Electronic Appendix

To "**1200 years of regular outbreaks in alpine insects**"

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A. Chronology development

Following standard dendrochronological procedures (Fritts 1976), a mean chronology averaging all 47,513 MXD measurements was compiled. This raw, non-detrended MXD chronology (figure S1*a*, blue curve) displayed long-term trends induced by changes in sample structure, and high frequency negative departures induced by LBM outbreaks. The low frequency component originated from the so-called "age trend" commonly found in raw tree-ring data, i.e., MXD values of individual trees showed decreasing values with aging (Schweingruber *et al.* 1978). As a consequence, the chronology tended towards lower values when the underlying data were on average from older tree-rings (e.g., the 11th-12th centuries), and sharply increased when old data dropped out and the chronology was refreshed with younger material (e.g., the 1200's). The timing of these effects was highlighted by the mean age and sample replication curves (figure S1*c*) accompanying the MXD chronology.

Figure S1

Figure S1. MXD chronology and LBM outbreak detection. (*a*) Original (blue) and gap-filled (red) MXD records combining data from 180 larch samples. (*b*) Difference series (blue) between the gap-filled and original data, and the age-effect corrected version of this record (orange). The correction was accomplished by excluding tree-rings younger than 63 years from the data (see figure S3). Values less than -0.005 g/cm^3 are shown. (*c*) Mean age curve of the MXD data (black) shown in (*a*), and sample replication of the gap-filled (blue) and age-effect corrected (orange) data. (*d*) Percentage of tree-rings affected by LBM outbreaks. These rings were removed from the data, and re-estimated using data from unaffected rings. The resulting record is shown in (*a*, red curve). Grey bars indicate low LBM intensity and low mean biological age periods in the 12th and 17th centuries.

B. Gap-filling LBM detection procedure

For LBM signal detection we analysed these raw data (sample-by-sample, year-by-year) for exceptionally low MXD values, removed the affected rings (figure S1*d*), and statistically re-estimated the gaps using data from trees unaffected during the year under investigation. In detail, for each year this gap-filling procedure comprised: *(i)* averaging the MXD values of the remaining rings, *(ii)* adjusting the variance of the mean values of un-affected rings to the variance of the measurement series from which the ring was removed, *(iii)* replacing the gap with the variance adjusted value obtained from un-affected rings, *(iv)* calculating a mean utilizing the gap-filled and unaffected data (figure S1*a*, red curve). A difference series between the original measurements and these gap-filled (LBM signal removed) MXD data (figure S1*b*, blue curve) provided the basic information on past LBM outbreaks.

The effects of this procedure on the single MXD measurement series are highlighted for the 1540-1560 period including the 1548 and 1556 LBM outbreak years (figure S2). Examination of wood samples and MXD profiles enabled the identification of 41 rings (70%) in 1548 and 42 rings (69%) in 1556 as being affected by defoliation events (negative spikes in figure S2*a*). Substitution of these data utilizing the MXD values from un-affected rings resulted in average densities of 0.83 g/cm^3 in 1548 and 0.91 g/cm^3 in 1556, and residuals between the mean original and gap-filled data of 0.31 g/cm^3 in 1548 and 0.28 g/cm^3 in 1556 (figure S2*c*).

Figure S2

Figure S2. Gap-filling procedure in individual MXD timeseries. (*a*) Original MXD measurement series including the 1548 and 1556 LBM outbreak years. Each series represents a single larch core sample from which density measurements were computed. (*b*) Gap-filled MXD measurement series with the LBM effects in 1548 and 1556 removed from the data. (*c*) Comparison of the original and gap-filled mean records.

C. Age-effect correction of the LBM reconstruction

The difference record between original and gap-filled data (figure S1*b*, blue curve) revealed a correlation between tree age and LBM signals, i.e., younger tree-rings were less severely affected by LBM defoliation. This age-effect in the outbreak record was analysed by aligning the original and gap-filled MXD data by biological age (Esper *et al.* 2003), and plotting the annual differences between these data against tree-age (figure S3). We iteratively removed successively larger proportions of the data from the youngest ages and fitted linear models of annual differences as a function of age.

It was found that removing data from ages <63 years resulted in a line with slope near zero, and from this concluded that 63 years was an optimal minimum age for detection of outbreaks. Consequently, we removed all juvenile tree-rings <63 years from the analysis, and calculated a MXD chronology and the gap-filling procedure from data considering mature tree-rings only. The difference series between these timeseries is shown in figure S1*b* (orange curve) together with the difference series between the "standard" gap-filled and original MXD timeseries including juvenile tree-rings (blue curve).

Removal of juvenile rings reduced sample replication (figure S1*c*, orange curve), but increased the LBM signal fidelity during periods of the past millennium when large proportions of juvenile tree-ring material suppressed the detection of budmoth events, e.g., the 12th and 17th centuries (grey bars in figure S1). The age restriction essentially accounted for the fact that younger larch trees are less affected by foliage feeding than are older trees.

Figure S3

Figure S3. Age-effect in LBM outbreak detection. (*a*) Larch sample replication (grey curve), number of gaps (black curve), and percent gaps (grey shading), all aligned by biological tree age. Gaps represent LBM-affected tree-rings that were removed from the MXD data. The percent record represents the number of gaps related to the total number of samples for each ring-age (1-460). (*b*) Mean original (grey) and gap-filled (black) MXD curves after aligning the data by biological age, with sample replication as in (*a*). Since the gap-filling procedure includes the substitution of LBM-affected (low density) with non-affected (higher density) tree-rings, the gap-filled series shows generally higher values than the original curve. The scatter plot at the bottom of the figure shows the annual differences between gap-filled and original MXD records, and the linear models fit to difference data <63 and >62 years.

D. Validation of the LBM reconstruction

In order to evaluate the accuracy of the methodologies and resultant outbreak reconstruction, results are compared with methodologically more conventional estimates of LBM abundance (figure S4). This involved comparisons of MXD and TRW anomalies between host (larch) and non-host (fir and spruce) data, i.e. common variations are interpreted as the result of climatic anomalies, while negative outliers in only the larch data are interpreted as the result of LBM outbreaks (Weber 1997; Rolland *et al.* 2001). Specifically, a 600-year record from

Tyrol in Austria (Esper *et al*. 2002) and a 1000-year record from Lauenen in Switzerland (Schweingruber *et al*. 1979) were compared (figure 1).

Figure S4

Figure S4. LBM outbreak reconstruction and validation. (*a*) Age-corrected LBM reconstruction as shown in figure S1*b*. (*b*) Difference records between larch (MXD and TRW) data and the non-host fir/spruce chronologies from Lauenen and Tyrol. (*c*) Combined larch MXD and lag-1 TRW record. For the lagged LBM response in the TRW data see figure S5. MXD and TRW data were detrended using flexible cubic spline filters before combination to emphasize inter-annual variations. Values exceeding one standard deviation are shown.

Correlations between the original (i.e. non gap-filled) larch and non-host Tyrol and Lauenen MXD chronologies were 0.36 and 0.34, respectively, calculated over the 1368-1975 common period. These correlations increased to 0.54 for both chronologies after removing the LBM signal from the larch record via gap-filling. Differences between the original host and non-host chronologies that exceeded one standard deviation were denoted as candidate LBM outbreak years (figure S4*b*). A comparison of the gap-filled reconstruction with these conventional approaches yields correlations ranging from 0.61-0.83 (1368-1975 period). These highly significant values indicated that the identification and substitution of LBM affected tree-rings within the gap-filling procedure resulted in reconstructions similar to time series utilizing more traditional approaches of host/non-host differences.

A further evaluation of the LBM reconstruction was accomplished via comparison of the series with negative deviations derived from a combined MXD plus lag-1 TRW larch record (figure S4*c*). The rationale for this approach was based upon the higher autocorrelation and lagged effects of defoliation signals in TRW data (figure S5). Comparison of the LBM reconstruction with the combined MXD plus lag-1 TRW record indicated a correlation of 0.50 (1368-1975 period).

Figure S5

Figure S5. LBM patterns in tree-ring data. Average MXD (g/cm^3) and TRW (mm) values centred on the 123 LBM outbreak events (year 0) and 5 years before and after these events (red curve). Grey shadings indicate two standard errors, and horizontal black lines the average MXD (0.838 g/cm3) and TRW (0.536 mm) values over the 11-year periods displayed here. Blue and green curves are the MXD and TRW patterns calculated using data before and after 1400, respectively. The means for these sub-periods have been adjusted to the average using all data (horizontal lines).

References

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