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The greenhouse effect and moths' response to it. I. How to compare climatic and insect phenology databases?

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Abstract. At present it has been firmly established that climate can be influenced by both natural forces and human activities. It is generally accepted that an increase in greenhouse gas (GHG) concentrations in the atmosphere results in the warming of the Earth's surface. Recent changes in the European fauna of Lepidoptera have been considered as a northward shift of entire distribution areas, caused by global warming. Northern territories are invaded by temperate species, and the process seemingly has a cyclic nature. An invasion of a new species is often followed by a rapid growth of its population and followed by its penetration into the neighbouring areas.

Key words: *Estonia, Lepidoptera, distribution of moths, climate change*

INTRODUCTION

Lepidopterous fauna of Estonia has been studied relatively well. This allows us to observe trends of its change during at least a century.

First communications in butterflies and moths of our territory are dated second half of the 19th century, taking into account faunistical papers by A. Bruttan (1862), J. H. W. Nolcken (1868, 1870, 1871), C. A. Teich (1878, 1899), summarised by W. Petersen (1902). W. Petersen has lead the investigations during the first decades of the 20th century as well, publishing a two-wolume monograph “Lepidopteren-Fauna von Estland” (Petersen, 1924).

K. Elberg (1999) delimits three periods in the history of faunistical investigations in Estonia, asserting a rise of study activity and effectiveness in years after the Second World War. Amateur lepidopterists in particular have been active, gathering data on the local distribution of butterflies and moths, and adding numerous new species to the list of Estonian fauna.

Faunistical data, summarised in printed catalogues of Estonian Macrolepidoptera (Möls & Viidalepp, 1969; Remm & Viidalepp, 1977; Remm & Viidalepp, 1986; Viidalepp, 1995) comprise 864, 889, 897 and 914 species, respectively. The last catalogue of Lepidoptera (Jürivete et al., 2000) contains data on the local distribution and abundance of 2238 species. 922 species listed therein belong to the informal Macrolepidoptera group of families. In addition, Estonian data concerning 9 species have been published subsequently (Õunap et al., 2002; Taal, 2002; Viidalepp, 2002). These data allow us to trace how 67 species of moths appeared first time in Estonia, and how they were distributed further. J. Viidalepp (1995) has stressed that immigrants from south and east prevail among newcomers in fauna, and that they proceed to distribute north- and westward.

Some other species, formerly reaching their absolute distribution borders in southern Estonia, have moved northwards, and their abundance in Northern Estonia has increased.

An invasion of southern species into Estonia is understood as an effect of global warming (Kruus & Viidalepp, 2001; Viidalepp & Kruus, 2001).

R. L. H. Dennis (1993) underlines three aspects of climate change which are relevant to butterfly biology: the rise in regional temperatures and consequent changes in other climatic attributes, the rate at which climate changes, the frequency and magnitude of extreme weather events.

The increase of CO_2 and other greenhouse gases is expected to cause an increase in the global mean temperature, with larger increases at high latitudes than elsewhere and larger increases during winter than summer (Climate Change, 1996).

There is scientific consensus that a small increase, approximately 0.5°C, in the average global temperature has taken place over the 19th century. According to R. Kivi (ed.) (1990), the annual mean temperature in Estonia has risen about 0.65°C since 1955.

The climate in a certain geographical location is dominantly influenced by atmospheric air masses and their movement. Estonia is geographically located at the crossing of different “imported” air masses. For the most part, local climate changes are generated by changes in general circulation. Global warming does not have a direct impact on global climate, but acts through the cyclogenetic and other dynamic processes. In Estonian conditions, winter is believed to be the most sensitive season to climate change. In summer and autumn, the climate-forming air currents can have a different origin and be more stable (Eerme, 1996).

Longer-term climatic patterns are determined by weather systems and influence the mean parameters of populations. Weather, changing every day, introduces extreme conditions for individual specimens and affects the mean density of population indirectly (Varley et al., 1978).

Consequently, climatic conditions create premises for the existence of a species, and weather conditions correct the result. In order to observe the development of a population, long-term trustworthy data on its abundance variation are needed, including complex investigations during its development, taking into account effects caused by parasitoids, diseases, etc.

Is the global warming indeed the only determining reason for the northward expansion of southern moth species? Further investigations will hopefully provide us with anwers to this question. Facts obtained by means of moth monitoring allow us to take it for granted.

K. Mikkola and L. Hulden (2000) represent the point of view that the increasing number of *Macrolepidoptera* in Finnish fauna as a result of climate change has not yet been sufficiently proved. According to the results from Finland, the relative change of the equilibrium point of the mean values of 800 resident species of *Macrolepidoptera* is very close to the relative change in summer mean temperatures (SMT) on decadal level in the 20th century. Since the 1960s, the annual mean temperature (AMT) has strongly deviated from the SMT. The AMT has increased by some 0.6°C while the SMT has varied only by ± 0.1°C since the 1940s.

MATERIALS AND METHODS

A pilot moth monitoring project was started in 1994 with tree sites for the Nordic moth monitoring scheme (2 traps in each: Elva, Vilsandi, Palmse) and four nationally financed sites in Estonia (1 trap in each: Tallinn Botanical Gardens, Ahtma/Klooga-ranna, Saue, Puka) (Söderman et al., 2000).

Continuous trapping (Karvonen et al., 1979) of moths by using Jalas-type light traps on eight Estonian sites (2 traps in each) during 1995–1998 (in the framework of the project *Nature Monitoring in the Eastern Baltics*) has resulted in phenological data consisting of more than 530,000 specimens of 647 species (Kruus & Viidalepp, 2001; Viidalepp et al., 2001).

During the years 1999–2000, the monitoring project proceeded on twelve sites, one light trap used in each. Two sites of former observations were closed (Elva and Vilsandi) and replaced by six new ones: Uhtna/Sämi, Nigula, Pähni, Saue, Salinõmme and Alatskivi/Saburi (Fig. 1). Data about 340 000 *Macrolepidoptera* specimens were added to the database.

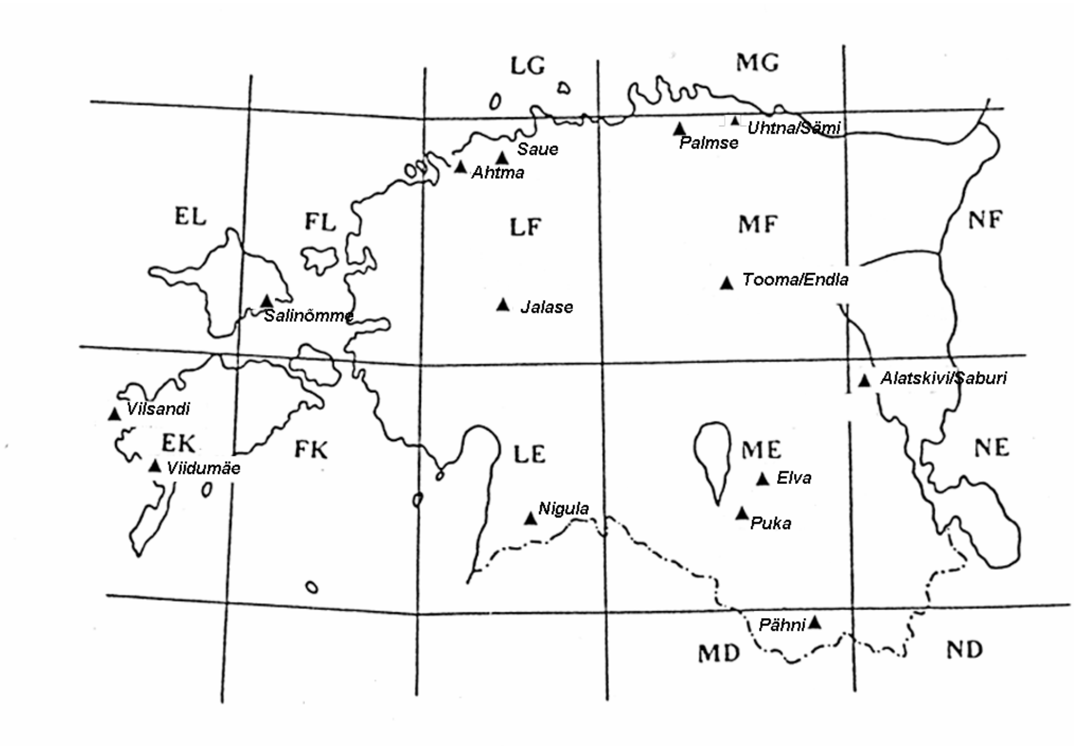


Fig. 1. Location of light traps for moth monitoring in Estonia in years 1994–2000.

During that period, in addition to Estonian *Macrolepidoptera* fauna there were discovered *Watsonilla binaria* (Hufnagel, 1767), *Campaea margaritata* (Linnaeus, 1767), *Peribatodes secundaria* (Denis & Schiffermüller, 1775), *Alcis bastelbergeri* (Hirschke, 1908), *Parectropis similaria* (Hufnagel, 1767), *Stegania cararia* (Hübner, 1790), *Epirhoe rivata* (Hübner, 1813), *Arctornis L-nigrum* (Müller, 1764), *Nycteola revayana* (Scopoli, 1772), *Xestia rhomboidea* (Esper, 1790), which are characterised by European distribution and nemoral ecology. All the named species (except *E. rivata*, associated with *Galium* spp. as foodplants, and *P. secundaria*, associated with *Picea excelsa, Juniperus communis* and other coniferous species, as foodplants), are confined to deciduous trees and shrubs – to *Quercus* robur, *Betula* spp*., Tilia* spp*., Acer* spp., *Corylus avellana* a.o. (Bergmann, 1953, 1954, 1955a, 1955b; Koch, 1984; Nowacki, 1998; Porter, 1997; Seppänen, 1970).

In addition to two well-known forest pests of the genus *Epirrita* Hübner, 1822 previously known to consume fresh leaves of deciduous trees, a third western taxon *Epirrita christyi* (Allen, 1906) has appeared first in Viidumäe Nature Reserve, the Island of Saaremaa, reaching high population density there in autumn 1998.

Of the species listed above, *Watsonilla binaria, Campaea margaritata* and *Epirhoe rivata* are to be bivoltine in Estonia, appearing in two generations during the vegetation period.

RESULTS AND DISCUSSION

Estonia is located on the eastern coast of the Baltic Sea between 57°30´N and 59°40´N. It represents a transition zone from the maritime climate type to the continental one. In spite of its comparatively small territory, climatic differences are significant, especially during the colder half of the year. For example, the mean air temperature in January varies from –2.5°C on the western coast of the Island of Saaremaa to up to –7.5°C in the coldest places in Estonia. The mean duration of snow cover varies between 75 and 130 days. Furthermore, temporal variability of meteorological values has been very high in Estonia. Weather conditions depend directly on cyclonic activity in the Northern Atlantic. Long-term fluctuations in their intensity reflect meteorological anomalies. Based on high variability of weather conditions, Estonia can be expected to be a region sensitive to possible climate changes (Jaagus, 1996).

In the present study, data from the Estonian Meteorological and Hydrological Institute (EMHI) meteorological database are used to characterise weather conditions for Tallinn (Harku), Tartu (Tõravere) and Pärnu stations, reflecting general differences in weather conditions between Western, Northern and Eastern Estonia. The mean air temperature is of most important meteorological value for revealing climate change. In Estonia the longest observation periods were: in Tallinn, representing Northern Estonia with the longest observation period 1828–1994; in Tartu (1866–1994), located in the continental part of the south-east; in Pärnu (1842–1994), situated on the coast of the Gulf of Riga in the south-west. There is very high correlation (more than 0.95) between the time series of annual mean air temperatures at the three stations. Therefore, data measured in Tallinn can represent the whole country quite well. Annual mean air temperature has increased by 0.7–1.0°C at every station in Estonia since the middle of the 19th century (Jaagus, 1996).

Table 1. Numbers of *Macrolepidoptera* specimens according to monitoring sites, 1994–2000.

	1994	1995	1996	1997	1998	1999	2000	Total
Ahtma	8,639	25,517	20,591	17,480	12,691	24,681	21,278	**130,877**
Jalase		14,599	13,254	9,714	8,860	9,656	7,469	**63,552**
Endla/Tooma		19,084	13,375	14,942	12,645	7,268	6,208	**73,522**
Elva	7,105	9,435	7,643	5,043	6,338			**35,564**
Puka	7,828	29,523	44,777	25,699	23,951	31,123	20,377	**183,278**
Palmse	19,702	19,305	19,969	23,591	16,358	16,092	12,597	**127,614**
Viidumäe		12,128	34,649	19,119	11,907	6,655		**84,458**
Vilsandi	8,277	11,097	9,304	3,707	637			**33,022**
Saue	3,438					10,226	8,015	**21,679**
Saburi						16,700	9,912	**26,612**
Pähni						14,513	13,737	**28,250**
Uhtna/Sämi						15,737	12,855	**28,592**
Salinõmme						1,736	4,169	**5,905**
Nigula						35,336	31,404	**66,740**
Total	**54,989**	**140,688**	**163,562**	**119,295**	**93,387**	**189,723**	**148,021**	**909,665**

The temporal course of air temperature is coherent with large-scale temperature changes in the Northen Hemisphere. A significant increasing trend existed over the period from the middle of the 19th century up to the 1930s. Then a stable period followed. However, the last decade of the 20th century was the warmest in Estonia. The warming was observed in spring (by 1.9°C), autumn (by 0.3°C) and winter (by 1.4°C) but not in summer. Remarkable periodicities in air temperature series were not determined. Air temperature in winter had the highest variations. The determined annual mean values of the climate change during the last 100–150 years have been marked. As a general tendency, the climate has become more maritime. The mean air temperature has increased, particulary over the colder half of the year. Snow cover duration has decreased significantly (Jaagus, 1996).

The accumulation of phenological data is the most significant result of moth monitoring projects in the observations of 1994–2000. The data have been recorded at weekly intervals.

The results of the moth monitoring demonstrate that the numbers of weekly trapped specimens are never homogenous. Aggregation of moths in light traps is greater in some years, presupposed due to relatively favourable weather conditions (Table 1). If comparing trapping results for the years 1995 and 1999, the difference is remarkable. The total productiveness of traps on Ahtma and Puka monitoring sites in 1999 exceeded twice the corresponding data for the year 1998 and was nearly equal to the number of moths trapped in 1995. During the seven-year monitoring period, high catches have been made in two years, 1995 and 1999. Also the total of occasional summer broods has been markedly high in 1995 (Söderman et al., 2000; Kruus & Viidalepp, 2001).

The preconditions for this phenomenon may be found in the weather peculiarities of the preceding years. September and November of 1993 were extremely cold and dry. These were the coldest September and November of the century. December was again warmer than usual with wet snow. The mean air temperature of 1994 in Estonia varied from 4.5°C in North-East to 6.5°C on the western coast. May and June were relatively cool months, July and the first decade of August, however, extremely warm. There was no real winter at the end of 1994. Temperature was continuously higher than the mean temperature at the beginning of 1995.

The year 1995 was quite warm, i.e. 1.0–1.7°C higher than the mean temperature of many years (Fig. 2). Remarkable heat waves hit Estonia in June and October.

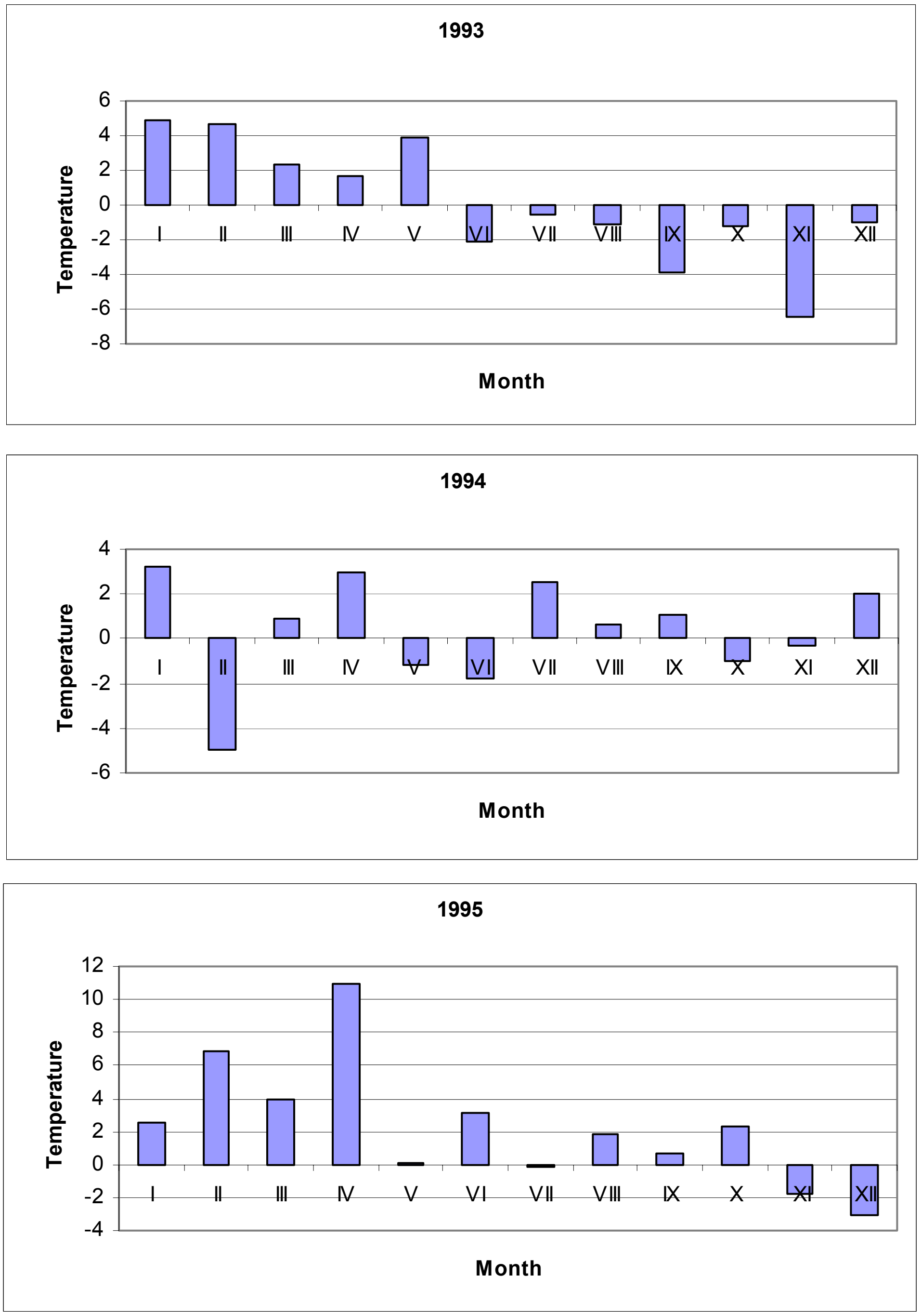
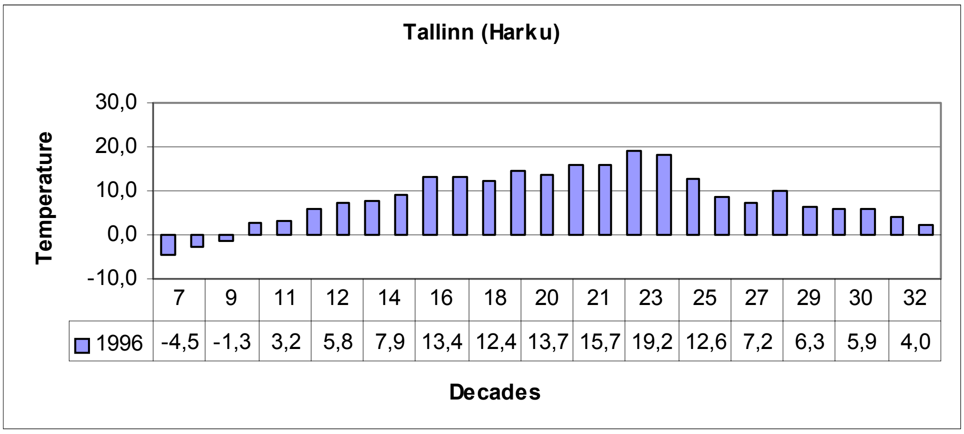
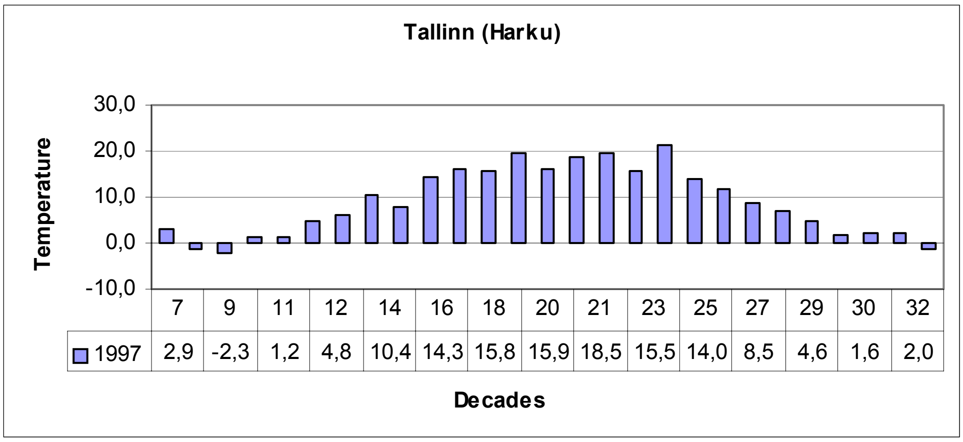


Fig. 2. Deviation of the mean temperature (°C) from the normal value in Estonia in 1993–1995. According to (Kotli, 1994, 1996; Pärnamägi, 1995).





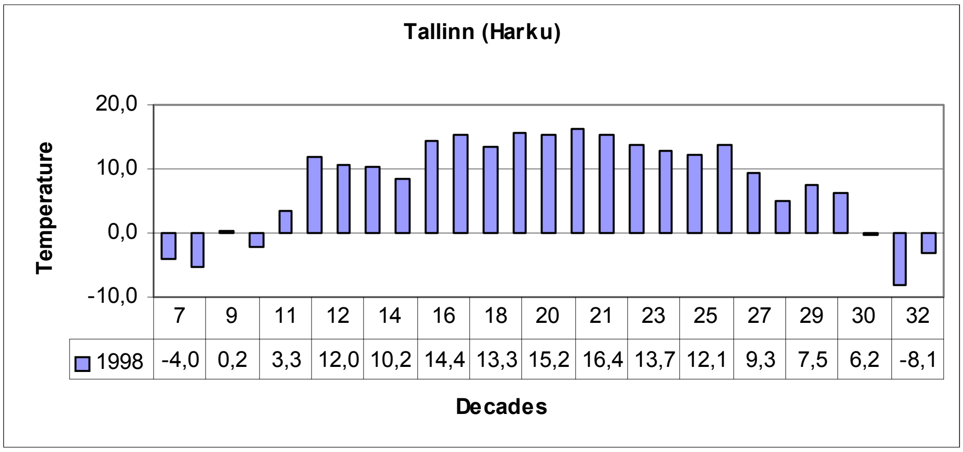
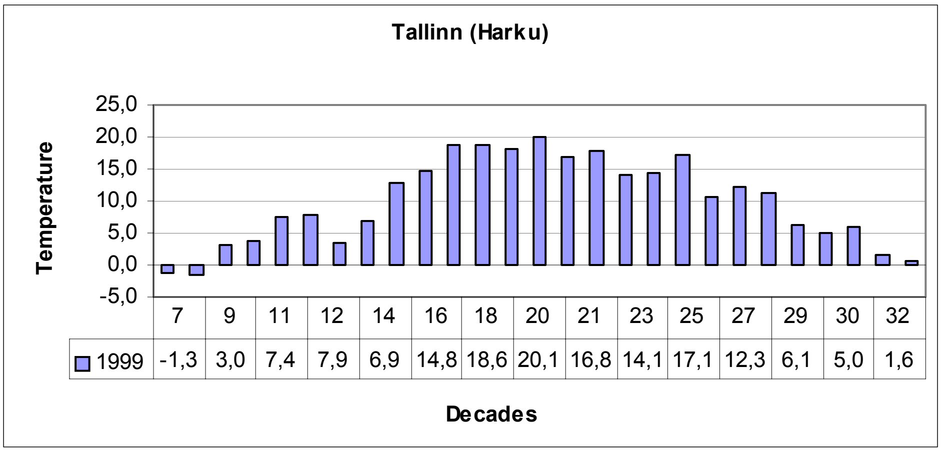
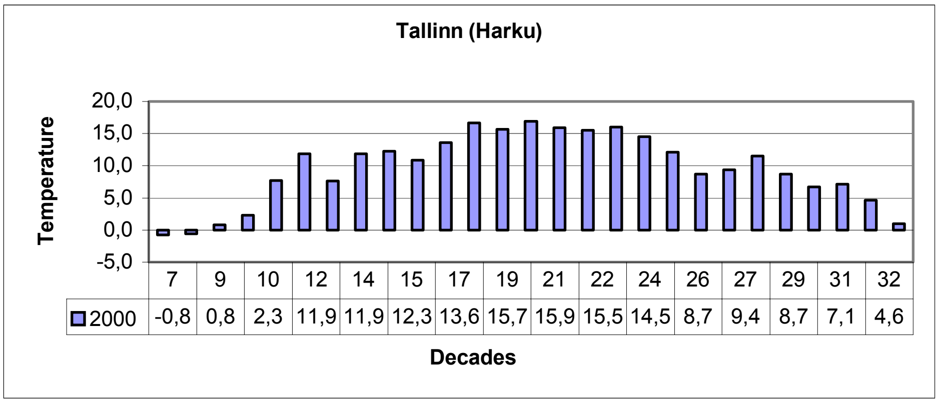


Fig. 3. Mean decade temperatures (°C) in Tallinn, 1996–1998; 7–33: decades from the beginning of the year.





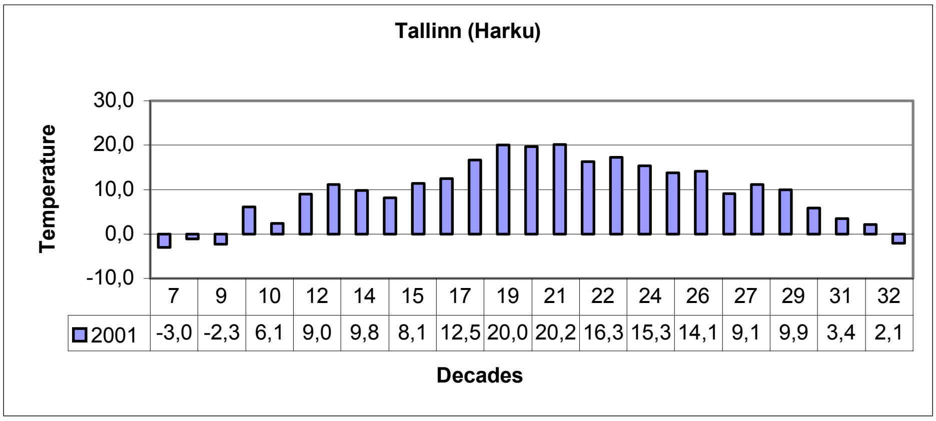
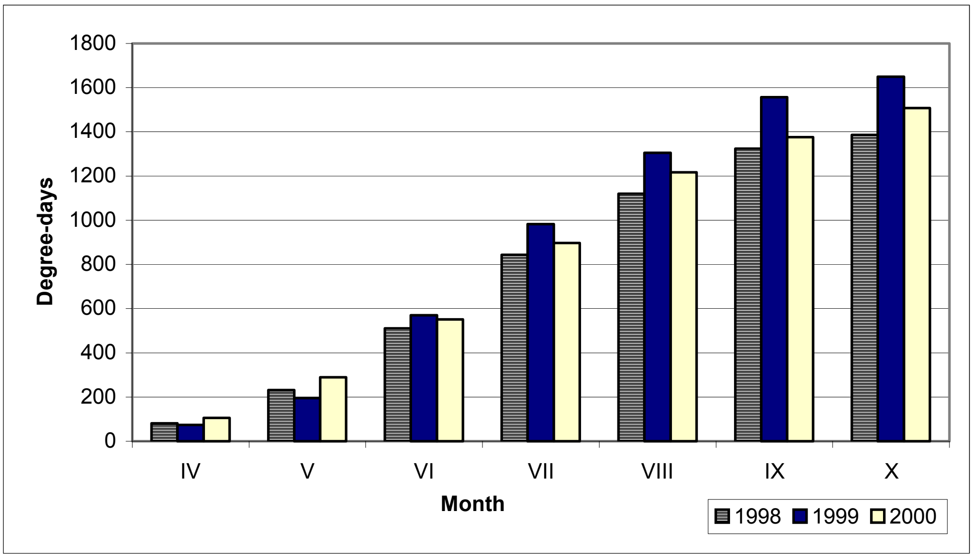


Fig. 4. Mean decade temperatures (°C) in Tallinn, 1999–2001; 7–33: decades from the beginning of the year.

In the year 1996, seven months of the year were cooler than usual; however, the mean temperatures of April and August were higher than usual. The spring and summer were very unsettled (Kotli, 1994, 1996, 1997; Pärnamägi, 1995, 1996).

In the year 1999, the mean air temperature was higher than normal from late May to late August (Fig. 3 & 4). Accordingly, the sums of effective temperatures in 1995 and 1999 exceeded those of preceding years (Fig. 5), and obviously both years were favourable for insect development.



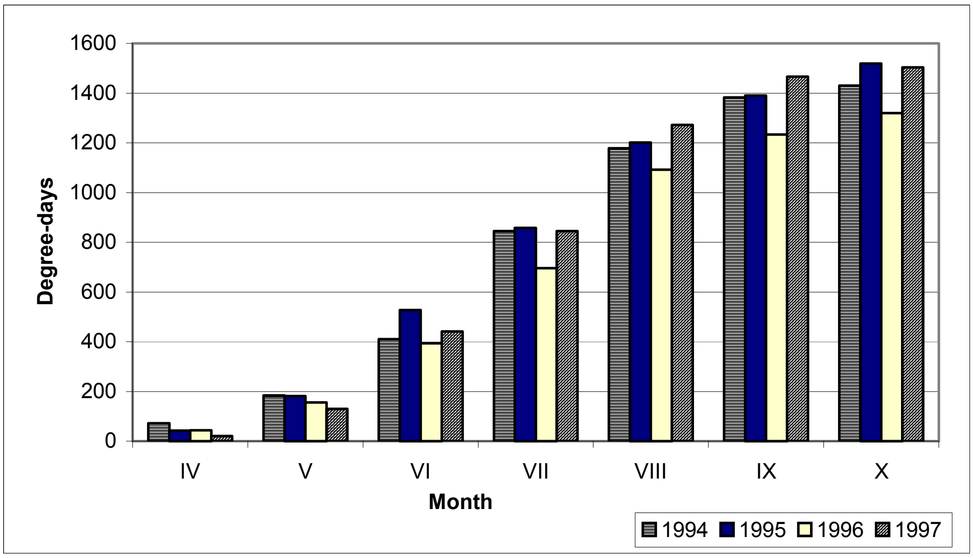


Fig. 5. Cumulative monthly sums of effective (> 5°C) temperatures (degree-days) in Tallinn, 1994–1997 (above) and 1998–2000 (below).

Table 2. Increase of abundance in *Campaea margaritata* on West Estonian monitoring sites, 1995–2001. 23…43: weeks from the beginning of a year.

	Week/ Year	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**Total**
Viidumäe	1995						1		1	1													3
Viidumäe	1996							2	1	1													4
Viidumäe	1997						1	3	6														10
Viidumäe	1998						2	3	1	1													7
Viidumäe	1999	1		5	4	3	5	1															19
Viidumäe	2000					12																	12
Viidumäe	2001					1	24		4										1				30

A change of voltinism in species is an effect of the temperature increase. In a warming environment, the eclosion of potentially bivoltine butterflies and moths is shifted to an earlier time and longer photoperiod. It results in partial or complete bivoltinism (Viidalepp & Kruus, 2000).

During the monitoring period, it has been found that three species just discovered occur bivoltine in Estonia, appearing twice during the vegetation period: *Watsonalla binaria*, *Campaea margaritata* and *Epirhoe rivata*.

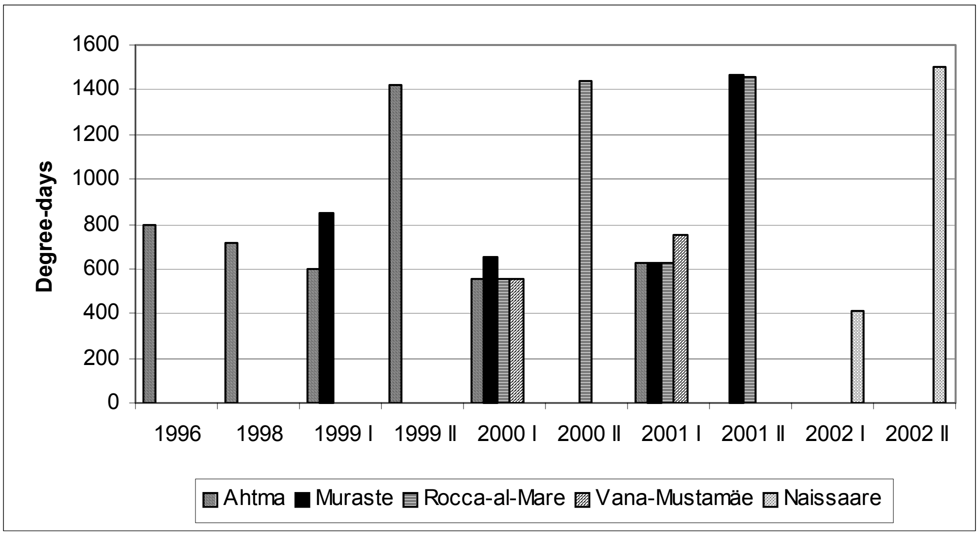


Fig. 6. Timing of flight periods of *Campaea margaritata* in Tallinn and its vicinity. The summer generation emerges at a sum of effective (> 5°C) temperatures (degree-days) above 1400, whereas the appearance of spring brood of moths seems to be determined by some other agents.

Table 3. First and subsequent records of *Campaea margaritata* in Estonia, 1995–2002. 23…43: weeks from the beginning of a year.

	Week/ Year	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**Total**
Viidumäe	1995						1		1	1													3
Viidumäe	1996							2	1	1													4
Ahtma	1996									2													2
Viidumäe	1997						1	3	6														10
Hirmuste	1997								20														20
Paldiski	1997								1														1
Viidumäe	1998						2	3	1	1													7
Ahtma	1998							2															2
Paldiski	1998							1															1
Viidumäe	1999	1		5	4	3	5	1															19
Ahtma	1999				1		1	5						1				1					9
Muraste	1999						1	1	1														3
Kaavi	1999						2																2
Viieristi	1999						15																15
Viidumäe	2000					12																	12
Ahtma	2000				1	2	18	9	1														31
Muraste	2000					3	4	5															12
Rocca-al-Mare	2000				1	3	1	17	5										1				28
Hindu	2000						1	3	2														6
Nõva	2000				1																		1
Sääre	2000				1																		1
Vana-Mustamäe	2000				1																		1
Mõntu	2000						1																1
Abruka	2000										1												1
Viidumäe	2001					1	24		4										1				30
Ahtma	2001					5	19	8									2	1	6	1	2	1	45
Muraste	2001					5	16	7	1	3	3						1	2	1	1			40
Rocca-al-Mare	2001					4	7	19	1	5						1	4	2		1			44
Keila-Joa	2001				1																		1
Viidumäe	2001					1	24		4										1				30
Palivere	2001					1																	1
Tagamõisa	2001						1																1
Vana-Mustamäe	2001						2																2
Puhtu	2001							1															1
Pullapää	2001							4															4
Naissaare	2002	3	29	2		9	12	1							2	7	9	9	2				85

The discovery of the nemoral geometrid *Campaea margaritata* in Viidumäe Nature Reserve, the Island of Saaremaa, in 1995 was perhaps less astonishing than its rapid further expansion and subsequent increase in abundance on other islands, and from Western Estonia up to the suburbs of Tallinn (Kruus, 1996, a.o.). In the years 1999, 2000 and 2002 it appeared to be bivoltine in Tallinn and its vicinity (Table 2 & 3; Fig. 6).

The species is regularly bivoltine in the beech and oak forests of Southern and Central Europe. However, its larvae feed on the foliage of *Fagus, Betula, Tilia, Corylus* a.o. deciduous trees and bushes as well (Bergmann, 1955; Koch, 1984; Schwenke, 1978; Seppänen, 1970). The abundance of *C. margaritata* is increasing.

CONCLUSIONS

A northward shift of the distribution areas of butterflies and moths due to the global warming is confirmed according to data of moth monitoring in Estonia, 1994–2000. The background meteorological data appear to be in accordance with the total catches of *Macrolepidoptera* and are found suitable for further detailed analyses of monitoring results.

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