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# Effect of Environmental Factors on Occurrence of Cockchafers (*Melolontha* spp.) in Forest Stands

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*Abstract*

Cockchafers (*Melolontha melolontha* and *Melolontha hippocastani*) are some of the most damaging forest insect pests in Europe. This study evaluated environmental factors that influence the occurrence of cockchafer grubs in forests, including location of the stand relative to open space, the stage of stand development, tree species composition, canopy openness, and cover of forest floor vegetation. To determine grub infestation in soil and to characterise forest stands, 300 sampling pits (1×0.5×0.5 m) were excavated in 12 stands in major centres of *Melolontha* spp. outbreak in Poland. A hurdle regression model was used to analyse the dependence of the occurrence of cockchafer grubs on environmental factors. Our results show that the boundary between open space and forest is associated with a significantly higher probability of occurrence of cockchafer grubs. Stands adjacent to meadows are particularly susceptible to infestation. The high numbers of grubs predicted by the model were observed in most stages of stand development. Characteristics associated with increased numbers of cockchafer grubs included moderate canopy openness (21–35%) and the presence of dense vegetation cover (>75%). Stands containing beech, birch and oak had slightly more cockchafers than stands containing pine, for which the predicted number of grubs was significantly lower.

**Key words:** Hurdle model, *Melolontha melolontha*, *Melolontha hippocastani*, Phytoclimate, Stand canopy openness, Stage of stand development.

## Introduction

Among the many insects that have substantial impacts on forest management in Europe, the cockchafers' genus *Melolontha* (Coleoptera, Scarabaeidae) are especially important. These include the common cockchafer *Melolontha melolontha* L. and the forest cockchafer *Melolontha hippocastani* F. (Švestka 2007, Woreta and Sukovata 2010, Wagenhoff et al. 2014). The distribution range of both species covers most of Europe. The area, in which the forest cockchafer occurs, is particularly large and extends to Mongolia, parts of Central Asia, and Siberia (Niemczyk and Neyko 2009). In Poland, both species occur at varied frequency throughout the country. However, the areas of their mass occurrence have increased a hundredfold over the last twenty years, to 125,799 ha in 2015 (Instytut Badawczy Leśnictwa 2016). Currently, the high population density of cockchafers threatens sustainability of forests in certain regions of Poland. Cockchafers are especially numerous in central and south-eastern Poland. In these regions both species of cockchafers occur in forests frequently.

*Melolontha* spp. have a 3- to 5-year life cycle; in Central Europe, the life cycle is typically four years (Švestka 2006, Sierpińska 2008). Their biology is very similar (Sukovata et al. 2015). During its life cycle, the insect undergoes a complete transformation characterised by varying morphology and behaviour at each life stage. Adult beetles feed in tree crowns, which causes defoliation, reduces photosynthetic capacity, and weakens the tree (Szujecki 1995). The larvae (grubs) are more problematic in forest management because they damage the roots of nursery plants, seedlings, and trees. According to the Instruction of Forest Protection (2012) 3 second instar grubs per 0.5 $m^2$ are likely to cause serious damage and economic losses in plantations and nurseries in areas with fertile soils. In areas with the poorest soils even 1 second instar larvae per sampled soil (0.5 $m^2$) is a critical number for young forest plantation.

The first records of cockchafer biology and of methods for reducing their populations in forests are from the 19th century, when the idea of planned forest management was introduced (Flatt 1829, Trąmpczyński 1856, Satkowski 1899). Since then, cockchafers have been acknowledged as one of the most serious forest insect pests, although their abundance changes periodically. The full outbreak cycle lasts for approximately 40 years (Altenkirch et al. 2002, Malinowski 2007), which means that the number of cockchafers in population has reasonably predictable patterns of change.

The current mass outbreak has more severe effects than previous occurrences, during which foresters had more options for controlling insect pests. In light of restrictions imposed on the application of chemicals for forest protection (EU Directive No. 91/414/EEC resulted in elimination of almost all insecticides used to control cockchafers), new (non-chemical) methods of controlling root pests are needed. Some research should focus on identifying environmental risk factors that increase the habitat value of forest ecosystems to cockchafers. Forest plant communities generate microclimates that affect the accessibility and attractiveness of the food source and of living conditions for cockchafer adults and grubs and their natural antagonists. In this context, it is important to investigate the ecological preferences of cockchafers so that silvicultural and forest protection measures that decrease the habitat value of forest ecosystems for this pest can be developed.

The aim of this study was to evaluate forest environmental factors, including stand location in relation to open space, the stage of stand development, species composition, canopy openness, cover of forest floor vegetation, and the influence of these factors on cockchafer abundance.

## Materials and Methods

***Study site***

Our research plots were located in three forest districts in south-eastern Poland: Ostrowiec Świętokrzyski (50°56’00” N 21°24’00” E), Lubaczów (50°09’33” N 23°07’19” E), and Narol (50°21’01” N 23°19’38” E). The mean annual temperature ranges from 7.2 °C in Lubaczów to 8.3 °C in Ostrowiec Św. The annual rainfall exceeds 700 mm in all research sites, and the growing season lasts for approximately 200 days. We selected these locations because the most important outbreak centres of cockchafers in Poland have occurred in these areas.

After preliminary verification of the most attractive habitats for cockchafers (Niemczyk 2012, 2013, 2015) we established plots in two types of forest sites: fresh mixed broadleaved forest and fresh broadleaved forest, in all stages of stand development. These stages included stand initiation (0–10 y), thicket (10–20 y), small pole stand (20–35 y), high pole stand (35–50 y), maturing stand (50–80 y), and mature stand (≥ 80 y).

***Study treatments***

In autumn 2012 and spring 2013, we evaluated the concentration of grubs in soil in 12 selected stands. In each stage of stand development, we chose two stands: one in fresh mixed broadleaved forest and the second in fresh broadleaved forest. During the study period, second-instar cockchafer larvae (L2) dominated in all the forest districts. The larvae of both cockchafer species are almost identical and there is no reliable diagnostic key that can be used for their discrimination (Krell 2004). Thus, the grubs counted in our study were only identified to genus level (*Melolontha* sp.) using the key presented by Sierpiński (1975). The instar was determined by measuring the width of the head capsule (L1: 2.6-2.7 mm, L2: 4.2-4.5 mm, L3: 6.5-6.9 mm) (Śliwa 1993).

In each stand, 25 sampling pits (1 × 0.5 m and at a depth at least of 0.5 m, (0.5 $m^2$); in accordance with Instruction of Forest Protection (2012)) were excavated in a network of 30 × 50 m to assess grub infestation in soil. The centre of the pit marked the centre of a 100-$m^2$ circular plot (5.65-m radius), in which vegetation cover (visual assessment in %) and species composition were recorded, including all trees with diameter at breast height (DBH) >7 cm. Hemispherical images were also taken, on each circular plot, to measure light conditions in the stand. To do this a Nikon D5000 camera with Sigma 4.5-mm F2.8 EX DC HSM circular fisheye lens, which creates a full 180° field of view, was used. The images were analysed using the Gap Light Analyser software (Frazer et al. 1999) based on thresholding; each pixel was classified as either sky (white) or non-sky (black) (Frazer et al. 1999). The consecutive step in the analysis calculated canopy openness as the percentage of total sky area in the forest overstory (Matusz 1960, Frazer et al. 1999).

***Statistical analysis***

The risk analysis of grub occurrence was performed using a regression approach. Observations with a score = 0 (i.e. no grubs) were made in 134 (45%) of 300 pits and were included in the analysis using hurdle generalised linear mixed models (hurdle-GLMM). The final hybrid model (hurdle regression) assumed a binomial distribution for modelling the occurrence of grubs, a negative binomial for modelling grub frequency (Xie et al. 2013), and a compound symmetry structure to determine the covariate matrices.

The probability of cockchafer occurrence (Model I) was modelled using binary logistic regression with a randomised structure of the covariance matrix based on the blocks defined by the sampling sections. For a number of positive results (Model II), a randomised negative binomial regression was used. The covariance blocks were calculated similarly as in Model I. Selection of the optimal model was made based on the generalised coefficient of determination. In addition, the global hypothesis regarding the equality of the effect of the risk drivers was examined, and a bootstrap method was used to adjust the confidence intervals.

We considered the following risk factors: stage of stand development; type of forest site; canopy openness; general vegetation cover; forest/meadow ecotone; and the presence of dominant tree species including Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.), English oak (*Quercus robur* L.), and silver birch (*Betula pendula* Roth.).

Because of the strong correlation between stand development stage and type of forest site, the latter was excluded from the model. This decision was based on the goodness-of-fit measure of the model as a whole.

Continuous scale factors, such as canopy openness and vegetation cover, were divided into categories. Canopy openness was classified into four intervals: 0–10%, 11–20%, 21–35% and 36–100%, taking into consideration ecological consequences such light conditions for plants and trees as well as number of observations in each interval. Vegetation cover was divided into four equal intervals. The analyses were performed using SAS software, version 12.3 (SAS Institute Inc., Cary, NC) with the significance level set at $\alpha = 0.05$.

## Results

### *Occurrence of cockchafer grubs in response to environmental factors*

During the study period the second instar larvae dominated (i.e. L2 = 96.2%, L1 = 1.2%, L3 = 2.6%).

Grub density varied among stands ($\alpha = 0.05$). The largest number of grubs was found in mature stands, whereas the occurrence of grubs was incidental in thickets (Table 1). The number of grubs in stands bordering open spaces (ecotones) was significantly higher than of stands in the forest interior. Understory light conditions in the stand (21–35% canopy openness) and dense vegetation cover (>76%) corresponded to increased numbers of grubs (Table 1).

**Table 1.** Average number of *Melolontha* spp. grubs per pit in relation to various environmental factors. Different letters indicate significant differences at $\alpha = 0.05$. *SE* denotes the standard error, Cl denotes confidence intervals, N = 300

| Environmental factors | | Number of grubs per pit | *SE* | 95% CI | 95% CI |
|---|---|---|---|---|---|
| Stage of stand development (years) | Stand initial stage 0–10 | 2.5 $^{bc}$ | 0.59 | 1.30 | 3.62 |
| | Thicket stage 11–20 | 0.1 $^{c}$ | 0.07 | 0.01 | 0.25 |
| | Small pole stand 21–35 | 4.6 $^{ab}$ | 0.78 | 3.03 | 6.09 |
| | High pole stand 36–50 | 2.6 $^{bc}$ | 0.50 | 1.60 | 3.56 |
| | Maturing stand 51–80 | 3.4 $^{b}$ | 0.85 | 1.75 | 5.09 |
| | Mature stand 80+ | 7.5 $^{a}$ | 1.17 | 5.20 | 9.80 |
| Forest/meadow ecotone | No | 1.7 $^{b}$ | 0.25 | 1.17 | 2.15 |
| | Yes | 5.9 $^{a}$ | 0.64 | 4.67 | 7.19 |
| Canopy openness (%) | 0–10 | 3.1 $^{ab}$ | 0.93 | 1.22 | 5.05 |
| | 11–20 | 3.3 $^{b}$ | 0.47 | 2.34 | 4.18 |
| | 21–35 | 5.9 $^{a}$ | 1.06 | 3.82 | 8.09 |
| | 36–100 | 2.3 $^{b}$ | 0.47 | 1.37 | 3.26 |
| Vegetation cover (%) | 0–25 | 0.8 $^{b}$ | 0.35 | 0.06 | 1.44 |
| | 26–50 | 2.3 $^{b}$ | 0.49 | 1.39 | 3.32 |
| | 51–75 | 2.4 $^{b}$ | 0.47 | 1.44 | 3.31 |
| | (76% +) | 5.0 $^{a}$ | 0.59 | 3.83 | 6.15 |

### *Modelling risk factors*

In Model I, which investigated the likelihood of occurrence of cockchafer grubs in the sampled soil (Figure 1), two factors were significant: the location of the stand in relation to open space (forest/meadow ecotone) and the stage of stand development (Table 2). The most threatened stages of stand development, in terms of the probability of grub occurrence, were high pole stands and stand initiation stage (model probability = 0.93 and 0.86, respectively). A high risk of cockchafer larvae occurrence was also estimated for small pole stands and mature stands (model probability = 0.77 and 0.43, respectively). However, the factor that was most significantly related to grub occurrence regardless of stand development stage was location relative to open area. The probability of grubs occurring in stands that were adjacent to meadows/open areas was significantly higher (model probability = 0.93) than that in interior stands (model probability = 0.15).

In Model II, the following factors were significant ($\alpha = 0.05$) in predicting the number of grubs in pits (in which grub occurrence was demonstrated in 166 of 300 pits): canopy openness, vegetation cover, and presence of Scots pine in the stand (Table 3). Among these factors, the largest number of grubs was predicted to occur in stands with canopy openness (during the

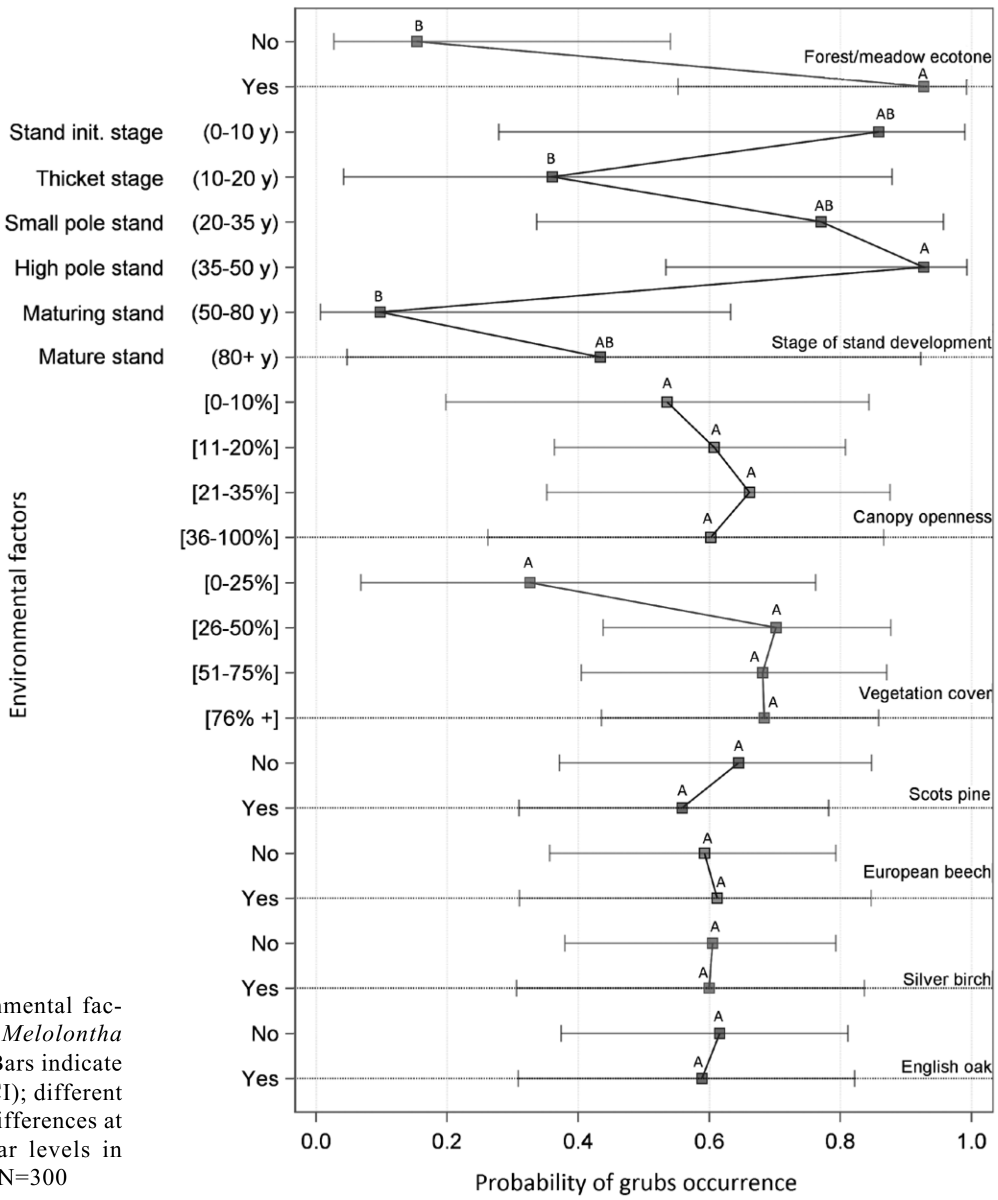


**Figure 1.** Effect of environmental factors on the probability of *Melolontha* presence in soil (Model I). Bars indicate 95% confidence intervals (CI); different letters indicate significant differences at $\alpha = 0.05$ between particular levels in each environmental factor, N=300

**Table 2.** Global *F*-test for Model I. Assumption $H_0$: probability of occurrence of *Melolontha* spp. grubs is equal for all levels in each environmental factor. Significant differences bolded ($p < 0.05$), N=300

| Environmental factor | Global *F*-test | *p*-value |
|---|---|---|
| Forest/meadow ecotone | **4.97** | **0.0266** |
| Stage of stand development | **2.34** | **0.0417** |
| Canopy openness (%) | 0.15 | 0.9271 |
| Vegetation cover (%) | 0.94 | 0.4209 |
| Scots pine | 0.54 | 0.4613 |
| European beech | 0.02 | 0.8877 |
| Silver birch | 0.002 | 0.9661 |
| English oak | 0.05 | 0.8168 |

**Table 3.** Global F-test for Model II. Assumption $H_0$: grub frequency is equal for all levels in each environmental factor. Significant differences bolded ($p < 0.05$), N=166.

| Environmental factor | Global *F*-test | *p*-value |
|---|---|---|
| Forest/meadow ecotone | 0.55 | 0.4577 |
| Stage of stand development | 1.04 | 0.3981 |
| Canopy openness | **6.50** | **0.0004** |
| Vegetation cover (%) | **4.10** | **0.008** |
| Scots pine | **24.40** | **<0.0001** |
| European beech | 3.24 | 0.0739 |
| Silver birch | 2.66 | 0.1049 |
| English oak | 2.50 | 0.1161 |

growing season) of 21–35% (predicted number of grubs per pit = 5.08). Fewer grubs were predicted for stands with gap light transmission of 11–20% or 36–100% (predicted number of grubs per pit = 3.93 and 3.44, respectively); the lowest numbers were estimated for the densest stands (light transmission <10%; predicted number of grubs per pit = 2.83).

Vegetation cover strongly influences the number of cockchafer grubs in stands by increasing the attractiveness of the feeding base. The modelled number of cockchafer grubs predicted per 0.25 m$^3$ increased with increasing plant cover (Figure 2). With regards to species composition of the stand, the tree species were differentially attractive to *Melolontha* spp. Deciduous trees (beech, birch, oak) slightly increased the attractiveness of the stand to cockchafers ($p > 0.05$), whereas the predicted number of grubs was significantly lower in stands with pine than in stands without pine (2.97 vs. 4.70) (Figure 2).

Although the stage of stand development was not a significant factor in Model II, and although the number of grubs did not differ among stages, most stages of stand development produced high-modelled values of soil infestation (Figure 2). The largest numbers of grubs were predicted for maturing stands, mature stands, and small pole stands (predicted number of grubs per pit = 5.63, 5.44, and 5.24, respectively). A high risk of infestation was also estimated for high pole

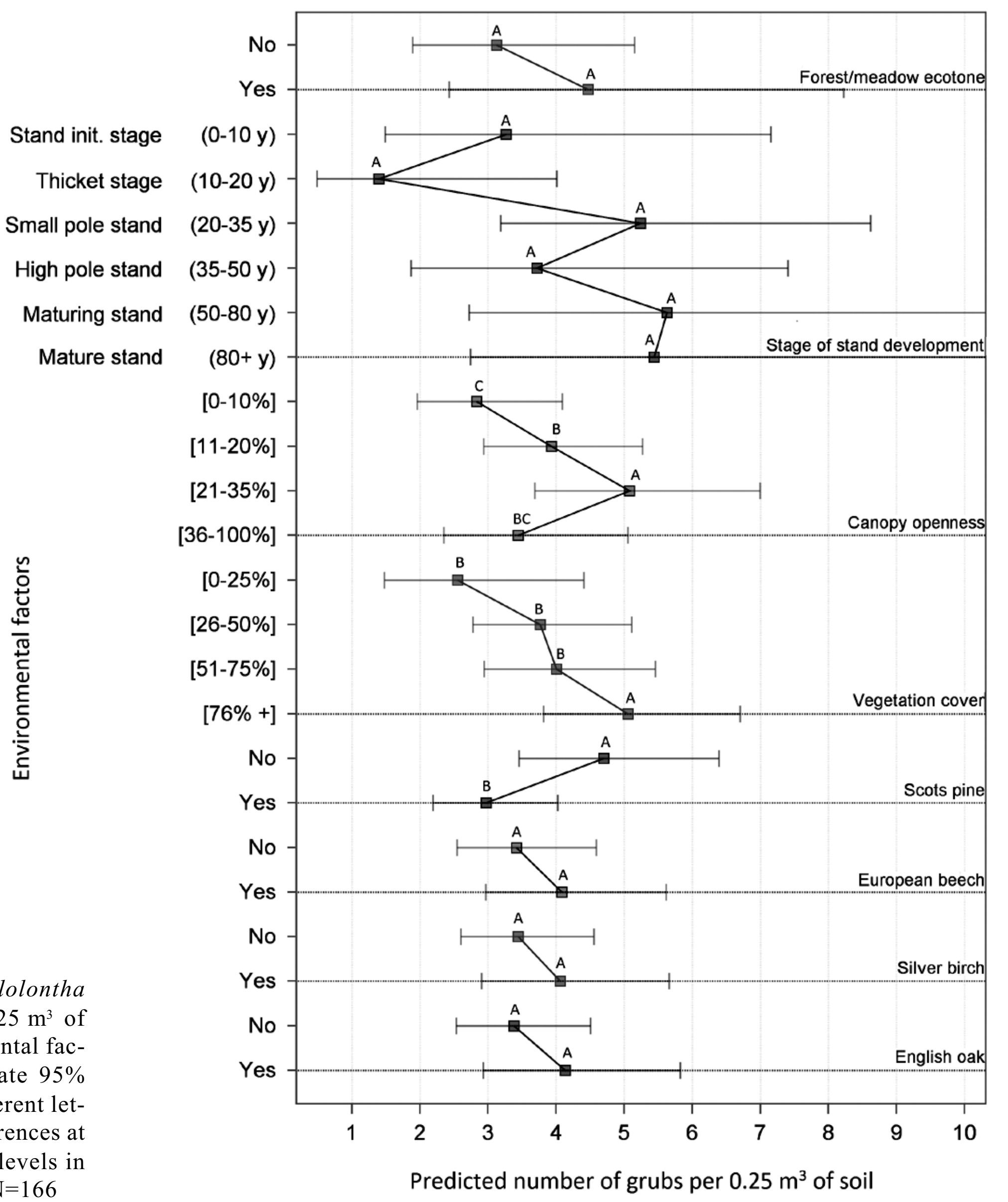


**Figure 2.** Prediction of *Melolontha* spp. grub frequency (per 0.25 m$^3$ of soil) in relation to environmental factors (Model II). Bars indicate 95% confidence intervals CI; different letters indicate significant differences at $\alpha = 0.05$ between particular levels in each environmental factor, N=166

stands and stand initiation stage (3.72 and 3.27 grubs per pit, respectively). The lowest value (1.40 grubs per pit) was predicted for the thicket stage.

## Discussion

*Melolontha melolontha* and *M. hippocastani* are typical eurytopic organisms, in that their natural habitat is extremely variable (Sierpiński 1975). The statistical model (randomised hurdle regression model) used in this study enabled us to identify stand characteristics that were significant risk drivers. In the constructed model, the factors associated with the highest probability of grub occurrence were stand location relative to open space (the forest/meadow ecotone) and stage of stand development.

The probability of grub occurrence in a stand is modified by the location of the stand with respect to open area, similar to the important role played by visual stimuli in locating host plants for many insect species (Prokopy and Owens 1983). After leaving the soil, cockchafers move towards taller objects including trees, poles, and houses, which create contrasting silhouettes on the backdrop of the horizon at dusk (Schneider 1952, Robert 1963). Until recently, the ability of cockchafers to differentiate trees from other objects was not known. However, it was discovered that *M. melolontha* is highly sensitive to light at 520 nm (green wavelength), which characterises the conditions of the tree canopy at dusk (Labhart et al. 1992, Hegedüs et al. 2006). This light sensitivity indicates the ability of cockchafers at an early stage of flight to be guided to host trees by visual stimuli, which can explain the high probability of cockchafer occurrence in ecotones. This also indicates that these stands are most attractive during supplementary feeding, after which females (which are generally in close proximity) lay eggs, thus determining where grubs (which lack the potential for long-range transport) will develop.

In connection with the other factors, the risk of cockchafer occurrence is influenced by the stage of stand development. However, the hurdle model revealed large irregularity in the distribution of grubs. Comparing the two models, a small probability of grub occurrence and small numbers of grubs were predicted only for the thicket stage. This could be explained by the high canopy density that shades the soil (overshadowing is connected with increasing humidity) and restricts the development of plant cover and by the presence of entomopathogenic microorganisms (Read 1968, Xie et al. 1995, Jagodziński and Oleksyn 2009). Švestka and Drapela (2009) reported similar results, in which only 10% of grubs survived to the next year despite a dense infestation of one-year grubs in the pine thicket stage. A different situation occurs in the stand initiation stage, in which the high probability and predicted number of grubs (>3 per 0.5 $m^2$ sampled soil) according to Instruction of Forest Protection (2012) can lead directly to the destruction of a stand.

The initial high density of the stand canopy decreases from the small pole stand stage as a result of natural succession and silvicultural management practices. These processes continue throughout the stand lifecycle, and microclimatic conditions that develop in the forest interior are conducive not only to the appearance of vegetation but also to the appearance of cockchafers.

Depending on the stage of stand development and silviculture management practice, the forest community forms a characteristic phytoclimate that can further increase the attractiveness of the stand to cockchafers. Therefore, stand composition is an important factor. The number of cockchafer grubs (L2) was lower in stands with pine and higher in stands in which pine was replaced by other species, such as European beech, English oak, and silver birch. Although these results reflect trends only, they confirm earlier reports about species preference of cockchafers (Švestka 2007). Experiments conducted by Woreta and Sukovata (2014) indicated that one-year-old cockchafer grubs feeding on both *Quercus* species characterized the lowest mortality. Additionally, the grubs feeding on the latter as well as on, *F. sylvatica* and *B. pendula* showed the largest relative increase in body weight. Moreover, the survival of older grubs (L2, L3) was relatively high (66.7–100%).

The relationship between stand canopy openness and the number of grubs indicates that *Melolontha* are more numerous in stands with medium canopy openness (21–35%). Light transmission enables the development of forest vegetation and natural regeneration (Matusz 1960, Canham 1988, Canham et al. 1994, Gray and Spies 1996, Wright et al. 1997, Nicotra et al. 1999, Robakowski et al. 2001, Beaudet and Messier 2002). In our model of grub frequency, locations with the least plant cover also had the lowest grub density. Similar results were obtained by Švestka (2007), who investigated the localisation of egg laying by female cockchafers and found the greatest damage in stands with a high degree of weed infestation, and significantly less damage in stands without vegetation cover. Švestka (2007) also found that females preferred areas shaded by canopy or other vegetation in selecting a location for their eggs. In Poland, both factors are important: moderately shaded stands and well-developed forest floor vegetation.

## Discussion and Conclusions

In summary, our results show that the boundary between open space and forest is an important factor that influences the occurrence of cockchafer grubs in soils. In stands that contain grubs, canopy openness is a significant determinant of the stand's attractiveness to cockchafers. Stands with high canopy density and shade are populated by cockchafers as a last resort. The best developmental conditions occur in stands with moderate light transmission and smaller temperature ranges as a result of canopy shading and with conditions that are conducive to the development of vegetation cover. The presence of dense plant cover influences the conditions for grub development because grubs, particularly at the first larval stage, feed only on the roots of herbaceous plants. The plant species composition of the stand influences the abundance of cockchafers in forest ecosystems.

Some of these environmental factors can be modulated by appropriate silvicultural practice to promote plant protection against these forest pests. In line with the results of our study:

• It is recommended to regulate species composition of tree stands, especially in the ecotone area, in order to obtain species less favourable to cockchafers.

• It is suggested to maintain high canopy density of tree stands, where stand vitality allows for such a solution.

• In order to make the forest environment less suitable for cockchafers while using artificial regeneration, it is recommended to employ higher planting densities, which would encourage quicker stand closure, soil shading and establishment of forest microclimate less suitable for cockchafers.

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