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Can we successfully monitor a population density decline of elusive invertebrates? A statistical power analysis on *Lucanus cervus*

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Abstract

Monitoring global biodiversity is essential for understanding and countering its current loss. However, monitoring of many species is hindered by their difficult detection due to crepuscular activity, hidden phases of the life cycle, short activity period and low population density. Few statistical power analyses of declining trends have been published for terrestrial invertebrates. Consequently, no knowledge exists of the success rate of monitoring elusive invertebrates. Here data from monitoring transects of the European stag beetle, *Lucanus cervus*, is used to investigate whether the population trend of this elusive species can be adequately monitored. Data from studies in UK, Switzerland and Germany were compiled to parameterize a simulation model explaining the stag beetle abundance as a function of temperature and seasonality. A Monte-Carlo simulation was used to evaluate the effort needed to detect a population abundance decline of 1%/year over a period of 12 years. To reveal such a decline, at least 240 1-hour transect walks on 40 to 100 transects need to be implemented in weekly intervals during warm evenings. It is concluded that monitoring of stag beetles is feasible and the effort is not greater than that which has been found for other invertebrates. Based on this example, it is assumed that many other elusive species with similar life history traits can be monitored with moderate efforts. As saproxylic invertebrates account for a large share of the forest biodiversity, although many are elusive, it is proposed that at least some flagship species are included in monitoring programmes.

Keywords

Lucanus cervus, Natura 2000 monitoring, elusive saproxylic beetles, Monte-Carlo simulation, population decline

Introduction

Monitoring global biodiversity is essential for nature conservation in order to understand and counter its current loss due to anthropogenic disturbances (Jones et al. 2015; Lindenmayer and Likens 2010; Reynolds et al. 2011). However, it has often been argued that species selected for monitoring or conservation are biased towards more familiar species (Clark and May 2002; Franklin et al. 2011; Regan et al. 2008), while invertebrates are often under-represented (Cardoso et al. 2011; D'Amen et al. 2013; Leather 2013). Among other reasons, technical issues, i.e. the difficulty to monitor these species, have been argued. Bosso et al. (2013), for example, highlight the difficulty of monitoring the elusive *Rosalia alpina* due to difficult detection in forests and its short life span of adults while Roets et al. (2013) mention the nocturnal activity, hidden phases of the life cycle and short activity period for the *Colophon* stag beetle. A monitoring plan should be designed effectively and cost-efficiently (e.g. Lindenmayer and Likens 2010; Reynolds et al. 2011). Statistical power analysis is a widely acknowledged tool for that goal (Di Stefano 2003; La Morgia et al. 2015; Reynolds et al. 2011) in which a simulation is used to calculate the probability for correctly rejecting the null hypothesis (H0) when the alternative hypothesis (H1) is true with a given monitoring scenario. In other words, what is the chance of detecting a simulated decline? Monitoring of elusive species, in general, yields a low power (e.g. Jones et al. 2015; Steenweg et al. 2016; Williams and Thomas 2009). Unfortunately, only a few power analysis studies on the populations trends of terrestrial invertebrates have been published in the peer reviewed literature (Bried and Pellet 2012; Lang et al. 2016; Schmucki et al. 2016, all on butterflies). Consequently, the possibility of adequately monitoring the population trends of invertebrates in general and elusive invertebrates in particular has hardly been evaluated.

The European stag beetle, *Lucanus cervus* (further called the stag beetle), is a good model species to investigate whether the population trend of a strongly elusive terrestrial invertebrate can be adequately monitored. This saproxylic species is often considered as an umbrella species, representing the large saproxylic diversity inhabiting forests and half open landscapes (Luce 1996; Thomaes et al. 2008). The stag beetle is included in the second annex of the European Habitats Directive and consequently, species specific protection and monitoring is mandatory for every member state. As this species can only be observed during a very narrow time window (Campanaro et al. 2016; Harvey et al. 2011a), it can be argued that monitoring this species would yield insufficient data to evaluate its population trend. The stag beetle life cycle takes 3 to 5 years (Fremlin, Hendriks and Thomaes unpublished data, Rink and Sinsch 2008) which are spent mainly in underground dead wood. After eclosion in late summer, the adults overwinter in a quiescent stage and become active above ground for mating and dispersal next summer. After emergence, males live for about 8 weeks while females can live up to 12 weeks (Harvey et al. 2011a). Even then, the species remains mostly hidden underground, being active during a short period around sunset (Campanaro et al. 2016; Rink and Sinsch 2007). Furthermore, the activity of adults strongly depends on temperature (Harvey et al. 2011a; Rink and Sinsch 2011; Sprecher-Uebersax 2001; Thomaes et al. 2008). Finally, relative humidity, rain, wind speed and other weather variables have been found to influence the stag beetles' activity (e.g. Fremlin and Fremlin 2010; Rink and Sinsch 2007). However, as these variables are likely to be related to temperature and none of them has been tested in combination with temperature, conclusions should be interpreted carefully. Finally, the stag beetles' activity is suggested to depend on the moon cycle (Mader 2009) but this has not been confirmed by Sprecher-Uebersax (2001) and Campanaro et al. (2016).

Different monitoring protocols have been evaluated for the stag beetle: acoustic larval detection (Harvey et al. 2011b), baited or unbaited traps (e.g. Chiari et al. 2014) and direct observations of living and/or dead beetles along transects (e.g. Campanaro et al. 2011; Campanaro et al. 2016; Fremlin and Fremlin 2010; Mader 2009; Sprecher-Uebersax 2001). Vrezec et al. (2012b) found detection efficiency of evening transects (>90%) to be higher than that of trunk surveys and pit fall traps in the ground or attached to a tree (about 30–50%). Other techniques of trapping or indirect monitoring have also yielded poor results (Chiari et al. 2014; Harvey et al. 2011b). Consequently, a walked transect in the evening currently seems to be the best available sampling technique. As it is a generally well known species, a citizen science approach with many simultaneous transects is a feasible monitoring strategy (www.stagbeetlemonitoring.org). Few transects have been followed up nearly daily. In most cases, a weekly follow up has been used with a fixed day (e.g. Campanaro et al. 2011) or with a variable day depending on the weather (Campanaro et al. 2016). Finally, it can be argued whether monitoring days should be concentrated around the short activity peak or over a longer period (Campanaro et al. 2016; Fremlin and Fremlin 2010; Vrezec et al. 2012a). Due to the short activity period within a day, only one evening transect can be walked per observer and, due to the short season, only a limited number of days per year are suitable for monitoring, especially under colder climatic conditions. Consequently, cost efficiency is low and the power of such monitoring can be questioned.

Here, data have been used from three transects in north-western Europe which have been monitored nearly daily for seven up to ten years to parameterize a simulation model that estimates the stag beetles' relative abundance. This model is then adjusted to include a population decline of 1%/year and used for a Monte-Carlo simulation. This decline was derived from European guidelines (European Topic Centre on Biological Diversity 2011) which state that a population decline of more than 1%/year within 12 years (short term) or 24 years (long term) should result in a negative report for this species. Finally, different monitoring scenarios are evaluated using the simulated data in order to determine the effort needed to successfully detect this population decline (power analysis). We hypothesize that despite a very narrow window of activity and a high variability in abundance, the stag beetle can still be successfully monitored with a moderate monitoring cost when the monitoring scenario is adapted to the phenology of this species.

Materials and methods

Abbreviations

C-Season: Centred measurement for the day of the season which is equal in each year calculated as: (Julian date (1 to 365) – 170) /30

T-Season: Centred measurement for the day of the season but shifted based on the temperature of that specific year to accommodate a season that was triggered by a certain temperature calculated as: (Julian date (1 to 365) – first day with 18°C or more + 1) /30

MAB: Median absolute bias on the trend estimation calculated as the median value of the absolute difference between the trend introduced in the simulation and the trend estimated by the validation model.

Data

The data were compiled from three published studies on transects that have been monitored daily during the activity period of the stag beetle, i.e. mid-May till early July, for several years (Table 1, full data published as Thomaes et al. 2016). The first transect is located in Basel (Switzerland) and was monitored between 1991 and 2000. The transect was walked from 21:00h to 22:15h (see Sprecher-Uebersax 2001 for further details). The second transect lies in Colchester (UK) and was followed up from 2005 to 2011. Stag beetles were recorded along the transect from 21:00h till 22:00h (from 2008 onwards, the transect was shortened from 21:30h till 22:00h, see Fremlin and Fremlin 2010 for further details). The last transect lies in Tairnbach (Germany) and was followed up from 2008 to 2014. This transect was walked between 21:00h and 22:00h and stag beetles, amongst other insects, were recorded (see Mader 2009; Mader 2013 for further details). The three sites represent quite distant and extreme situations in north-western Europe: Colchester lies near the western distribution border of the species and comprises a very Atlantic climate; the site in Basel is situated at 262 m asl. and might represent a more mountainous population of this species while Tairnbach represents a more eastern situation for the populations in north-western Europe (although the species is found up to the Ural mountains). Furthermore, each site represents a different typical habitat for the species (Table 1). The methodology of slowly walking a short transect in about one hour is very similar for the three transects. However, these studies inevitably encompass small differences in monitoring protocol (e.g. length and duration of the transect walk and starting time) which were optimised to local conditions or needs. Nevertheless, it is believed that sampling methods were sufficiently consistent to provide reliable and comparable estimates of temporal variation in population abundance when the duration of the transect walk is used as offset. A similar method of combining monitoring data was used by Meyer et al. (2010). Weather data (air temperature, rain, wind, relative humidity and air pressure) during the transect walks were compiled from nearby weather stations (Basel: Lufthygieneamt

Table 1. Metadata of the stag beetle transect walks including location, longitude, latitude, altitude, start, end year, habitat, duration and reference to the protocol and number of transect walks (#).

Location	Long (°E)	Lat (°N)	Alt (m)	start year	end year	Habitat	Duration of transect walk	Reference for protocol	#
Tairnbach (Germany)	8.75	49.25	191	2008	2014	Forest edge	1h	Mader (2009)	681
Basel (Switzerland)	7.58	47.57	262	1991	2000	Park	1.25h	Sprecher-Uebersax (2001)	510
Colchester (UK)	0.88	51.88	28	2005	2011	Urban	0.5–1h	Fremlin and Fremlin (2010)	459

in Sprecher-Uebersax 2001, Colchester: http://www.tijou.co.uk in Fremlin and Fremlin 2010 & Tairnbach: http://www.worldweatheronline.com). Rain and air pressure data are not available for Basel. Moon cycle data were calculated as the visible part of the moon as a percentage (http://aa.usno.navy.mil/data/docs/MoonFraction.php). Data compilation resulted in 1610 transect walks.

Model selection

It is assumed that the number of individuals observed along the transects mirrors the local population density as there is no population density function available for this species. This situation is common for many monitored species (Reynolds et al. 2011). Two variants of a generalised additive model (GAM) with Poisson family and log link explaining the number of stag beetles observed during the 1610 transect walks were compared. The first part is identical for both model variants and includes an offset, the transect (Basel, Colchester, Tairnbach) and the year per transect interaction. The natural logarithm of the duration of the transect walk (in hours) was added as the offset term. In this way the models express the abundance per hour of monitoring rather than the observed abundance (Zuur et al. 2009). The interaction between year and transect will give the log-linear trend for each transect. The year was centred to the first year of the transect to enhance the numerical stability of the model.

As mentioned in the introduction, the stag beetle abundance shows a strong seasonal and temperature-dependent pattern. Therefore, the second part estimates the temperature effect using a spline smoother. This smoother was included to gain insight into the relationship between temperature and stag beetle abundance, being linear or multi-polynomial. The latter option is based on the observation that stag beetles' activity increases until they are fully active from 18°C onwards (Fremlin and Fremlin 2010; Harvey et al. 2011a; Hawes 2008; Rink and Sinsch 2007; Smit and Krekels 2008). To prevent that the smoother would fit every detailed random temperature effect, the maximum degrees of freedom was set to four. The third part of the model explains the seasonal effect using two different variants (C-Season or T-Season). C-Season represents a constant season over the different years. A centred measurement was used to enhance the numerical stability of the model calculated as the Julian date (1 to 365) minus 170 (as a mean value) and divided by 30 to get a result in approximated months. T-Season represents a shifted season based on the temperature of that specific year to accommodate a stag beetle season that is triggered by a certain temperature. Vrezec et al. (2012a) have argued that stag beetle emergence depends on the temperature resulting in such a shifting season. Therefore, the first day of T-Season was defined as the first transect day with 18°C or higher, resulting in a negative season before that day. Days of this shifted season were again divided by 30. C-Season or T-Season was included with a spline smoother (with a maximum of four degrees of freedom):

stag beetles ~ Intercept + offset (log(transect duration)) + transect + year:transect + s(temperature) + s(C-Season)

or

stag beetles ~ Intercept + offset (log(transect duration)) + transect + year:transect + s(temperature) + s(T-Season)

The two variants of the explanatory model were, in the first place, evaluated based on the analysis of the model residuals in relation to model variables. As both variants performed equally well, the best model was finally selected by the AIC criterion (see results). Model residuals were plotted against weather variables that were not used in the model (see section 2.1) and moon cycle data to detect any remaining variability and correlation coefficients were calculated to decide whether to include these variables in the explanatory model.

Monte-Carlo simulation of a 1% population decline

New data sets were created consisting of 10 up to 100 transects, with each transect simulated for 12 years (cfr. European Topic Centre on Biological Diversity 2011). Transects data was generated from 10 May till 4 July each year to accommodate an 8 weeks period that included the abundance peak of the stag beetle and that was mainly within the monitoring range of the original transects. The duration of the transect walk was set to 1 hour.

The observed temperature data was modelled with a generalised linear mixed model (GLMM) including season as a second degree polynomial as explanatory variable and transect and year as crossed random effects:

Temperature ~ Intercept-temperature + C-Season + C-Season^2 + (1|Transect) + (1|Year)

To generate simulated temperature data, the GLMM with the original coefficients was converted to a GLM by changing the random effects in normally distributed fixed effects with zero as mean and their sigma as variance. The auto-correlation was set to 0.7, based on visual and empirical interpretation (Suppl. material 1: Figure A.1). Further, we added a normal distributed random part to the intercept with zero mean and a low standard deviation (σ=0.01) between simulations.

The number of stag beetles observed per transect walk was simulated based on the selected explanatory model from the model selection. To facilitate the simulation, this GAM model was simplified to a GLM simulation model including a second degree polynomial of temperature and third degree polynomial of C-Season, based on the degrees of freedom in the original model. The third degree of temperature was not used in the simulation model as its significance in the explanatory model depended on the year:transect interaction and is therefore not an overall population characteristic but a statistical compensation for this interaction. Moreover, the temperature effect of a second or third degree polynomial on the number of stag beetles observed remains very similar (Suppl. material 1: Figure A.2). Year and transect were included as normally distributed fixed effects with zero as mean and their variance based on the explanatory model. Each transect was given a fixed trend which encompasses a 1% population decline per year (cfr. European Topic Centre on Biological Diversity 2011). The model can be presented as:

stag beetles ~ rpois(Expected count /transect duration)

$$\text{Log (Expected count /transect duration)} = \text{Intercept} + \text{transect}_i + \text{year}_j + \text{poly(temperature, 2)} + \text{poly(C-Season, 3)} + ((1-0.12)^{1/12}) * \text{year}$$

$$\text{transect}_i \sim \text{Normal}(0, \text{sd}_{\text{transect}})$$
$$\text{year}_j \sim \text{Normal}(0, \text{sd}_{\text{year}})$$

Statistical power analysis

Four monitoring scenarios (Weekly, Warmest of 7d, Peak temperature and Daily) were applied to the simulated data to comply with different monitoring protocols. In the Weekly scenario, each transect was monitored weekly during one up to eight weeks centred around the period with peak abundance. In the Warmest of 7d scenario, the transect was monitored on the warmest day of each week representing a monitoring protocol that depends on the weather forecast for the coming seven days. This is a simplification of the method proposed by Campanaro et al. (2016) where only the days from Monday till Thursday were used for monitoring. In the Peak temperature scenario, the monitoring started on the first day with a temperature of 18°C or higher and was continued for one up to eight consecutive days. These three scenarios (each including one up to eight days of monitoring per year and transect) were compared with a Daily scenario which includes daily monitoring during one up to eight weeks (7 to 56 days per year and transect).

On the subsets of data sampled with the different scenarios, a GLM validation model was fitted similar to the simulation model, but without year and transect effects to improve the processing time (they could be left out as these were centred around zero). If the subset included data of less than four weeks, then C-Season was left out of the validation model as the period is too short to fit the season effect properly. When modelling data from the Peak temperature scenario, both temperature and C-Season were left out of the validation model for the same reason. From each validation model, the parameter estimate and p-value for year were extracted.

Simulations were run 1000 times for each of the different simulation options, i.e. 10 to 100 transects (sample size), one to eight days/weeks of monitoring per year and transect (frequency) and for each of the four scenarios. Power (1 - type II error) was calculated as the percentages of $p<0.05$ (type I error) with parameter estimate <1 (i.e. prediction of a declining trend) for each of the simulation options. Based on these results, the minimum effort (= frequency * sample size) needed to reach a power > 90% was assessed. A threshold of 90% has been repeatedly suggested for reliable trend detection (e.g. Meyer et al. 2010; Steidl et al. 1997) in order to balance type II and type I errors (Di Stefano 2003). The median absolute bias on the trend estimation (MAB) for each scenario was also calculated to evaluate the accuracy of the trend estimation. MAB is sometimes used as an alternative for the power to optimise the effort of monitoring (Jones et al. 2015; La Morgia et al. 2015).

Finally, the power of three existing monitoring protocols was calculated: two in Flanders and one in Slovenia. In Flanders (Northern Belgium) a monitoring protocol for this species was designed including 36 transects and eight weeks of monitoring during the presumed warmest day of the week (Thomaes 2014), further called the Flanders scenario. As a start-up, this protocol was downscaled to 15 transects with three to eight weeks of monitoring (scenario Warmest of 7d) and 30 other transects that would be monitored only once a year (Flanders start-up). This downscaling was due to the fact that few volunteers have experience with stag beetles. It was simulated as three transects with eight, seven and six weeks of monitoring, two transects with five, four and three and 30 transects with one yearly random monitoring in a three week period around the abundance peak. In Slovenia, the monitoring includes two transects that are walked yearly plus eight that are walked every two years with three assessments within a period of about five weeks (Al Vrezec, pers. comm.). To assess its power, this protocol was implemented as a five week period with monitoring in the first, third and fifth week with the scenario Warmest of 7d. Al statistics were performed in R 3.3.1 (R Core Team, 2015) with mgcv, lme4 and ggplot2 as libraries (Wood 2011; Bates et al. 2014; Wickham 2009).

Results

Model selection

The model with C-Season had a lower AIC (7971) than the model variant with T-season (AIC = 8743) meaning that the hypotheses presented in Vrezec et al. (2012a) explaining the emergence of stag beetles at a certain temperature threshold could not

Table 2. Coefficients of the explanatory GAM model variant with lowest AIC which explains the stag beetle abundance. The table includes coefficients and their significance, estimated degrees of freedom for the smoothers of C-season and temperature and percentage deviation explained by the model (%dev. expl.: % deviation explained).

Coefficients						edf		%dev. expl.
Transect			Year x Transect			s(Temp)	s(C-Season)	
Basel	Colchester	Tairnbach	Basel	Colchester	Tairnbach			
-1.13***	0.24***	-0.11	-0.12***	0.11***	0.26***	2.898***	2.991***	47.4

***: <0.001

be confirmed. Therefore, the model variant with C-Season (Table 2 and Suppl. material 1: Figure A.3) was used as a selected explanatory model. The smoother for temperature (Suppl. material 1: Figure A.2) confirmed the finding that stag beetles are fully active from about 18°C onwards (see earlier). Model residuals showed no relation with other weather variables or moon cycle data (Suppl. material 1: Figure A.4), so no updates were made to include these variables in the explanatory model. As all these weather data were correlated with temperature (Suppl. material 1: Figure A.5), it can be assumed that temperature is a robust variable of weather conditions in general.

Statistical power analysis

Only with three of the four scenarios, a power of 90% was achievable but the effort and number of transects needed differed (Figure 1). The lowest effort to reach this power corresponded to the Warmest of 7d scenario with 80 transects and 2 days per year and transect (resulting in 160 days/y) (Figure 2). With the same scenario, many other options were possible to yield a power of 90% with 30 up to 100 transects with respectively 8 and 2 days per year and transect resulting in an effort between 180 and 240 days/y. The Weekly scenario required a slightly higher effort, at least 240 days/y with a combination of 80 transects and 3 days per year and transect. Again, many other options were also possible and only needed a slightly higher effort. The Daily scenario had the highest effort needed to reach a power of 90%. Here, an effort of 420 days/y was needed with a combination of either 20, 30 or 60 transects and respectively 3, 2 or 1 week of monitoring per year and transect. However, it was the only scenario that allowed successful monitoring with 20 transects. With the Peak temperature scenario, it was not possible to reach a power of 90%; with 100 transects and 8 days per year and transect, a power of 88.5% was reached. Based on the fairly coincidental lines in Figure 2, it is clear that the scenario and effort are of main importance to optimise the power, while the individual combinations of number of transects and frequency are of lesser importance.

The MAB criteria provided very similar results compared to the power (Suppl. material 1: Figure A.6). All scenarios with a power above 90%, yielded a low MAB (i.e. 0.01 to 0.04 or 1.4–3.7% of the real trend) and vice versa (Suppl. material 1: Figure A.7).

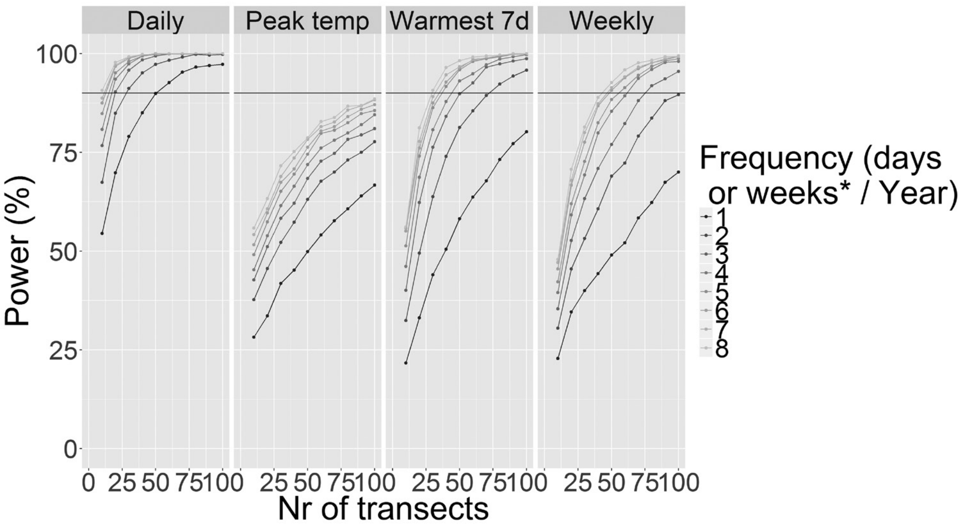

Figure 1. Statistical power for different scenarios, number of transects and frequency as number of days (for Peak temperature, Weekly and Warmest of 7d) or weeks (for Daily) per year and transect for monitoring the stag beetle (*Lucanus cervus*).

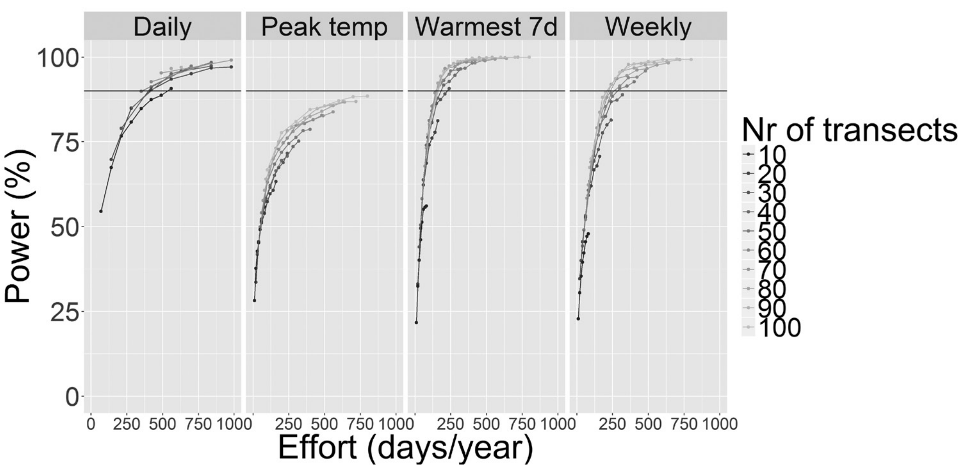

Figure 2. Statistical power for different scenarios, efforts as number of days/year (limited to 1000) and number of transects for monitoring the stag beetle (*Lucanus cervus*).

Thus, the MAB criteria yielded little additional insight for selecting the optimal scenario and effort.

The original monitoring for Flanders, Flanders scenario, yielded a power of 95% within 12y. The Flanders start-up scenario still had a power of 79%. The scenario of Slovenia, with only ten transects, yielded a power of 23%. This was quite low but, for a period of 24y the power increased to 81%.

Discussion

With the statistical power analysis presented, it was shown that it is at least feasible to monitor population density changes of the stag beetle with an effort of 240 days/y. This effort can be applied successfully with different combinations of scenarios, number of transects (between 30 and 100) and frequency. Before concluding which monitoring strategy and effort is most advisable to employ, the impact and alternatives for the missing density function, the limitations of the data used and the consequences of methods used for the results of the power analysis will be discussed first.

One of the main methodological problems for population trend analysis is the use of a relative abundance measure (here number of stag beetles found along a transect) to estimate the absolute population size (e.g. Bried and Pellet 2012; LaCommare et al. 2012; Williams and Thomas 2009). In many cases, the relationship between them is unknown and consequently a linear relationship must be assumed (LaCommare et al. 2012). Although a linear relationship might often be reasonable, several exceptions have been mentioned including differential population declines across sexes or life-history stages (Shea et al. 2006; Reynolds et al. 2011). For example, it is known that stag beetle transect walks are biased towards observations of male adults (e.g. Vrezec et al. 2012b). Consequently, threats affecting males in a selective way might result in an overestimate of the real population decline. Solutions that have been suggested to cope with this are distance sampling, mark-recapture procedures and presence-absence methods. Distance sampling is not realistic to apply to flying insects and mark-recapture procedures have yielded little recaptures for stag beetles (e.g. Chiari et al. 2014). Joseph et al. (2006) determined that for low density and hard-to-detect species, presence-absence methods equated or outperformed abundance methods at tracking changes in population size. For the stag beetle, this does not seem to be the case as the effort suggested by Campanaro et al. (2016) to assess the presence is 3 transect walks per year and transect which is comparable to some of our conclusions. However, presence-absence methods in general need many more transects than abundance methods so the overall effort will be higher.

The between-site variation on the number of the stag beetles observed is difficult to assess as only three sites have been monitored. Bart et al. (2004) mention that the variability in habitat and environment between sites is important when balancing the number of sites and monitoring frequency per site. As our three sites represent quite distant locations and habitats in north-western Europe, the results can be interpreted as based on maximal between-site variation and, consequently, as estimates of the outer limits of effort needed for monitoring the species in north-western Europe or countries within this region. Outside this region, the species response to temperature and season might differ and possibly also the effort needed to monitor it. LaCommare et al. (2012), Pais et al. (2014) and Jones et al. (2015) also concluded that the optimal monitoring strategy might differ across locations. Consequently, care must be taken when applying the results in other parts of the range of the species. For example, it might be expected that the species is less temperature restricted in warmer climates and consequently lower effort is needed. Furthermore, if the monitoring covers a large area, more variability between sites is likely to be expected and therefore more transects should be selected (Meyer et al. 2010; Pollock et al. 2002).

The most efficient way of monitoring the stag beetle seems to involve a scenario with weekly transects walks during the warmest evening. The scenario with transect walks concentrated after a first evening with 18°C or higher seems to have missed the period with abundance peak resulting in a very low power. Possibly, the stag beetle emergence in this region is triggered by lower temperatures and this causes the mismatch. However, if this peak period can be predicted, then the power of such a monitoring scenario might be much higher. When T-season is used in the simulation model instead of C-season, the Peak temperature scenario has the lowest effort needed to reach a power of 90% (results not shown). This is due to the fact that the simulation model and data sampling are then ideally tuned as both are based on the same hypothesis i.e. the period with abundance peak starts on the first evening with a temperature of 18°C. In reality, the start of this peak might be more complex and therefore more difficult to predict. Especially in different regions, stag beetle emergence might be expected to respond differently and thus different monitoring protocols might be needed for each region if this were to be applied. Consequently, it might be difficult to organise a large network of transects and instruct volunteers if the monitoring differs at each transect depending on the local temperature or climate zone. In that case, it might be easier to have transects that need to be walked weekly on the warmest day or even on a fixed day.

The Warmest of 7d scenario is simulated with the simplifications of a perfect weather forecast (i.e. the warmest evening is known at the beginning of the week) and so, in reality, the power might decrease slightly due to an imperfect weather forecast. However, as the power of the Weekly scenario is quite similar, this effect is expected to be limited. For more southern locations, this effect might be even smaller as days with unsuitable weather become rare.

An advantage of the Warmest of 7d above the Peak temperature scenario is that the effect of season remains evaluated. By this, changes in seasonality can also be detected. For example, climate change is expected to negatively affect the activity period (Rink and Sinsch 2011) which might not be detected with a Peak temperature scenario. Furthermore, data sampled in other periods (due to different monitoring strategies) or additional transect walks can still be included in the analysis as season and temperature remain in the validation model. This is not possible for the Peak temperature scenario where season and temperature are left out of the validation model and consequently balanced data is needed, thus making this scenario less robust (cfr. Schmucki et al. 2016).

Daily sampling clearly results in oversampling of a site in terms of population trend detection and is therefore not advised when trying to optimise the monitoring effort. However, this sampling technique might be very useful when only a limited number of transects is available or to study other population parameters, e.g. gaining insight into the period with peak abundance.

When comparing different options with the same effort, it seems that, in the presented simulation, the number of transects and frequency has little additional impact on the power. Thus, different combinations can be used to bring this monitoring into practice. Due to some simplifications that were included in the simulation, e.g. constant seasonal effects at all locations and equal decline at all sites, it is not advisable to use the lowest sufficient effort calculated but rather select a more robust estimate of the effort needed. Therefore, it is concluded that any combination with the Warmest of 7d scenario and an effort of minimal 240 days per year and between 40 and 100 transects can be used to realise the monitoring of this species to detect the given trend. A higher number of transects only slightly improves the power (cfr. Meyer et al. 2010). However, it is also important to take into account the costs for selecting and installing additional transects and finding and training volunteers (cfr. Jones et al. 2015; Lang et al. 2016; Williams and Thomas 2009). Therefore, it might be more realistic to realise only 40 transects with 6 days of monitoring per year and transect than 80 transects with 3 days per year and transect.

When comparing our results with other studies, it is concluded that the effort needed to monitor this elusive stag beetle (240 surveys/y) is not higher than for other invertebrates. Bried and Pellet (2012) concluded that the minimum allowable effort for occupancy monitoring of the Karner blue butterfly was 360 (40 sites x 9 surveys) for the spring generation and 200 (20 sites x 10 surveys) for the summer generation. Keizer-Vlek et al. (2012) found that more than 1000 sites must be sampled to detect a 40% change in the frequency for monitoring rare river inhabiting macroinvertebrates (50 sites for common species). Lang et al. (2016) found the need for about 600 to 2200 transect and four survey events to detect a population decline of frequent and rare butterflies respectively. However, as the scales, methods and detection thresholds differ, a one to one comparison is not possible.

Based on the current study, it is assumed that many other elusive species with similar life history traits can likely be monitored with a similar magnitude of effort. Many other stag beetles species share the short activity period, crepuscular activity and temperature dependence (e.g. Roets et al. 2013) and thus it is likely that comparable efforts are needed to study them. Other saproxylic beetles, like *Rosalia alpina*, *Morimus asper* or *Cerambyx cerdo* (all European Habitats Directive species), also share these life history traits despite being mainly monitored by trapping (respectively Bosso et al. 2013; Buse et al. 2008; Vrezec et al. 2012b) and consequently might need efforts of comparable magnitude.

It is concluded that it is possible to monitor a rather small population density decline of 1% per year for the elusive stag beetle with a moderate monitoring cost of 240 transect walks per year. Based on this example, it is assumed that many other elusive species with similar life history traits can be monitored with moderate efforts. This finding is especially important as saproxylic insects represent a large share of the total forest biodiversity (e.g. Müller et al. 2008, Horak et al. 2012) although many are elusive. Based on the current finding, we propose that at least some flagship species of this group are included in species monitoring programmes as their monitoring seems feasible.

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Supplementary material 1

Figures of statistical support

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Data type: statistical data

Explanation note: Different figures wich give statistical support to the paper. These figures are refered to within this paper.

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