan version 2.26.1. Parts of R code to fit the Bayesian model in Stan was taken from the web site: https://github.com/stan-dev/example-models/tree/master/BPA made available by Hiroki Itô who translated the original WinBugs code by Kéry and Schaub to Stan. We run four independent Markov chains for 2000 iterations plus 1000 cycles of initial warmup and a thinning value of 5. Convergence and mixing were visually checked for every chain. Since the number of captured individuals were very different for the two sexes, the estimate of their population sizes was done separately.

An analysis of the allometric distribution was computed following Romiti, De Zan, et al. (2017): the scaling relationship between EL and ML traits was analysed using the linear and segmented regression models (segmented R package, Muggeo, 2008), with segmentation expected in case of a strong allometric trend as often observed in the species (Romiti, De Zan, et al., 2017). The Davies test was used to check for a change in slope in the fitted linear model (Davies, 1987), and the two models were further compared using AIC and BIC values. Morphometric characters were natural log transformed (log_e) before the analyses to allow for direct comparison with the results of Romiti, De Zan, et al. (2017).

RESULTS

Capture and recapture success, population phenology and demography

We captured 651 individuals of *L. cervus* (of which females represented 9.8%), of which 51 were recaptured once and 2 were recaptured twice (Table 1). No individual was ever recaptured in a transect different from that where it had first been captured. Furthermore, no individuals of *L. tetraodon* were found. Males were captured on trees (36%), in flight

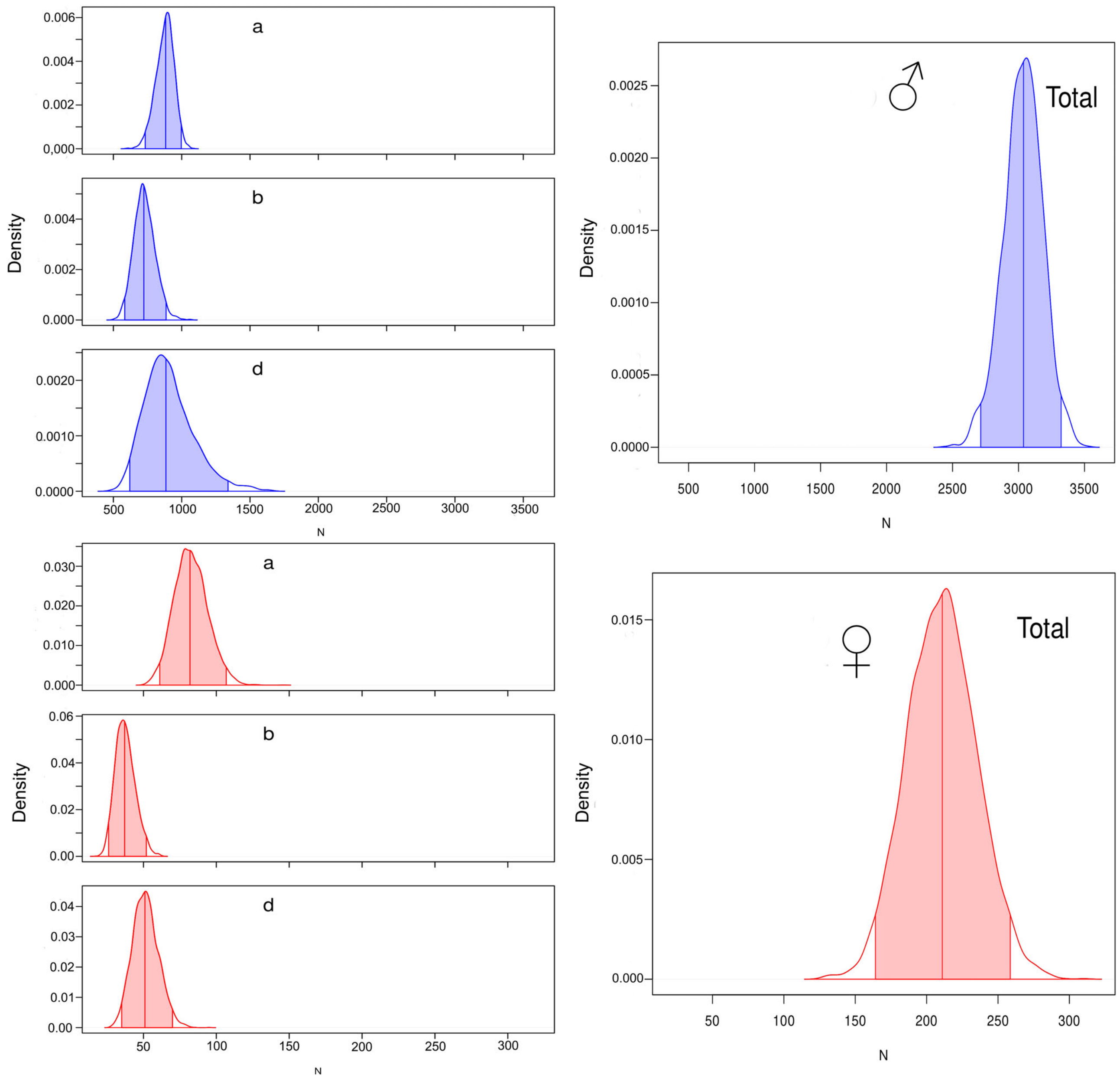

FIGURE 5 Density plot of the posterior distribution of total population size of *Lucanus cervus* and the population size in the three sites based on the Capture-Mark-Recapture data (site a, Bosco della Capannella; site b, Conecofor; site d, Piana Marechesi). The absence of any recapture for Site (c) did not allow any realistic estimates of population size in that area.

below 2 m (31%), on the ground (24%) or in flight above 2 m (8%). Females were mostly captured on trees (53%), or on the ground (31%), while more rarely in flight and only below 2 m (15%).

The daily number of captures varied from 9 to 67 for males (mean ± SD: 4.8 ± 3.2), and from 0 to 9 for females (mean ± SD: 39.5 ± 18.8) (Figure 3).

Deadwood influence on *L cervus* abundance

The number of deadwood pieces counted and measured was 1251 (21.8 m^3/ha). Small- to medium-sized branches included 877 items, while their diameter was 10 ± 4 cm and their length 60 ± 38 cm (mean ± SD), for a total volume of 5.4 m^3/ha. Large branches and tree trunks deadwood included 206 items, while their diameter was 29 ± 6 cm and their length 107 ± 129 cm, for a total volume of 14.9 m^3/ha. Finally, tree stumps included 168 items, while their diameter was 27 ± 10 cm and their length 14 ± 4 cm, for a total volume of 1.5 m^3/ha. The distribution of deadwood pieces in the different sampling sites is illustrated in Table 2.

We detected a highly significant relationship between the number of *L. cervus* individuals collected and the number of large branches and tree trunks ($\chi^2 = 6.95$, $p = 0.008$), a weaker relationship with small to medium-sized branches ($\chi^2 = 5.07$, $p = 0.024$),

TABLE 3 The value estimated by the Bayesian procedure to evaluate the population of *Lucanus cervus* (male and female) in the field sites (site a, Bosco della Capannella; site b, Conecofor; site c, Monte Castione; site d Piana Marchesi).

Area	Sex	Mean *N*	Std. err.	2.5 percentile	97.5 percentile
Site (a)	♂♂	877	3.28	733	923
	♀♀	83	0.31	61	107
Site (b)	♂♂	727	4.01	582	777
	♀♀	38	0.25	26	52
Site (c)	–	–	–	–	–
Site (d)	♂♂	907	8.52	618	1341
	♀♀	52	0.27	35	70
Total	♂♂	3034	7.45	2712	3134
	♀♀	211	1.16	194	259

and no significant relationship with tree stumps ($\chi^2 = 0.11$, $p = 0.735$; See Figure 4).

Population size estimate across different sites

All Bayesian runs of the model to predict population sizes of *L. cervus* populations seem to produce sensible results, with good mixing and convergence to stable parameters values. The analyses were carried out separately for each site except site (c), as no recaptures occurred there. Moreover, we carried out an additional round of analyses on capture and recapture data from all four sites together. Resulting estimated values for the individual populations are shown in Figure 5 and Table 3.

As expected from capture and recapture data, the Bayesian procedure estimated a much higher population size for males with respect to females (Table 3 and Figure 5). The estimated sizes were on the same order of magnitude for the three populations where recaptures were recorded (the mean male population size ranged from 727 of Site b to 907 of Site d). Estimated female population sizes are and order of magnitude lower, ranging from 38 of Site (b) to 83 in Site (a) (Table 3 and Figure 5). The uncertainty measured by standard errors about this numbers were quite low (Table 3). Credible intervals are reported in Table 3.

Air daily temperature seems to significantly affect the probability of capture of both male and females. Looking the overall population the estimated slope of the linear relationship (*beta*) between these two variables is positive and higher for females than males (Figure 6).

Morphology and male allometry

Prior to their logarithmic transformation, ML data were normally distributed ($W = 0.94$, $p < 0.001$), while EL data were not ($W = 0.99$, $p = 0.081$). However, after logarithmic transformation, both EL and ML variables were normally distributed (LnEL: $W = 0.99$, $p = 0.003$; LnML: $W = 0.99$, $p = 0.004$).

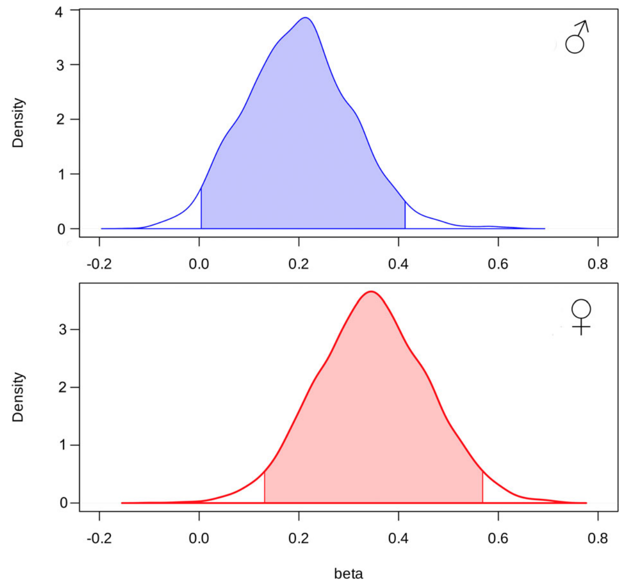

FIGURE 6 Density plot of the posterior distribution of slope (beta) of the linear relationship between centred daily temperature and probability of capture based on data from all samples from the four sites.

A simple regression test supported the relation between LnML and LnEL to be very significant ($t1,571 = 17.43$, $p < 0.001$, $R2 = 0.35$), while the significance was lower in a segmented regression test ($t1,569 = 2.31$, $p = 0.021$, $R2 = 0.34$). Also the Davies' test did not support the existence of a significant slope change ($k = 1000$, $p = 1.000$), and AIC and BIC values of the two models indicated a better fit for the simple regression model as compared to the segmented regression (AIC: −105 vs. −102; BIC: −92 vs. −80). See Figure 7.

DISCUSSION

During our two-week sampling campaign, we collected a remarkably high number of *L. cervus* individuals (651), much greater than usually reported in other studies. For instance, the average number of collected individuals among sampling campaigns conducted across 23 sites in seven European countries was 123 (Bardiani et al., 2017; Chiari et al., 2014; Della Rocca et al., 2020; Méndez & Thomaes, 2021). These results may be largely dependent on different sampling methodologies employed across these studies. However, we suggest that the 'Parchi di Carrega' Regional Park may represent an important and so far overlooked site for the conservation of this species in the Po Plain, highlighting the efficiency of the sampling protocol we applied in collaboration with volunteers (Campanaro et al., 2016; Castracani et al., 2020; Chandler et al., 2017). As expected, most of the captured individuals were males, which were more frequently encountered in flight compared to females, probably due to their greater tendency to disperse (Rink & Sinsch, 2007) and to fly more intensively to search for females (Tini, Bardiani, Campanaro, Chiari, et al., 2017). Since females disperse less and

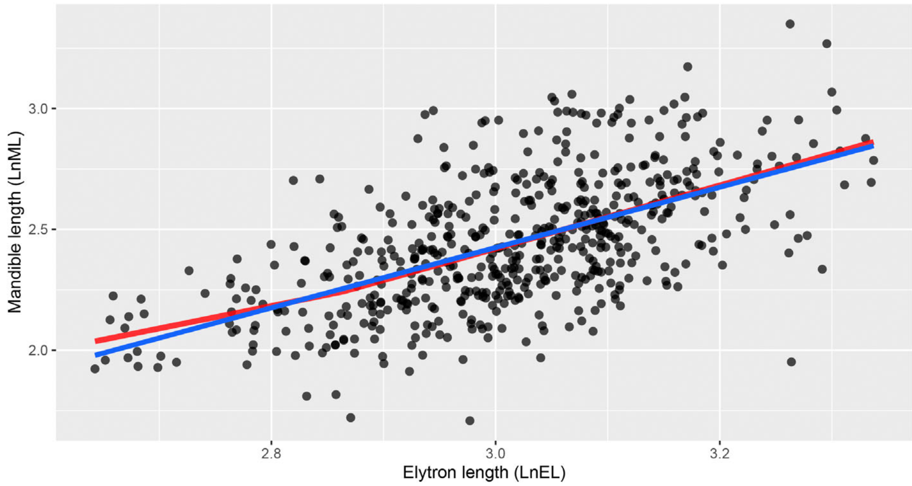

FIGURE 7 Relationship between logarithmically transformed values of mandible length (LnML) and elytron length (LnEL) of the captured *Lucanus cervus* individuals according to the simple regression (blue) and segmented regression (red) models.

may spend more time hiding and searching for suitable oviposition sites on ground, a sampling bias against them may be possible (Tini et al., 2018). Higher temperatures increased capture probability (Campanaro et al., 2016). No long distance dispersal between different sites of the woodland was detected, and the number of captured *L. cervus* individuals greatly varied between them.

While the areas were largely similar in terms of vegetation and climate, their strong differences in deadwood availability were found to correlate well with the presence of *L. cervus*. In particular, our analyses suggest that a higher abundance of large branches and tree trunks favours *L. cervus*, while small to medium-sized branches may play a minor role and tree stumps do not play a significant role in the investigated areas. The importance of large deadwood pieces such as large branches and tree trunks for the reproductive success of *L. cervus* was expected. A reason lies in the amount of food these can offer to the larvae, since its larvae need to feed up to 250 cm^3 of deadwood per month (Hendriks & Méndez, 2018; Tochtermann, 1987) and normally develop within the same deadwood piece in which they hatched and started to dig their galleries. However, microclimatic conditions and sheltering opportunities are also expected to differ markedly between deadwood pieces of different size. While tree stumps were abundant in the investigated areas and can also play a significant role (Hendriks & Méndez, 2018; Tini, Bardiani, Campanaro, Mason, et al., 2017), local characteristics such as soil humidity may influence their viability for saproxylic beetles (Ols et al., 2013). Moreover, the importance of lying dead trees and old living trees with extensive portion of deadwood is often emphasised (e.g., Tochtermann, 1992), yet our study area lacked living trees with such characteristics and lying dead trees were exceptionally rare. The abundance of larger deadwood fragments was essentially the product of the organised tree-cutting activity conducted by the Park's forest service, which resulted in relatively short deadwood pieces, whose length was of 1 m on average.

A peculiar trait of the *L. cervus* population we investigated was the remarkable lack of a usual allometric distribution, and in particular, the absence of large-sized male morphs with exaggerated mandibles. The distribution of *L. cervus* populations along a dimorphic allometric trend is highly variable due to local factors, and perhaps influenced by climate (Romiti, De Zan, et al., 2017). The latitudinal gradient hypothesis proposed by Romiti, De Zan, et al. (2017) does not explain the condition we encountered in our study area, situated in between sites where Romiti, De Zan, et al. (2017) recorded marked allometric trends. On the other hand, since the size and allometry of males is the product of the quantity and quality of food ingested during larval development, it is possible that a role was played by deadwood characteristics in the study area, such as the aforementioned lack of naturally decaying wood from old trees or the scarcity of lying dead trees providing a very large amount of deadwood volume in a single piece. At the same time, given the behavioural and evolutionary dimensions of the different strategies associated with the morphological variation of male stag beetles, eco-ethological implications of these characteristics deserve further studies.

The CMR protocol allowed us to compare the abundance of *L. cervus* at the investigated sites by obtaining for the first time populations size estimates based on the standardised transect protocol (Campanaro et al., 2016), instead of trapping (Chiari et al., 2014). Population size estimates through CMR protocols are highly valuable tools for species monitoring due to the quality of data obtained, yet in most other investigations on *L. cervus* using CMR the obtained data were not analysed to compute a population estimate (e.g., Fremlin, 2008; Hawes, 2008). Compared to the only other CMR-based population size estimate on this species performed by Chiari et al. (2014), we detected a larger disparity between sexes, with a smaller proportion of females: while 25 females and 111 males (0.22 f/m ratio) were found by Chiari et al. (2014), we found 64 females and 587 males (0.11 f/m ratio). However, the low number of female captures and recaptures in both studies may pose a problem to the statistical accuracy of these predictions. Relying on the participation of citizen scientists was key to managing the time consumption costs associated with such methodology. We encourage the use of CMR in combination with a citizen science approach to data collection in order to overcome the necessity of a large amount of data necessary for reliable estimates of population size. Our approach may be considered as a monitoring method for the aims of Habitats Directive reporting, as a valid alternative to visual encounter surveys (Bardiani et al., 2017; Campanaro et al., 2016; Campanaro & Bardiani, 2012) or tree surveys (Della Rocca et al., 2020). In this regard, we plan to submit our method to ISPRA (Italian National Institute for Environmental Protection and Research), the agency of the Environment Minister in charge of the Article 17 reporting for the Habitats Directive, as a complementary protocol for monitoring the conservation status of *L. cervus*. The engagement of citizen scientists in the sampling activity of a protected species should always include a careful training. Moreover, it is important to outline that the engagement of citizens does not only produce important data for conservation (Chandler et al., 2017, Zapponi et al., 2017), but also impacts and benefits at the social level (Turrini et al., 2018): increasing awareness of the protection of insects and old forests, educating to the ecology and biology of insects, disseminating conservation measures carried out in protected areas.

CONCLUSION

We succeeded in characterising multiple separate aspects of a *L. cervus* population during a short sampling campaign alongside a network of citizens. The population we studied resulted to be numerous and constituted by averagely small-sized individuals (estimated to be almost 3400). The cost-efficiency of this effort was achieved only thanks to the involvement of citizen scientists in the data collection process. The results support the hypothesis that a woodland composed by relatively young trees can host a significantly large population of *L. cervus* if its management makes a sufficient amount and quality of deadwood available for larval development. This may open up interesting opportunities to the conservation of *L. cervus* as compared to other saproxylic species that strictly require more natural environmental conditions and older forests to thrive, including several whose conservation status is less favourable (e.g., Bosso et al., 2018; Carpaneto et al., 2015; Russo et al., 2011).

AUTHOR CONTRIBUTIONS

Daniele Giannetti: Conceptualization; investigation; writing – original draft; methodology; data curation; formal analysis; visualization; software. **Enrico Schifani:** Conceptualization; writing – original draft; validation; methodology; formal analysis; data curation; visualization; software. **Stefano Leonardi:** Formal analysis; validation; data curation; methodology; writing – review and editing; software. **Emanuele Fior:** Writing – review and editing; investigation; resources; funding acquisition; methodology; validation. **Silvia Sangiorgi:** Investigation; writing – review and editing; data curation. **Cristina Castracani:** Writing – review and editing; supervision; validation; methodology. **Marco Bardiani:** Writing – review and editing; supervision; methodology; validation. **Alessandro Campanaro:** Supervision; writing – review and editing; methodology; validation. **Donato A. Grasso:** Conceptualization; methodology; funding acquisition; writing – review and editing; project administration; supervision; resources; validation.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1: Supporting Information.

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