Operational monitoring of the nun moth *Lymantria monacha* L. (Lepidoptera: Lymantriidae) using pheromone-baited traps – a rationalization proposal

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ABSTRACT: The annual risk assessment of Scots pine (*Pinus sylvestris* L.) stands in the federal state of Brandenburg and subsequent decisions on the application of insecticides are based on operational surveillance data on *L. monacha*. The objective of the study was to rationalize the operational pheromone capture method. Data from operational monitoring with pheromone-baited traps in Brandenburg were analyzed. The records included data from a total of 11,761 traps and covered the development of populations of this insect from normal to outbreak densities and back during the years 2000–2009. Statistical analysis of the data suggested that a capture period of 15 June to 10 August, which is shorter than the period used hitherto, is sufficient to determine whether more precise monitoring by a census of adult females is required at a given site in the following year owing to increasing population densities. If this suggested shorter capture period had been implemented in 2000–2009, approximately 33% fewer trap inspections would have been required.

Keywords: *Lepidoptera; Lymantria monacha; Pinus sylvestris*; monitoring method; forest pest; forest protection

The nun moth *Lymantria monacha* Linnaeus, 1758 (Lepidoptera: Lymantriidae), is one of the most important pest insects in pine and spruce forests in Germany. In the federal state of Brandenburg, 72% of the forest and woodland area is dominated by Scots pine *Pinus sylvestris* L. Annual risk assessments of Scots pine stands in Brandenburg and subsequent decisions on the application of insecticides are based on operational surveillance data on *L. monacha*. Insecticides should be applied only in the areas in which complete defoliation and subsequent death of a proportion of the pines are expected.

Lymantria monacha has been monitored in Brandenburg by a stepwise surveillance method for many years. Large-scale, approximate monitoring methods are used initially to identify areas with high population densities of *L. monacha*, in order to focus on the most endangered stands of pine forest. Subsequently, these smaller areas are monitored by more precise methods, which involve a more detailed survey of at-risk stands (Möller et al. 2007). In the first phase of the monitoring process, *L. monacha* males are captured with pheromone-baited traps to identify incipient local outbreaks. The second phase of monitoring is implemented in the following year at those sites where the total number of *L. monacha* captured per trap per year had reached the threshold of 1,000. During the second phase (census of adult females), adult females are counted that are resting on the lowermost 3-m section of selected pine trunks (i.e. the section that is located closest to the ground). For the whole region, such local censuses of adult females are implemented at slightly different times, and initiated when the first males arrive at the pheromone trap nearest to each locality. Data on adult females are related more strongly to the potential damage caused by subsequent larvae in a specific location and thus are more suitable for predicting this damage than the data obtained from the capture of males (Möller et al. 2007).

During operational monitoring in Brandenburg, the pheromone-baited traps are suspended in areas of Scots pine, spruce, or mixed pine and spruce forests, as well as in areas of mixed pine or spruce forest that contain up to 30% of deciduous trees. Targeted forest stands are 30–80 years old and the trap density in these stands is 1 per 10 km^2 of the respective forest. Hitherto, the pheromone traps have been suspended on 15 June each year, and then checked approximately every third day, whereupon the captured *L. monacha* are counted and removed (this is referred to as "trap inspection" in the following text). Each trap is recovered during the first trap inspection after 15 August at which the trap is empty. The objective of the study described herein was to rationalize the operational pheromone capture method used in Brandenburg and consequently to reduce working hours and costs.

MATERIAL AND METHODS

Pheromone traps

In the present study, data from the operational monitoring of *L. monacha* with pheromone-baited traps in Brandenburg were analyzed. The records included data on a total of 11,761 traps and covered the development of *L. monacha* populations from normal population densities to outbreak densities and back to normal densities in the years 2000–2009 (progradation phase in 2002 and 2003, and culmination of the outbreak in 2004 in most regional locations). The traps were suspended and *L. monacha* specimens were counted by many foresters and lumbermen in more than 500 forest districts over the 10-year period. During this period, two different pheromone lures were used. Until 2004, the traps were baited with disparlure, the pheromone of *Lymantria dispar* Linnaeus, 1758, which attracts both *L. dispar* and *L. monacha* species. Since 2005, a *L. monacha* volatile blend that contained five components, namely, (±)-disparlure, (±)-monachalure, and 2-methyl-Z-7-octadecene (Gries et al. 1996), was used, but at a lower dose than disparlure alone to allow the total numbers of captured *L. monacha* to be compared (D. Häussler, personal communication). The traps used were Variotraps (Flügel GmbH), which are a type of nonsaturating funnel trap. They were suspended at a height of 1.5–2.0 m a.g.l. (Fig. 1).

Fig. 1. Variotrap, the type of pheromone trap used

Statistical analysis of pheromone trap data

Records from stands other than those of Scots pine, the dominant tree species in Brandenburg, were excluded from the statistical data analysis. The numbers of *L. monacha* counted per trap were used to calculate daily values, maximum daily values, total sums, and accumulated subtotals for statistical analysis. Daily value is defined as the number of *L. monacha* captured at one trap inspection divided by the number of capture days since the previous trap inspection. The inspection interval is the number of days between one count of the number of *L. monacha* captured in a trap and the subsequent count. Maximum daily value refers to the highest daily value per trap per year. Total sum is defined as the sum of all the *L. monacha* captured in a single trap in one year. Accumulated subtotals are defined as the total number of *L. monacha* captured from the start of the capture period to 20 June, to 30 June, and so on.

The data were analyzed by SPSS Statistics 19 programme. In all cases, a significance level of $\alpha = 0.05$ was assumed. No variable was distributed normally. As a consequence, Spearman's rank correlation coefficient was used to measure statistical dependence between the variables. To analyze the relationships between variables that were strongly correlated, and for practical significance, a simple linear regression analysis was carried out. Given that the assumptions of normality and homoscedasticity

Table 1. Descriptive statistics of the dataset (n = 11,761)

Pheromone trap captures		Mean	Median	Standard deviation
Total sum		594.280	460.000	503.174
Maximum daily value		32.084	23.750	29.140
Accumulated subtotal until	20 June	0.268	0.000	3.532
	30 June	4.208	0.000	15.873
	10 July	41.437	10.000	85.481
	20 July	148.373	85.333	180.151
	31 July	337.794	245.667	302.118
	10 August	479.393	365.333	407.950
	20 August	559.462	431.000	476.183
	31 August	588.562	455.333	497.520
	10 September	593.485	460.000	502.250
	20 September	594.208	460.000	503.127
	30 September	594.272	460.000	503.174
	10 October	594.274	460.000	503.176

had been violated, dependent and independent variables were transformed by the fourth root.

RESULTS

Pheromone traps

Descriptive statistics of the dataset are given in Table 1. Fig. 2 shows the dynamics of capture of nun moths per day during the flight period from 2000 to 2009. For 90% of the traps, the flight period started between 20 June and 16 July and finished between 17 August and 17 September. The mean date for the beginning of the flight period was 4 July, whereas the mean date for its end was 1 September. The latest capture date over the 10 years studied was 5 October. With respect to the maximum daily values, 90% were reached between 9 July and 15 August. The flight period lasted between 40 and 78 days in 90% of the traps and had the mean duration of 60 days.

The mean maximum daily value for the capture of *L. monacha* was 32 specimens. In 95% of the traps, the maximum daily value was not higher than

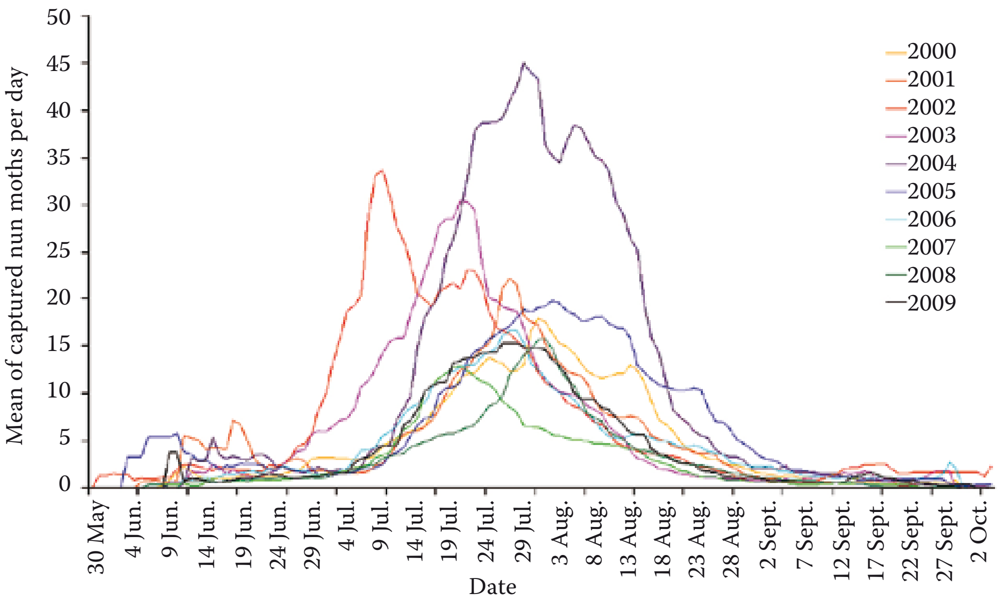

Fig. 2. Flight curves of *L. monacha* based on pheromone trap captures in 2000 to 2009 (n = 700,130)

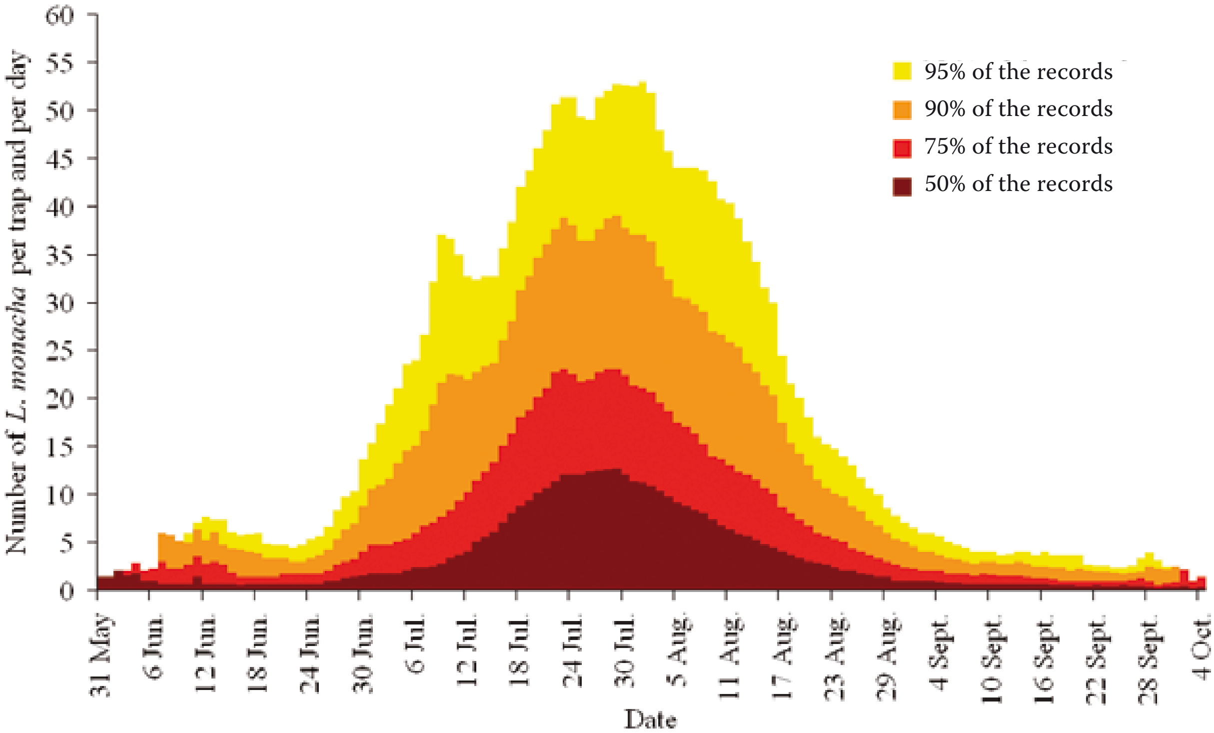

Fig. 3. Histogram of the maximum number of *L. monacha* captured per trap and per day in a defined percentage of records (n = 700,130)

85 specimens, and the highest maximum daily value reached was 360 specimens. Owing to the fact that the number of males that were found when a trap was checked was divided by the number of days since the trap was checked for the last time, the calculated daily numbers should be slightly lower than the actual numbers. The mean number of captures per trap over the entire flight period (total sum) was 594 males. The threshold value of 1,000 males was reached in 15% of the traps. In 5% of the traps, 1,547 or more males were captured. The maximum total sum was 5,064 males.

Pheromone trap inspection intervals

In operational monitoring, it is preferable that the number of *L. monacha* captured per trap inspection does not exceed 100 specimens (D. Häussler, K. Möller, personal communication). It is difficult to count more than 100 specimens from one trap in the field. As a consequence, the inspection intervals should be short to reduce the likelihood of catching more than 100 moths per trap inspection. The tested inspection intervals had to be easy to apply in operational monitoring and also had to take into account weekends. As a consequence, intervals of 3 days, as used hitherto, and of 7 and 14 days, were tested. With an interval of 3 days, not more than 33.3 specimens should be captured per day (7 days: 14.3 specimens, 14 days: 7.1 specimens) to ensure that the favoured levels are not exceeded. Percentiles of the number of *L. monacha* captured per trap per day were calculated to determine how often the threshold value of 100 specimens would be exceeded upon the application of the different intervals. In Fig. 3, the highest numbers of *L. monacha* captured per trap and per day for a defined percentage of records with the lowest numbers of *L. monacha* captured are presented. Fig. 3 shows, for instance, that the daily threshold of 33.3 *L. monacha* would be exceeded in 5% of the records (while 95% of the records would have fewer than 33.3) during the time period from 9 July to 14 August.

As a supplement to Fig. 3, Table 2 lists the time periods during which the daily captures exceeded the thresholds in more than 5% of the records. On the basis of these data, appropriate inspection in-

Table 2. Time periods in which daily thresholds were exceeded

Trap inspection interval	Daily threshold to avoid the capture of more than 100 specimens per trap	Time period during which the threshold was exceeded in more than 5% of the records
14 days	7.1	12 June–30 August
7 days	14.3	1 July–23 August
3 days	33.3	9 July–14 August

Table 3. Recommended trap inspection intervals

Time period	Recommended inspection interval
15–30 June	7 days
1 July–23 August	3 days
9 July–14 August	3 days might be too long
24–30 August	7 days

tervals were determined for different time periods from June to August that should ensure that the threshold of 100 specimens is not exceeded in more than 5% of the trap inspections (Table 3).

Pheromone trap capture period

Table 4 lists Spearman's rank correlation coefficients between the total sum of captured *L. monacha* and the maximum daily value, as well as the accumulated subtotals. Strong significant correlations were found between the total sum of captured *L. monacha* and the maximum daily value (r = 0.932) and between the total sum and the accumulated subtotal up to 31 July (r = 0.901) and beyond.

The scatterplots in Fig. 4 illustrate the strong correlations described above. The higher scores that were obtained using disparlure are due to its use during the progradation phase and the culmination of the outbreak, during which high densities of *L. monacha* occurred. The *L. monacha* volatile blend was applied during the retrogradation phase and latency, when low densities were present. The scatterplots illustrate an increase in the correlation between the total sum and accumulated subtotal as the accumulation time increased. The scatterplots of the total sum and accumulated subtotal up to 20 August or beyond display a nearly straight line. The correlation between the accumulated subtotal up to 10 August and the total sum (r = 0.975) was stronger than that between the maximum daily value and the total sum.

To rationalize the operational monitoring, correlation coefficients that were higher than 0.9, but lower than 1, were analyzed further. The objectives of the simple linear regression analysis were to describe the relationships between the total sum and different accumulated subtotals, as well as to predict the total sum. The untransformed variables did not meet the assumptions of normality and homoscedasticity for regression analysis. The assumptions were met best by the fourth root transformation. In spite of this transformation, the assumption of normality of the variate was still clearly violated. Linear regression analysis has been described as less sensitive to departures from a normal distribution when sample sizes are sufficiently large (Lumley et al. 2002). Table 5 shows some of the results of the regression analysis. All coefficients listed in Table 5 and the regression models are statistically significant.

To validate the regression model, the data were divided at random into two parts. For each part, the regression equation was calculated and then applied to the other section of the data to predict the total sum values. The last row of Table 5 presents the error rates of these predicted values with re-

Table 4. Spearman's rank correlation coefficients for the total sum of captured *L. monacha* (n = 11,761)

Correlation of total sum with		Correlation coefficient	Two-sided significance
Maximum daily value		0.932	0.000
Accumulated subtotal until	10 June	0.004	0.643
	20 June	0.002	0.806
	30 June	0.164	0.000
	10 July	0.322	0.000
	20 July	0.687	0.000
	31 July	0.901	0.000
	10 August	0.975	0.000
	20 August	0.995	0.000
	31 August	1.000	0.000
	10 September	1.000	0.000
	20 September	1.000	0.000
	30 September	1.000	0.000
	10 October	1.000	0.000

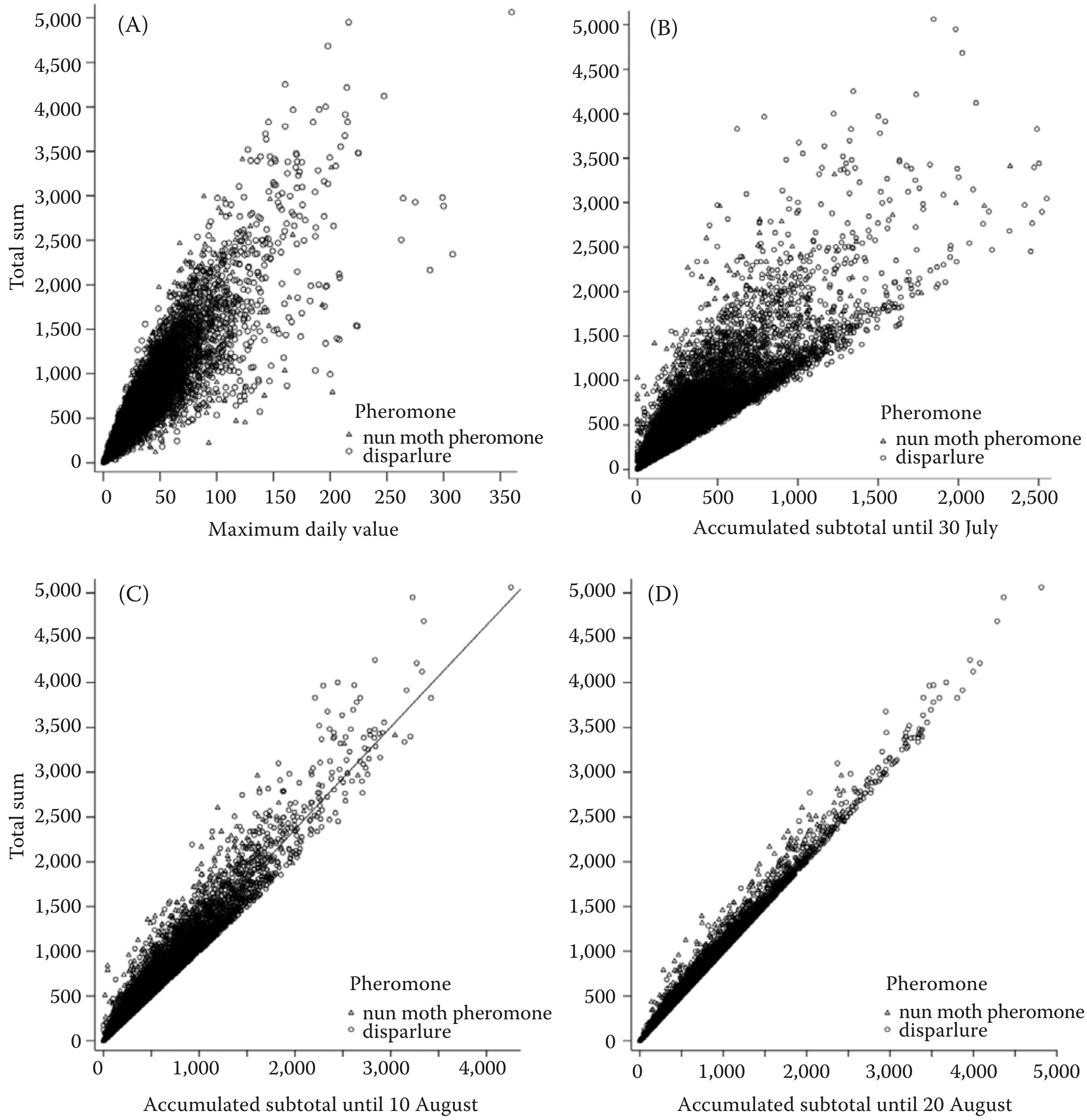

Fig. 4. Scatterplots for the total sum and maximum daily value as well as the accumulated subtotals for different time segments, C with transformed back regression function from data transformed by the fourth root (A–D: n = 11,761)

spect to over- or underestimation of the threshold value of 1,000 captured *L. monacha*, which is used as an indicator of an incipient outbreak. An error rate of 5% seems to be acceptable. Consequently, the capture period from 15 June to 10 August with an error rate of 4.1% was determined to be sufficient to monitor *L. monacha* using pheromone traps in Brandenburg (Fig. 4C). Over the last 10 years, the mean date on which trapping ceased was 1 September. A new threshold value of 825 specimens for the proposed shortened capture period was calculated using the regression equation (Table 5) and the former threshold value of 1,000 specimens.

DISCUSSION

The utilization of operational surveillance data on *L. monacha* in the present study is associated with many potential sources of error and with high risks of error, as compared with highly standardized investigations that use data from specially designed experiments. The pheromone traps were suspended and the *L. monacha* specimens were counted by many foresters and lumbermen in more than 500 forest districts over 10 years. The public enterprise Forst Brandenburg provided detailed in-house instructions about where and how to sus-

Table 5. Results of linear regression analyses with the total sum of captured *L. monacha* as dependent variable, maximum daily value or accumulated subtotals as independent variable and fourth root transformation of the dependent and independent variables (n = 11,761)

Simple linear regression with fourth root transformation	Independent variables			
	maximum daily value	accumulated subtotal until		
		31 July	10 August	20 August
Adjusted R^2	0.868	0.799	0.952	0.992
Standard error of estimate	0.35623	0.44036	0.21542	0.08855
ANOVA *df* of regression	1	1	1	1
ANOVA *F*-value	77,505.806	46,654.750	232,348.360	1432,830.196
ANOVA significance	0.000	0.000	0.000	0.000
Intercept	0.418	0.890	0.189	0.026
Standard error of intercept	0.016	0.018	0.009	0.004
Intercept significance	0.000	0.000	0.000	0.000
Coefficient of independent variable	1.896	0.941	1.014	1.010
Standard error of coefficient	0.007	0.004	0.002	0.001
Coefficient significance	0.000	0.000	0.000	0.000
Mean error rate by over- or underestimation of the threshold of 1,000 (%)	7.0	8.8	4.1	1.5

pend the pheromone traps and how to count the specimens, which enabled the monitoring to be standardized as much as possible. The huge number of records and traps (n = 11,761) could not have been achieved in the context of a completely standardized experiment; hence, the expected high error rates were accepted.

With respect to the difficulties that are associated with counting larger numbers of *L. monacha* per trap inspection, an alternative approach could be to weigh the specimens instead of counting them. The disadvantages of weighing the specimens are:

– the variability in the adult weight of *L. monacha*, which depends on the environmental conditions during development, such as the availability of food resources for caterpillars and the climatic conditions,
– the presence of by catch, which would have to be segregated from *L. monacha*,
– the effect of the accumulation of water in the trap on the weight.

As a consequence, we prefer to count the specimens (K. Möller, personal communication).

The timing of the flight period of *L. monacha* depends on several factors, and varies by up to three weeks among different locations in the same year and by a longer period among different years in Bavaria (Feicht 1997). Before the flight period, the temperature during the development of immature stages has an impact on the subsequent flight period (Skuhravy 1987). The date of emergence of adults is determined mainly by the temperature sum (in degree days) that has been reached. In addition to such exogenous factors, endogenous factors, such as the phase of the outbreak and physiological constitution or provenance of the insects, influence the timing of the flight period (Skatulla, Feicht 1995). The most important parameter that determines flight activity is the temperature during the evening and at night. In spruce stands in Southern Bohemia, the maximum rate of capture was registered at an evening temperature of 15–22°C (Skuhravy, Zumr 1981; Skuhravy 1987). Below 10°C, flight activity ceased in both Bohemia and Bavaria (Skuhravy, Zumr 1981; Skuhravy 1987; Feicht 1997).

Hochmut and Skuhravy (1977) proposed a capture period from mid-July to the end of August for the surveillance of *L. monacha* in former Czechoslovakia, in which forests and woodland are dominated by spruce and fir at higher altitudes. In their opinion, this proposed capture period was sufficient to realize 90% of the potential captures. The results of our study, which were derived from different locations in Brandenburg and were obtained over 10 years with different climatic conditions, suggested that a capture period from 15 June to 10 August is appropriate. Capture should start on 15 June, as practised to date, because of the variation of the eclosion date by approximately one month, the fact that the temperature increases more rapidly within pine stands than within spruce stands, and the expected continuation of climate change.

Skatulla (1989) implemented a surveillance method that is based on temperature-dependent maximum values for the number of nun moths captured in Bavaria. Lohmann (2005) detected a correlation between maximum values and total sums with respect to selected data for pheromone traps in Brandenburg. As a consequence, she recommended a capture period that lasts from the start of the flight period to the second consecutive trap inspection in which the number of *L. monacha* captured does not increase. Lohmann (2005) proposed that the date of the start of the flight period and the maximum value should be used for risk assessment of pine stands. Majunke et al. (2009) analyzed selected data for pheromone traps from pine and spruce stands in the south of the federal state of Brandenburg and in the free state of Saxony, which lies to its south. They found that 83.9% of the maximum values were reached between 15 July and 15 August. They recommended the utilization of the maximum values to estimate the total sums, a capture period from 15 July to 15 August, and trap inspection intervals of 3–4 days for pine stands in the south of Brandenburg and in Saxony. Our results show that the subtotal up to 10 August has a stronger correlation to the total sum than the maximum daily value. However, the greatest difficulties when using the maximum approach are in accurately determining the date of the maximum, which varies over time, and coping with multiple maxima (Fig. 2). As a consequence, a longer capture period is needed to determine the maximum value. If a longer capture period is necessary anyway, an accumulated subtotal can be determined and used to predict the total sum without further effort.

The relationships between trap captures using pheromones and other methods of *L. monacha* surveillance have been studied in Brandenburg and Bavaria. To date, no or only weak correlations have been detected between data obtained from capture with pheromone traps and those from the census of adult females near the traps (Apel et al. 1984; Morewood et al. 2000). Under conditions of a high population density and abundant widespread natural *L. monacha* pheromone (Feicht 1997), as well as additional chemical and acoustic stimuli from females over short distances (D. Häussler, personal communication), the pheromone traps become less attractive to males. Strong positive correlations have been detected between the number of male moths captured with pheromone traps using the *L. monacha* volatile blend and the number of faecal pellets from larvae that are collected on a sheet of cloth (1 m^2) placed on the forest floor under a dominant pine or spruce near the traps (Häussler et al. 2000; Morewood et al. 2000).

CONCLUSION AND RECOMMENDATIONS

As a result of the study reported herein, rationalization of the operational monitoring of *L. monacha* using pheromone traps in Brandenburg is recommended. A capture period from 15 June, as practised hitherto, to 10 August seems to be sufficient to predict incipient local outbreaks. A new threshold value of 825 specimens for the total sum of nun moths over the proposed capture period was calculated. If the suggested shorter capture period had been implemented in 2000–2009, approximately 33% fewer trap inspections would have been required.

The trap inspection intervals should be changed as follows:

- from 15 to 30 June, the traps should be checked every seventh day,
- from 1 to 8 July, the traps should be checked every third day,
- from 9 July to 10 August, the traps should continue to be checked every third day, with the following exception: if more than 100 moths are captured in one trap in the interval between two trap inspections, the local executor can decide to check it every other day.

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