ISSN 1995-4255, Contemporary Problems of Ecology, 2021, Vol. 14, No. 7, pp. 822–826. © Pleiades Publishing, Ltd., 2021.
Russian Text © The Author(s), 2021, published in Lesovedenie, 2021, No. 4, pp. 372–378.

Consequences of the Outbreaks of the Poplar Leaf Miner and Other Mining Microlepidoptera in St. Petersburg

Bùi Đình Đức[a, b], L. L. Leont'ev[b], S. V. Baryshnikova[c], and A. V. Selikhovkin[a, d, *]

[a] *Vietnam National University of Forestry, Xuan Mai Town, Hanoi, 13417 Vietnam*
[b] *St. Petersburg Forestry University, St. Petersburg, 194021 Russia*
[c] *Zoological Institute of the Russian Academy of Sciences, St. Petersburg, 199034 Russia*
[d] *St. Petersburg State University, St. Petersburg, 199034 Russia*
**e-mail: a.selikhovkin@mail.ru*

Received February 17, 2020; revised November 8, 2020; accepted April 6, 2021

Abstract—The poplar leaf miner *Phyllonorycter populifoliella*, a well-known pest from the Gracillariidae family, was first recorded in St. Petersburg in the middle of the last century. This species had its first outbreak in 1991–1999, followed by death of a significant part of poplars in the city and suburbs. Despite the prominence of this pest group, there are limited data on the effect on the host-plant state from mining-insect damage to the trees' assimilation apparatuses. The changes in the radial growth of the Berlin poplar *Populus* × *berolinensis* (70–80 years), which was intensely damaged during the outbreak, and the white poplar *Populus alba* (the average age is 100 years) were compared, and the damage to the latter was much less severe. The growth of white poplar slightly decreased during the outbreak (1991–1998), from 4.79 mm (1942–1990) to 3.61 mm (1991–1998), and then quickly recovered to the initial values and up to 4.86 mm (1999–2018). The growth of the Berlin poplar over the same time periods fell sharply, from 6.29 to 2.45 and 1.80 mm, respectively. It was shown that the growth of Berlin poplar sharply decreased within 5–7 years from the beginning of the outbreak and that the low growth levels persisted afterwards. This indicated that there may be irreversible consequences for poplars in the case of prolonged and intense damage by mining pests. the significant impact of mining pests on the plantation state requires monitoring and measures to control the spread of pests of this group. The problem is further aggravated by the appearance of three species of invasive mining lepidoptera, the lime leaf miner *Ph. issikii*, the horse-chestnut leaf miner *Cameraria ohridella*, and the leaf blotch miner moth *Acrocercops brongniardella,* on the territory of St. Petersburg and the surrounding territories.

Keywords: poplar leaf miner, leaf mines, radial growth, stands' state
DOI: 10.1134/S1995425521070039

INTRODUCTION

Outbreaks of microlepidoptera from the family of the leaf miner (Lepidoptera: Gracillariidae) have attracted increasing attention in the last two decades. This is largely due to the simultaneous invasive activity of representatives of this family during a relatively short time interval in the late XX to the early XXI centuries. During this period, *Parectopa robiniella* Clemens, 1863, *Macrosaccus robiniella* (Clemens, 1859), *Caloptilia roscipennella* (Hübner, 1796), *Cameraria ohridella* Deshka et Dimić, 1986, *Phyllonorycter issikii* (Kumata, 1963) and *Phyllocnistis citrella* Stainton, 1856 (Skhvitaridze et al., 2006; Antyukhova, 2010; Shchurov, Rakov, 2011; Maslyakov, Izhevskii, 2011; Gninenko et al., 2011; Karpun, 2018) appeared as pests on the territory of Russia, expanding their range.

Three species of leaf miner, the lime leaf miner *Ph. isikii*, horse-chestnut leaf miner (Ohrid miner) *C. ohridella*, and leaf-blotch miner moth *Acrocercops brongniardella* (Fabricius, 1798), have penetrated the plantations of St. Petersburg in the last two decades, while their secondary ranges reached the northern boundary of the distribution of forage species (Selikhovkin et al., 2018, 2020; Bùi Đình Đức et al., 2020).

The poplar leaf miner (hereinafter referred to as the poplar moth) *Phyllonorycter populifoliella* (Treitschke, 1833) also belongs to the *Gracillariidae* family. It is a widespread, mass pest of poplar with long-term outbreaks of mass reproduction, especially in urban areas. In a fundamental article by I.V. Ermolaev (2019), the distribution and features of the biology of this species at the population-species and organism levels based on the literature and her own data is considered in detail. The poplar moth has been known in St. Petersburg and the surrounding area since 1974 (L'vovskii, 1994). Prior to that, the only reliable find was made by A.M. Gerasimov in 1936 (Selikhovkin et al., 2018). The mass planting of poplars in the postwar years allowed the spread of this pest in St. Petersburg and

the emergence of an outbreak of mass reproduction of the poplar moth in 1992–1999 (Selikhovkin, 2010; Selikhovkin et al., 2012).

The poplar moth and the aforementioned invasive species, the lime speckled moth, the Ohrid miner, and the broadminded oak moth, are well known as serious pests with mass outbreaks. Continuous damage to leaves and their early abscission sharply reduce the aesthetic appearance of plantations and lead to significant deterioration in the condition of tree species damaged by them: the poplar, linden, oak, and horse chestnut. In particular, with a population density of two to three mines per leaf, there is a significant decrease in radial growth and shoot lengt, and a deterioration in the reproductive characteristics of the poplar (Ermolaev and Zorin, 2011). It was also shown that there was slight decrease in the growth of the quaking aspen *Populus tremuloides* Michx. in North America as a result of the reproduction of the miner moth *Phyllocnistis populiella* Chambers, 1875 (Phyllocnistidae) (Wagner et al., 2008). However, a study of the relationship between the dynamics of radial growth and the population density of the lime moth in St. Petersburg by Yu.A. Timofeeva (2015) did not reveal significant correlations at a population density of one to four mines per leaf. The author rightly notes that there are more environmental stress factors in St. Petersburg than in the area studied by I.V. Ermolaev and D.A. Zorin (2011). Accordingly, at a relatively low population density, the effect of insect damage to leaves is not so pronounced, and a much larger amount of material is required to obtain a representative sample.

The complexity of the analysis of the relationship between the growth and damage of the assimilation apparatus by pedunculate oak insects is well-illustrated by the example of the influence of precipitation and other meteorological factors on the reproduction of the green-oak leafworm and other phyllophagous lepidoptera (Rubtsov and Rubtsova, 1984). Radial growth is a cumulative indicator that depends on a combination of a number of factors. In addition, it is necessary to take into account the adaptive reactions of deciduous trees, which make it possible to minimize the loss of growth during a single defoliation of crowns. Accordingly, estimates of the growth losses turn out to be more accurate not for one year but for longer periods (Rubtsov and Utkina, 2008). Such studies have been carried out for open-living phyllophagous insects (Varley, Gradwell, 1960; Rubtsov, Rubtsova, 1984; Simmons et al., 2014), but, with regard to mining species, we know only of the aforementioned work of I.V. Ermolaeva and D.A. Zorin (2011) and the publication of N.M. Zavada (1987, cited from: Ermolaev and Zorin, 2011), according to which the annual oak defoliation by a leaf-blotch miner moth leads to a decrease in radial growth. However, the latest review of the literature on this pest does not contain such information (Utkina, Rubtsov, 2019).

Thus, the role of microlepidoptera (which are becoming increasingly important as pests of the assimilation apparatus of woody plants) in plantation weakening is unclear. The goal of our work was to clarify the influence of outbreaks of the mass reproduction of mining lepidoptera on changes in the state of woody plants in terms of changes in radial growth.

EXPERIMENTAL

The main object of research was the poplar moth, which provided the only, well-localized in time, very strong, and extremely prolonged outbreak of mass reproduction in St. Petersburg in 1991–1999 (Bondarenko, 2008; Selikhovkin, 2010; Selikhovkin et al., 2012, 2018). The Berlin poplar *Populus berolinensis* Dippel and balsam poplar *Populus balsamifera* L. predominate in St. Petersburg. During the outbreak, all leaves on all poplars belonging to these species were completely covered with mines. The leaves were observed to drop earlier. The development of shoots from dormant buds partially compensated for the loss of the assimilation apparatus; however, mines of the first and, more often, second generation appeared on the leaves of these shoots. There is also the white poplar *Populus alba* L. in St. Petersburg. During the outbreak, these poplars were practically undamaged by the poplar moth. The average number of mines on one leaf varied from one to four. The proportion of leaves damaged by the poplar moth did not exceed 10% with one or, rarely, two mines per leaf.

The moth species during the outbreak was in all cases determined by the imago. Seven hundred males were analyzed. All individuals belonged to the same species, *Phyllonorycter populifoliella* (Treitschke, 1833) (Lepidoptera: Gracillariidae). In this regard, damage to poplars by this moth was chosen as a model object to assess the impact of damage on changes in the tree states.

Radial growth is adopted as a tool for the assessment of the change in the tree states.

The cores for the assessment of the dynamics of growth change were taken from old poplars, the age of which varied from 70 to 100 years. Cores were taken from the white poplar In the park of the Forestry University (20 cores, coordinates of 59°59′41″ N, 30°20′16″ E) and from the Berlin poplar in Palevsky square and next to, it near Elizarov Avenue (20 cores, coordinates of 59°53′37″ N, 30°25′02″ E). Seedling measurements were carried out with an MBS-9 binocular microscope.

All calculations were performed with the taken core samples. For each point, the mathematical expectation of the arithmetic mean was calculated for all cores for each year of growth. The increments were compared and the differences assessed for the totality of all trees in each variant for all years in the period before the outbreak (1942–1991) and after the outbreak

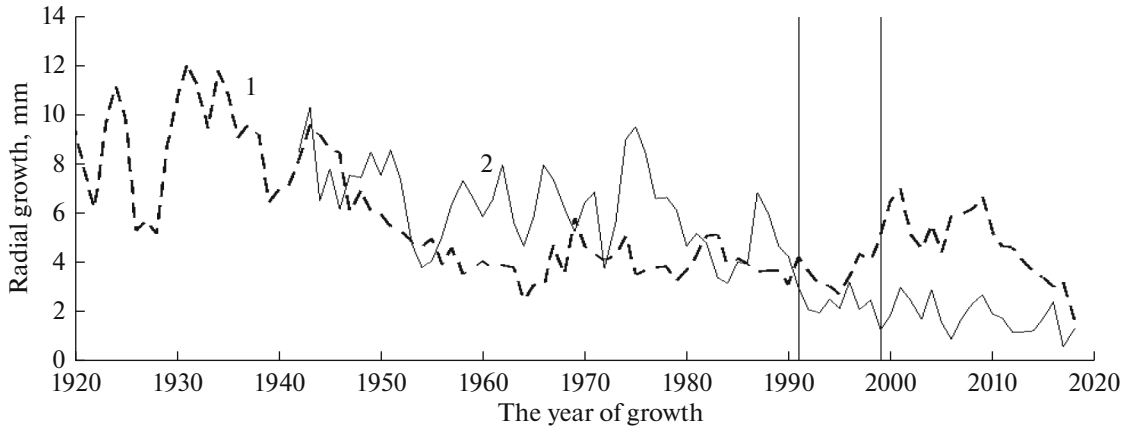

Fig. 1. Consequences of mass reproduction of the poplar leaf miner *Phyllonorycter populifoliella* and other miner microlepidoptera in St. Petersburg. 1, white poplar; 2, Berlin poplar. The two vertical lines correspond to the period of the outbreak of mass reproduction of the species.

(1992–2018). The hypothesis that the samples belong to the same general population was tested with the Student's *t*-test.

RESULTS AND DISCUSSION

Table 1 and Fig. 1 show the change in growth before and after the outbreak of mass poplar-moth reproduction. The outbreak lasted from 1991 to 1999. In three cases, these data illustrate significantly different rates.

1. Before the outbreak, the average growth of the Berlin poplar from 1942 to 1990 was higher than the growth of the white poplar.

2. During and after the outbreak, from 1991 to 2018, the average growth of the Berlin poplar was significantly lower than the average growth of the white poplar.

3. After the outbreak, the average growth of the Berlin poplar from 1999 to 2018 has significantly decreased in comparison with the previous period and reached the minimum values for the entire growth period; at the same time, the white-poplar growth increased and reached the initial values of the period 1942–1990.

It should be noted that all of the poplars of the taken cores were approximately of the same age, 100–70 years old; the white poplar was 100 years old, and the Berlin poplar were 70–80 years old. A significant decrease in the growth of moth-damaged Berlin poplars and younger poplars in comparison with white poplars clearly illustrates the negative consequences of the outbreak of mass poplar-moth reproduction. A distinct decrease in the growth rate begins to manifest itself 5–7 years after the onset of the outbreak. It can be seen from Fig. 1, which illustrates the overall growth dynamics. At the same time, a sharp decrease in growth is notable on the graph in the fifth or sixth year of the outbreak. We calculated the average values of growth for two periods: (1) before the appearance of a probable response from trees, which manifested as a sharp decrease in growth, 1942–1996; (2) the beginning of a sharp decline in growth as the manifestation of a likely response to injury, 1997–2018. For these periods, we obtained the following average values of the increment in mm: 5.88 ± 0.27 and 1.85 ± 0.14, respectively, for the Berlin poplar (the differences are significant at $p \le 0.001$) and 4.64 ± 0.22 and 4.80 ± 0.28 for white poplar (differences are insignificant). These indicators illustrate a significant delay in the response to severe damage in the Berlin poplar and the absence of a delayed response in the case of weak damage in the white poplar.

The presented results show a significant decrease in growth after damage by the poplar leaf miner. A sharp decrease in growth 5–7 years from the beginning of the outbreak of reproduction and the subsequent preservation of growth at a low level is indicative of a fundamental deterioration in the condition of trees after repeated damage by the poplar moth. A decrease in

Table 1. Average values of poplar growth (mm) for different time periods associated with an outbreak of mass reproduction of the poplar leaf miner *Phyllonorycter populifoliella* (Treitschke, 1833) in St. Petersburg

Poplar type	1942–1990*	1991–1998* (outbreak)	1999–2018*
* Berlin poplar *Populus* × *berolinensis*	6.29 ± 0.24*	**2.45 ± 0.16	**1.80 ± 0.15
* White poplar *Populus alba*	***4.79 ± 0.24	*3.61 ± 0.21	***4.86 ± 0.31

* Differences are significant at $p \le 0.001$. ** Differences are significant at $p \le 0.01$. *** Differences are not significant.

white-poplar growth should also be noted. The average number of mines per leaf on this poplar species during the outbreak did not exceed four, but even such relatively low damage to leaves led to a noticeable decrease in growth. This is consistent with the conclusions made earlier in relation to the lime moth: a growth decrease was noticeable at a mining density of one to two mines per leaf (Ermolaev and Zorin, 2011). Trees, apparently, recover quickly after this not very significant damage to leaves. In particular, although the average age of the white poplar trees in our case was 30 years older than the Berlin poplar, the white-poplar growth quickly recovered and did not decrease further.

It is known that mining pests have a significant effect on plant physiology. Damage to the leaf mesophyll by these insects leads to a decrease in the intensity of photosynthesis, disruption of metabolic processes, decreased growth, and plant weakening (Raimondo et al. 2003; Wanhua et al., 2015). In the lime and poplar leaf miners, the mines are located on the underside of the leaf. This has a particularly strong negative effect, since it disrupts the stomata (Welter, 1989; Ermolaev, 2011). In our case, during the outbreak of poplar-moth reproduction, the leaves lost their photosynthetic ability by the end of July and started to fall by mid-August. All leaves were damaged during the outbreak, including those on shoots that developed from dormant buds.

The leaf damage on summer shoots was caused by caterpillars of the second generation. They did not have time to fully develop and died, but the leaves were still damaged quite badly. Three to eight mines formed on each leaf (Bondarenko, 2008; Selikhovkin, 2010).

In addition to direct leaf damage, the mass reproduction of mining microlepidoptera can apparently contribute to the spread of mycogenic diseases (Gottwald et al., 2007). It was proposed earlier that the mass death of poplars in roadside alley plantations in St. Petersburg and the Leningrad region in the late 1990s and early 2000s is associated with the consequences of a poplar-moth outbreak, in particular, the weakening of poplars and the spread of pathogens (Selikhovkin, 2010; Selikhovkin et al., 2018).

Despite the obvious importance of the problem of the mass reproduction of mining microlepidoptera, no serious attention is paid to the control of the population density of species of this group in the system of forest pathological monitoring or the protection of urban and suburban plantations from this group of insects. Since 2017, a stable poplar moth focus has formed in St. Petersburg, and its population density is gradually increasing (Mamaev, 2019; Sitnikova, 2019). The appearance in St. Petersburg of invasive species—the chestnut, lime leaf, and leaf-blotch miner moths—is of serious concern. The aforementioned negative consequences of leaf damage can appear after an increase in the number of Ohrid, lime leaf, and leaf-blotch miner moths, as well as other leaf-mining pests with a tendency toward a sharp increase in population density. The population density of the horse-chestnut leaf miner in 2019 has already reached a high level. The number of lime and leaf-blotch miner moths is still at a low level. However, it is known that the adaptation of invaders to new habitats can take a very long time (Alimov, Bogutskaya, 2004). In particular, poplar moths were rare in St. Petersburg until 1974 (L'vovskii, 1994). Then, 17 years after the widespread appearance of poplars in city plantations, a powerful and prolonged outbreak of mass reproduction occurred.

CONCLUSIONS

The mining microlepidoptera undoubtedly exert a negative impact on the state of mass propagation stands, as shown by the example of the poplar leaf miner. Damage by this species has a strong and, apparently, irreversible effect on the state of adult poplars as a result of a prolonged (more than 5 years) outbreak of mass reproduction with annual damage to most of the plant assimilation apparatuses. The significant influence of this pest group on the state of plantings during outbreaks of mass reproduction and the possible subsequent death of plantings lead to the need for monitoring and measures to control the spread of this pest group.

COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflicts of interest. This article does not contain any studies involving animals or human participants performed by any of the authors.

REFERENCES

Alimov, A.F. and Bogutskaya, N.G., *Biologicheskie invazii v vodnykh i nazemnykh ekosistemakh* (Biological Invasions in Aquatic and Terrestrial Ecosystems), Moscow: KMK, 2004.

Antyukhova, O.V., The locust digitate leafminer (*Parectopa robiniella* Clemens) is dangerous pest of *Robinia pseudoacacia* L. in Transnistria, *Izv. S-Peterb. Lesotekh. Akad.*, 2010, no. 192, pp. 4–11.

Bondarenko, E.A., An outbreak of the poplar leafminer *Phyllonorycter populifoliella* Tr. (Lepidoptera, Gracillariidae) in St. Petersburg, *Izv. S-Peterb. Lesotekh. Akad.*, 2008, no. 182, pp. 45–55.

Bùi Đình Đức, Denisova, N.V., Baryshnikova, S.V., Shevchenko, S.V., and Selikhovkin, A.V., Actual changes in the species composition and population density of phyllophagous insects in St. Petersburg, *Izv. S-Peterb. Lesotekh. Akad.*, 2020, no. 230, pp. 73–99. https://doi.org/10.21266/2079-4304.2020.230.73-99

Ermolaev, I.V., Ecological mechanisms of nonperiodical population wave: a case study of the poplar leafminer *Phyllonorycter populifoliella* (Lepidoptera, Gracillariidae), *Zh. Obshch. Biol.*, 2019, vol. 10, no. 6, pp. 451–476.

Ermolaev, I.V. and Zorin, D.A., Ecological consequences of invasion of *Phyllonorycter issikii* (Lepidoptera, Gracillariidae) in lime forests in Udmurtia, *Entmol. Rev.*, 2011, vol. 91, no. 5, pp. 592–598.

Gninenko, Yu.I., Kostyukov, V.V., and Kosheleva, O.V., New invasive insects in forests and green plantations of Krasnoyarsk krai, *Zashch. Karantin Rast.*, 2011, no. 4, pp. 49–51.

Gottwald, T.R., Bassanezi, R.B., Amorim, L., and Bergamin Filho, A., Spatial pattern analysis of citrus canker-infected plantings in São Paulo, Brazil, and augmentation of infection elicited by the Asian leafminer, *Phytopathology*, 2007, vol. 97, no. 6, pp. 674–683.

Karpun, N.N., The structure of complexes of harmful organisms of wood plants in the humid subtropics of Russia and biological substentiation of protection measures, *Doctoral (Biol.) Dissertation*, Sochi: All-Russ. Res. Inst. Floricult. Subtrop. Crops, 2018.

Liu, W.H., Dai, X.H., and Xu, J.S., Influences of leaf-mining insects on their host plants: a review, *Collect. Bot.*, 2015, vol. 34, p. e005.

L'vovskii, A.L., Lepidoptera insects (Insecta, Lepidoptera) within St. Petersburg, *Izv. Khar'k. Entomol. O-va*, 1994, vol. 2, no. 1, pp. 4–48.

Mamaev, N.A., Outbreak of mass reproduction of the poplar leaf miner *Phyllonorycter populifoliella* in the Nevsky district of St. Petersburg, *Materialy III Mezhdunarodnoi nauchno-prakticheskoi konferentsii molodykh uchenykh "Aktual'nye voprosy v lesnom khozyaistve," Sankt-Peterburg, 6–8 noyabrya 2019 g.* (Proc. III Int. Sci.-Pract. Conf. of Young Scientists "Urgent Problems in Forestry," St. Petersburg, November 6–8, 2019), St. Petersburg: Poligraf-Ekspress, 2019, pp. 205–207.

Maslyakov, V.Yu. and Izhevskii, S.S., *Invazii rastitel'noyadnykh nasekomykh v Evropeiskuyu chast' Rossii* (Invasions of Herbivorous Insects into the European Part of Russia), Moscow: Inst. Geogr., Ross. Akad. Nauk, 2011.

Raimondo, F., Ghirardelli, L.A., Nardini, A., and Sallee, S., Impact of the leaf miner *Cameraria ohridella* on photosynthesis, water relations and hydraulics of *Aesculus hippocastanum* leaves, *Trees*, 2003, vol. 17, pp. 176–382.

Rubtsov, V.V. and Rubtsova, N.N., *Analiz vzaimodeistviya listogryzushchikh nasekomykh s dubom* (Analysis of the Interaction of Leaf-Eating Insects with Oak), Moscow: Nauka, 1984.

Rubtsov, V.V. and Utkina, I.A., *Adaptatsionnye reaktsii duba na defoliatsiyu* (Adaptive Responses of Oak to Defoliation), Moscow: Grif i K, 2008.

Selikhovkin, A.V., Specific population dynamics of the poplar leaf miner *Phyllonorycter populifoliella* Tr. (Gracillariidae), *Izv. S-Peterb. Lesotekh. Akad.*, 2010, no. 192, pp. 220–235.

Selikhovkin, A.V., Denisova, N.V., and Timofeeva, Yu.A., Population density dynamics of mining microlepidoptera in St. Petersburg, *Izv. S-Peterb. Lesotekh. Akad.*, 2012, no. 200, pp. 148–159.

Selikhovkin, A.V., Baryshnikova, S.V., Denisova, N.V., and Timofeeva, Yu.A., Species composition and population dynamics of dominant dendrophagous moths (Lepidoptera) in St. Petersburg and its environs, *Entmol. Rev.*, 2018, vol. 98, no. 8, pp. 963–978.

Selikhovkin, A.V., Drenkhan, R., Mandel'shtam, M.Yu., and Musolin, D.L., Invasions of pests and fungal pathogens of wood plants in the northwest of the European part of Russia, *Vestn. S-Peterb. Univ., Nauki Zemle*, 2020, vol. 65, no. 2, pp. 263–283

Shchurov, V.I. and Rakov, A.G., Invasive species of dendrophilous insects in Krasnodar krai, *Izv. S-Peterb. Lesotekh. Akad.*, 2011, no. 196, pp. 287–294.

Simmons, M.J., Lee, T.D., Mark, J., Ducey, M.J., Elkinton, J.S., Boettner, G.H., and Dodds, K.J., Effects of invasive winter moth defoliation on tree radial growth in Eastern Massachusetts, USA, *Insects*, 2014, vol. 5, no. 2, pp. 301–318.

Sitnikova, D.D., Population density of the poplar leaf miner *Phyllonorycter populifoliella* (Treitschke, 1883) (Lepidoptera: Gracillariidae) of various geographic zones in 2019, *Materialy III Mezhdunarodnoi nauchno-prakticheskoi konferentsii molodykh uchenykh "Aktual'nye voprosy v lesnom khozyaistve," Sankt-Peterburg, 6–8 noyabrya 2019 g.* (Proc. III Int. Sci.-Pract. Conf. of Young Scientists "Urgent Problems in Forestry," St. Petersburg, November 6–8, 2019), St. Petersburg: Poligraf-Ekspress, 2019, pp. 217–220.

Skhvitaridze, O., Loladze, Z.P., and Partsvaniya, M.Sh., The citrus leafminer (*Phyllocnistis citrella*), *Zashch. Karantin Rast.*, 2006, no. 2, pp. 42–43.

Timofeeva, Yu.A., The influence of deciduous pests on the state of linden in parks of St. Petersburg, *Cand. Sci. (Biol.) Dissertation*, St. Petersburg: St. Petersburg State For. Tech. Univ., 2015.

Utkina, I.A. and Rubtsov, V.V., The leaf blotch miner moth (*Acrocercops brongniardella*) is widely known but less studied species, *Izv. S-Peterb. Lesotekh. Akad.*, 2019, no. 228, pp. 42–57.

Varley, G.C. and Gradwell, G.R., The effect of partial defoliation by caterpillars on the timber production of oak trees in England, *Proc. 11th Int. Congr. of Entomology, Vienna, Austria, August 17–25, 1960*, Vienna, 1960, pp. 211–214.

Wagner, D., DeFoliart, L., Doak, P., and Schneiderheinze, J., Impact of epidermal leaf mining by the aspen leaf miner (*Phyllocnistis populiella*) on the growth, physiology, and leaf longevity of quaking aspen, *Oecologia*, 2008, vol. 157, pp. 259–267.

Wanhua L., Xiaohua D.i, and Jiasheng X., Influences of leafmining insects on their host plants: A revie , *Collectanea Botanica*, 2015, vol. 34.005.

Welter, S.C., Arthropod impact and plant gas exchange, in *Insect-Plant Interactions*, Boca Raton, FL: CRC Press, 1989, vol. 1, pp. 135–150.

Translated by P. Kuchina