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Probability of the Emerald Ash Borer *Agrilus planipennis* Fairmaire (Coleoptera, Buprestidae) Spreading by Flight in the Green Spaces along the M10 Highway from Moscow to St. Petersburg

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Abstract—The emerald ash borer (*Agrilus planipennis* Fairmaire) was introduced to Moscow, from where it began active radial spreading since the mid-2000s outbreak, advancing in the northern directions much less than in the southern ones. *Agrilus planipennis* is able to spread both by flight and by hitchhiking, covering long distances directly on vehicles or with transported goods. The emerald ash borer disperses by flight in case of the presence and abundance of host plants (ash trees) along its dispersal route. Although *A. planipennis* was first recorded in St. Petersburg in 2020, it could have probably got there by hitchhiking. The emerald ash borer could hardly have reached the city on its own, since there are no continuous ash stands in the largest part of the area between Moscow and St. Petersburg. There is also no sufficient food resource (ash trees) along the M10 highway, linking these cities; the ashes and their stands are scanty and separated by long distances. Knowing the distribution pattern of the food resources along the *A. planipennis* supposed flight path, it is possible to draw conclusions about the prospects for its movement in one or another direction, make distribution forecasts, and, in some cases, prevent the local advancement of *A. planipennis* making gaps in the stands of host plants, for example, in roadside plantings.

Keywords: emerald ash borer, invasion, host plant *Fraxinus*, automobile route, green spaces

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INTRODUCTION

Invasion of the East Asian emerald ash borer (*Agrilus planipennis* Fairmaire) (Coleoptera: Buprestidae) into Europe was associated with its initial introduction to Moscow (Russia), presumably in the late 1990s; the borer was first identified there in 2003 (Izhevsky, 2007; Shankhiza, 2007). It has led to the mass loss of ash trees (*Fraxinus*) in Moscow since the mid-2000s. Further radial distribution of *A. planipennis* from Moscow raised the question of its potential dispersal in Europe.

Since its introduction in Moscow, *A. planipennis* has covered a distance of approximately 600 km to the south of Moscow and reached Ukraine (Drogvalenko et al., 2019; Orlova-Bienkowskaja et al., 2020). It has penetrated Yaroslavl (240 km northeast of the Moscow suburbs) as well (Vlasov, 2020). Until recently, *A. planipennis* has also been known to travel northwestward from Moscow to Tver and its surrounding areas, where it remains now (Musolin et al., 2021), with the first record there in 2015 (Peregudova, 2019). However, in 2020, further in the northwestern direction from Tver, *A. planipennis* was found in the western environs of St. Petersburg (Volkovich and Suslov, 2020) at a vast separation (490 km) from the main invaded area. Thus, in the European part of Russia, there is uneven distribution of *A. planipennis* from its primary invasion area (Moscow).

In North America, *A. planipennis* was first recorded in Detroit in 2002 and has now spread to the south (to

Georgia) and to the northeast (to Quebec) over a distance of about 900 km. Moreover, the minimum abundance of ash trees (*Fraxinus*), sufficient for the spread of *A. planipennis* by flight, was established. It is approximately 3–5 trees per 1 km of the road (McKenney et al., 2012). It was also revealed that the maximum flight range of *A. planipennis* is up to 20 km during an outbreak of one generation (Tailor et al., 2010). At the same time, it is indicated that two seasons are required for the emerald ash borer generation to develop in Moscow (Orlova-Bienkowskaja and Bieńkowski, 2016). On this basis, it can be assumed that the spread of *A. planipennis* by flight in the European part is limited by the low abundance of ash trees and the low rate of its distribution—up to 20 km in 2 years. These conclusions coincide with the previously calculated average distribution rate of *A. planipennis* in Central Russia—10 km/year (Baranchikov and Kurteev, 2012).

Analysis of geobotanical literature sources (Aleksandrova et al., 1989) has shown that in the area between Tver and St. Petersburg, the composition of forests is represented mainly by spruce, pine, and secondary deciduous forests (Fig. 1); oak groves with the common ash (European ash—*Fraxinus excelsior*) are occasionally indicated only in a small area of the Valdai Hills in Valdai geobotanical region with predominance of secondary aspen and birch forests. Therefore, it can be assumed that the independent spread of *A. planipennis* in wild stands in the direction from Tver to St. Petersburg is impossible.

Linear structures, such as railways and highways, are significant for the spread of emerald ash borer (Selikhovkin et al., 2017; Short et al., 2020). Research in 2013 (Volkovich and Mozolevskaya, 2014), 2016, and 2018 (Selikhovkin et al., 2018), in 2017 (Afonin et al., 2020) showed that there were ash tree plantations, mainly *Fraxinus pensylvanica,* along the M10 automobile route (Moscow – Tver – St. Petersburg) (Fig. 1). The plantations are located in a mosaic pattern, which makes obstacles to the spread of *A. planipennis* from Moscow towards St. Petersburg. Thus, we hypothesized that the spread of *A. planipennis* from Tver towards St. Petersburg was possible in two ways: on some sections of the route, there could be a spread of the pest by its flight in ash tree plantations along the M10 highway, and on others, it could be humanly assisted, where *A. planipennis* travels more likely by hitchhiking: directly on vehicles or transported goods. *A. planipennis* has long been associated with such stratified dispersal that represents the combination of local, natural short-distance and human-mediated long-distance dispersal (Hengeveld, 1989; Muirhead et al., 2006). Therefore, it is significant to identify the sections of the pest's natural dispersal and the sections that *A. planipennis* travels more likely by hitchhiking to work out the most effective phytosanitary and quarantine regional strategy to prevent widespread dispersal of *A. planipennis* in the area between Moscow and St. Petersburg. The identification of such sections can be based on the analysis of the peculiarities of the distribution of the ash stands along the M10 highway.

Recent surveys in the green spaces along the M10 highway within the section between St. Petersburg and Tver (Volkovich and Mozolevskaya, 2014; Selikhovkin et al., 2018; Musolin et al., 2021), which includes green spaces of Torzhok and Vyshny Volochek (Peregudova and Musolin, 2020), showed no evidence of the emerald ash borer settling on ash trees. It should be noted that the emerald ash borer was found in Tver and St. Petersburg in 2015 and 2020, respectively; however it had settled in ash trees in these cities earlier. The analysis of wood showed that the *A. planipennis* distribution on ash trees in Tver occurred back in 2010 (Demidko et al., 2020). Yu.A. Baranchikov (2020) analyzed the presence of damages on the crown of gray ash trees (*Fraxinus pennsylvanica*) in the photographs with the use of Yandex-Panorama and Google Street View Internet services and suggested that the emerald ash borer had already begun to spread in the place of its present outbreak in the western suburb of St. Petersburg in 2014–2016. Thus, it can be seen that in the area from Tver to the west outskirts of St. Petersburg, the possibility of the ash trees being colonized by the emerald ash borer has already existed since 2010, since its emergence in Tver. However, the settling of *A. planipennis* in ash trees in St. Petersburg could also come from another source of its distribution.

This study is aimed to clarify the methodology for assessing the abundance and spatial distribution of ash trees as well as investigate the possibility of *A. planipennis* spread along the M10 Moscow–St. Petersburg automobile route by flight, taking into account the abundance of ash trees and the disunity of their plantings.

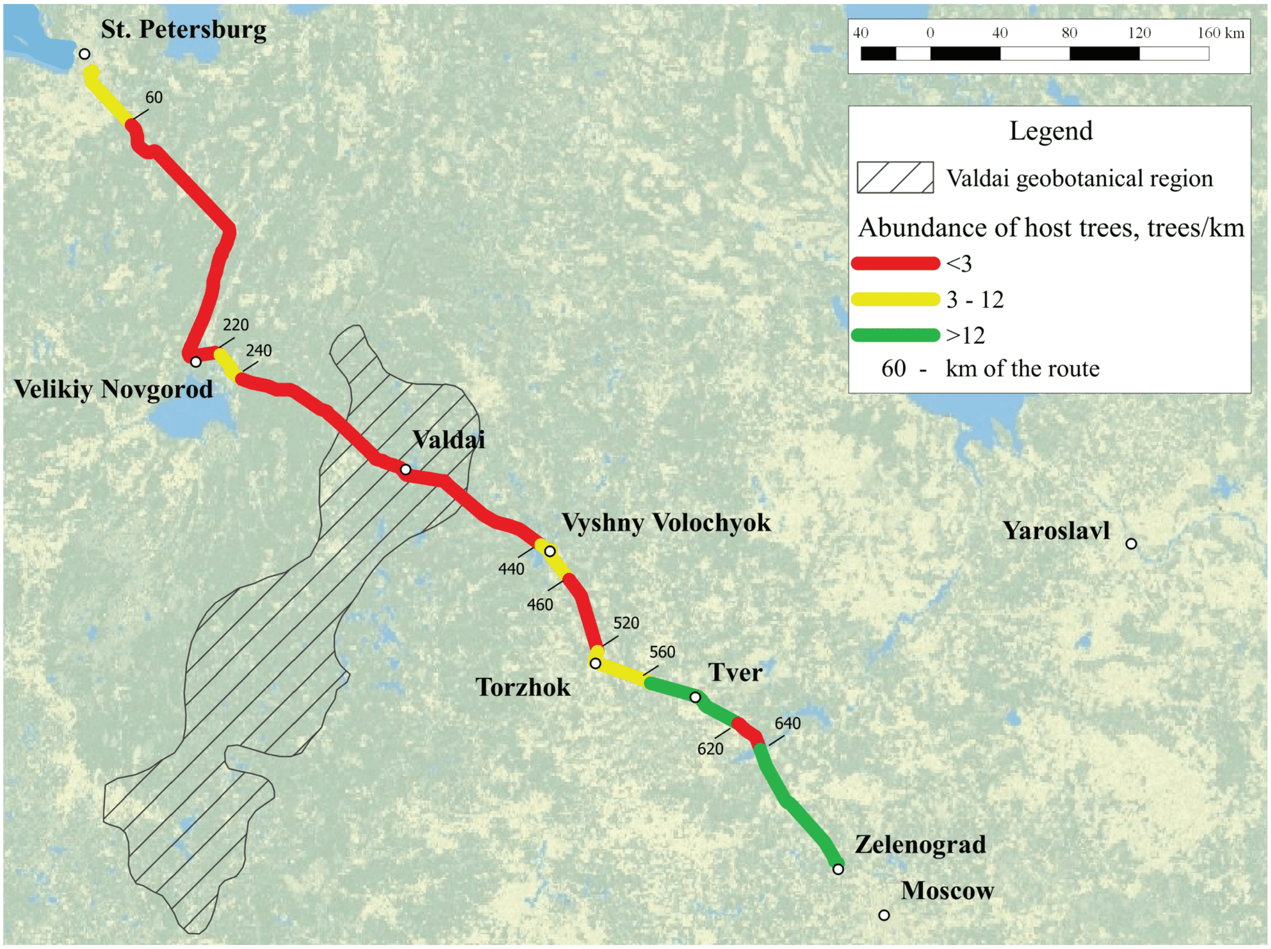

Fig. 1. A site of the survey on the presence of ash trees along the M10 automobile route from St. Petersburg to Zelenograd (a suburb of Moscow).

MATERIALS AND METHODS

In October 2017 we carried out a route field study of the distribution of the ash stands along the M10 Moscow–St. Petersburg automobile route (Fig. 1). The study area covered roadside plantations from the southeastern suburbs of St. Petersburg to the northwestern suburbs of Moscow (Zelenograd was the endpoint of the route). Former highway sections, which have been replaced by the straightened sections of the route, were also explored.

Ash trees were counted out of the car window at a speed of 60–80 km/h by their typical autumn color of the crown against the background of other trees. If necessary, stops were made to clarify the trees' genus and ash trees' characteristics. Based on the data on the maximum possible distribution rate of emerald ash borer over a distance of 20 km for each generation during the outbreak (Tailor et al., 2010; Musolin et al., 2017), the entire section of the M10 highway from the southeastern suburbs of St. Petersburg to the northwestern suburbs of Moscow was divided into 20 km plots. As a result, the entire route of the survey was divided into 35 20 kilometer plots. The sections were named according to the number of the kilometer in the direction from St. Petersburg; for example, the section of the route between the 520th and 540th kilometers was named "the segment (or section) 520 km." On each 20 km plot of the route, the number of single ash trees and their groups was noted, taking into consideration their age: young—up to 5 m high, and mature—above 5 m. According to the number of trees, groups of ash trees were divided into large and

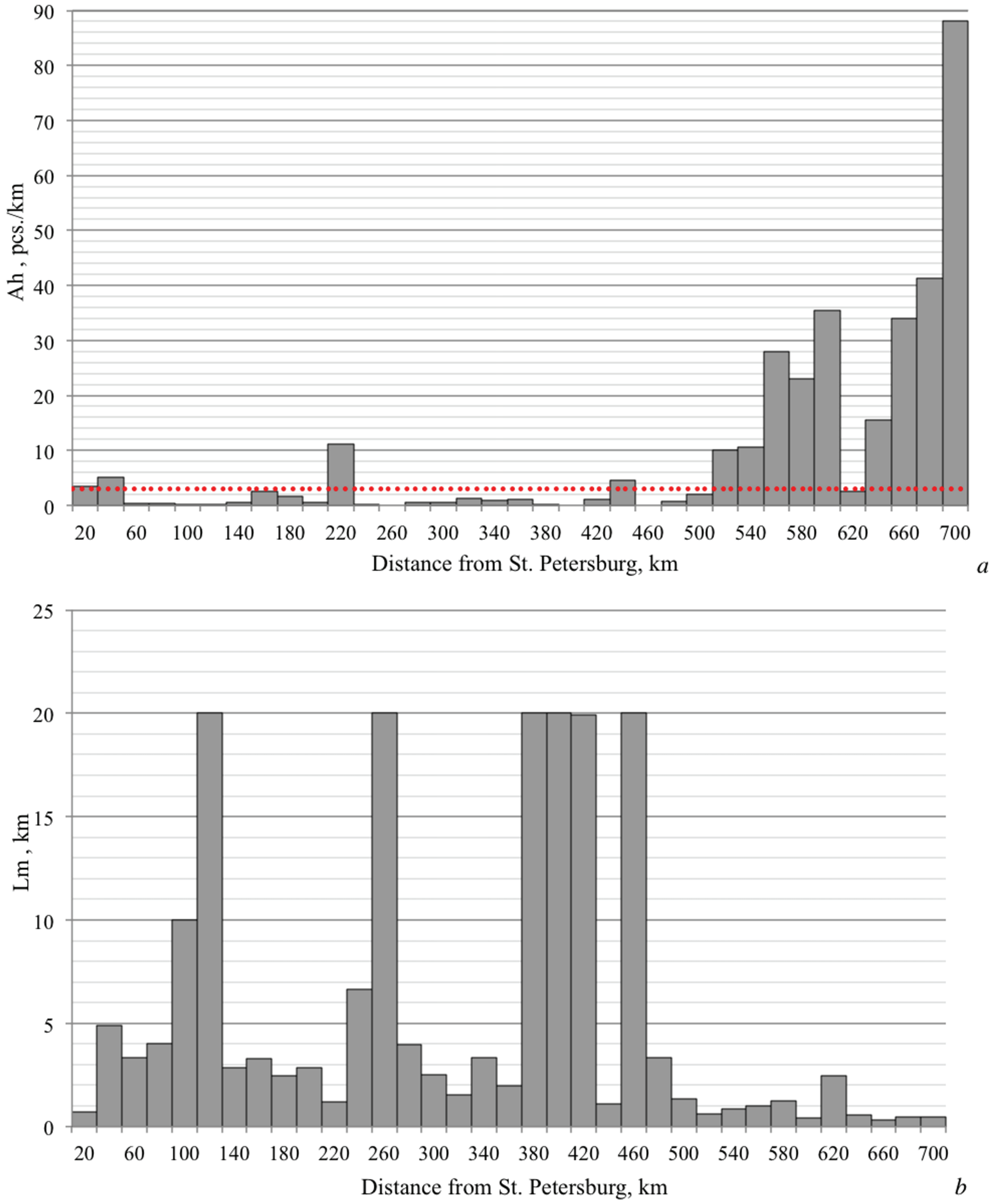

Fig. 2. The abundance of host trees (*Ah*, pcs./km) (*a*) and the average distance between host objects (*Lm*, km) (*b*) ash trees on the section of the M10 highway from the southeastern outskirts of St. Petersburg to Zelenograd (a northwestern suburb of Moscow). October 2017. The red line represents the minimum abundance of ash trees (3 trees per 1 km), which is sufficient for the spread of *Agrilus planipennis* Fairmaire by flight (by: McKenney et al. (2012)).

small. For large groups of trees, we indicated their length measured by the automobile distance recorder. Small groups included several ash trees. For further analysis of the data, it was assumed that the group of young ash trees should consist of 5 trees, mature ones, of 3 trees. The data were recorded in the field diary; they are presented in Table 1.

According to the field data, two indicators were further calculated: the abundance of ash trees (*Ah*) and the average distance between groups of trees at each 20 km plot (*Lm*). *Ah* was defined as the number of ash trees on a 20 km plot (trees/plot)., *Lm*, as the average distance between individual trees, groups, and bands of trees in km in a 20 km plot; it shows the average distance *A. planipennis* needs to fly from one ash to another.

RESULTS

A survey of the M10 route within the distance from the southeastern outskirts of St. Petersburg to Zelenograd, a northwestern suburb of Moscow (Fig. 1), in October 2017 showed an uneven distribution of the food resource for *A. planipennis* (Fig. 2, *a*). Moreover, the 20 km plots with the abundance of ash trees (*Ah*) equal to 3 or fewer trees, which serve as a barrier to the spread of the ash borer (McKenney et al., 2012), cover the most of the M10 route and refer to the following plots: 60–200, 240–420, 460–500, and 620 km. The share of 20 km plots between Tver and St. Petersburg with $Ah \leq 3$ and not inhabited by *A. planipennis* (20–560 km plots) is 75%.

The average distance between individual trees, groups, and bands of trees along the M10 route is uneven and tends to decrease when approaching the northwestern outskirts of Moscow. The diagram (Fig. 2, *b*) shows that to the northwest of the suburbs of Tver, there are plots where the distance between bands of trees and individual ash trees is more than 19.9 km (120, 260, 380, 400, 420, 460 plots). The share of such 20 km plots between Tver and St. Petersburg with $Lm \geq 19.9$ km and not inhabited by *A. planipennis* (20–560 km plots) is 21%.

It should be noted that in the area between Torzhok and Tver (520–580 km) (Fig. 1), there are sections that are, in terms of the ash abundance, appropriate for infestation by the emerald ash borer ($Ah \geq 10$; $Lm = 0.601–1.267$).

DISCUSSION

As the analysis of the data shows, the spread of *A. planipennis* by flight in the Tver–Saint Petersburg section is impossible due to the absence of continuous natural stands of ash trees and high values of *Lm* indicator (more than 20 km) between individual trees, groups of trees, and bands of ash trees along the M10 route. Three adjacent 20 km plots (380, 400, and 420) will become a particularly serious barrier for the dispersal of *A. planipennis* (Fig. 2, *a*).

The appearance of *A. planipennis* in St. Petersburg is probably associated with its introduction into the city with some plant materials. This assumption is confirmed by model calculations of the *A. planipennis* flight from Tver to St. Petersburg over the last 10 years. If we consider the development period of a generation to be 2 years, and the highest potential for free flight to be 20 km for a generation, then, under the most optimal conditions, the flight potential of *A. planipennis* during this period could be 100 km (noting that in such case we should forget that there is evidence that *A. planipennis* needs at least 7 years to settle in a new place for further flight from the place of its introduction (Siegert et al., 2014)).

As mentioned above, the distribution of *A. planipennis* at the northern limit of its distribution in Canada is affected by the abundance of ash trees in forest belts (McKenney et al., 2012). The limit for such distribution when recalculated according to McKenney et al. (2012), is 3–5 ash trees per 1 km of the road. As the analysis of our data on the abundance of ash trees along the M10 highway shows, there are only a few plots with abundance of ash trees over 3 (near St. Petersburg (20–40 km plots) and near Veliky Novgorod (220 km plot)) in the section from the southeastern outskirts of St. Petersburg to Tver, that is unsettled by *A. planipennis*. Similar conclusions were made earlier by M.G. Volkovich and E.G. Mozolevskaya (Volkovich and Mozolevskaya, 2014): *A. planipennis* dispersal by flight to the northwest of Tver is unlikely due to the lack of food supply. In Tver and its environs (520–560 km plots), not inhabited by *A. planipennis*, the number of ash trees already exceeds the value of 3 trees/km significantly and is at least 10 trees/km. The absence of the emerald ash borer in this section may be connected with the relatively short history of its dispersal or with the

Table 1. Accounting records of host-plants (ash trees) of *Agrilus planipennis* Fairmaire

Distance from St. Petersburg, km	Coordinates		Number of mature trees, pcs.	Number of young trees, pcs.	Number of the groups of mature trees, pcs.	Number of the groups of young trees	Length of the rows of mature trees, m	Number of the rows of mature trees, pcs.	Length of the rows of young trees, m	Number of the rows of young trees, pcs.	Total number of trees	Abundance of host trees (Ah), trees/km	The space occupied by trees on a 20 km plot, km	Average distance between host objects (Lm) km / object
	N, deg	E, deg												
20	59.86255	30.38869	22	2	–	2	200	1	–	–	70	3.5	0.331	0.728
40	59.71355	30.56123	3	–	–	–	500	1	–	–	103	5.15	0.515	4.871
60	59.61383	30.74364	4	1	1	–	–	–	–	–	8	0.4	0.038	3.327
80	59.47037	31.00641	4	–	1	–	–	–	–	–	7	0.35	0.035	3.993
100	59.34773	31.23604	–	1	–	1	–	–	–	–	4	0.2	0.011	9.995
120	59.21904	31.47694	–	1	–	–	–	–	–	–	1	0.05	0.003	19.997
140	59.06510	31.61276	5	–	2	–	–	–	–	–	11	0.55	0.055	2.849
160	58.92298	31.51461	1	1	3	–	200	1	–	–	51	2.55	0.253	3.291
180	58.74079	31.42246	4	1	1	1	100	1	–	–	31	1.55	0.146	2.482
200	58.57342	31.2847	5	–	2	–	–	–	–	–	11	0.55	0.055	2.849
220	58.53413	31.55258	12	–	1	2	–	–	500	1	221	11.05	0.590	1.213
240	58.41735	31.75012	3	–	–	–	–	–	–	–	3	0.15	0.015	6.662
260	58.36691	32.06827	–	–	–	–	–	–	–	–	0	0	0.000	20.000
280	58.32561	32.32095	3	–	2	–	–	–	–	–	9	0.45	0.045	3.991
300	58.22301	32.60439	7	–	1	–	–	–	–	–	10	0.5	0.050	2.494
320	58.09988	32.85107	8	2	2	–	50	1	–	–	26	1.3	0.126	1.529
340	58.00308	33.13421	1	1	2	1	40	1	–	–	19	0.95	0.086	3.319
360	57.93703	33.46255	6	–	3	–	40	1	–	–	23	1.15	0.115	1.989
380	57.87478	33.70318	1	–	–	–	–	–	–	–	1	0.05	0.005	19.995

Table 1. (Contd.)

Distance from St. Petersburg, km	Coordinates		Number of mature trees, pcs.	Number of young trees, pcs.	Number of the groups of mature trees, pcs.	Number of the groups of young trees	Length of the rows of mature trees, m	Number of the rows of mature trees, pcs.	Length of the rows of young trees, m	Number of the rows of young trees, pcs.	Total number of trees	Abundance of host trees (Ah), trees/km	The space occupied by trees on a 20 km plot, km	Average distance between host objects (Lm) km / object
	N, deg	E, deg												
400	57.76229	33.95022	–	–	–	–	–	–	–	–	0	0	0.000	20.000
420	57.70752	34.19734	–	–	–	–	100	1	–	–	20	1	0.100	19.900
440	57.61398	34.48068	6	2	4	4	300	2	–	–	92	4.6	0.426	1.087
460	57.44377	34.73816	–	–	–	–	–	–	–	–	0	0	0.000	20.000
480	57.36586	34.84405	–	2	2	2	–	–	–	–	14	0.7	0.051	3.325
500	57.19905	34.93928	5	4	–	5	–	–	40	1	40	2	0.115	1.326
520	57.0881	34.99678	12	2	8	2	380	6	200	2	200	10	0.781	0.601
540	56.99413	35.18333	5	1	6	6	350	3	250	2	212	10.6	0.763	0.836
560	56.93036	35.48227	8	–	–	4	2700	5	–	–	560	28	2.770	1.014
580	56.89002	35.7465	9	–	–	–	2190	4	30	1	459	22.95	2.265	1.267
600	56.80891	36.00867	16	7	2	7	2300	5	500	4	710	35.5	2.984	0.415
620	56.72847	36.28233	1	1	3	1	100	1	40	1	50	2.5	0.201	2.475
640	56.59886	36.48311	4	2	4	12	590	5	350	6	312	15.6	1.116	0.572
660	56.42392	36.62923	8	9	11	11	800	3	1090	12	679	33.95	2.205	0.330
680	56.29011	36.81168	7	2	13	8	270	2	1750	8	826	41.3	2.316	0.442
700	56.15930	37.02250	6	1	5	8	595	4	3990	8	1761	88.05	4.753	0.476
Total:			**176**	**43**	**79**	**77**	**11805**	**48**	**8740**	**46**	**6544**	–	–	–

low heat supply during the development period of the pest (Afonin et al., 2020).

In the space between Tver and St. Petersburg, unsettled by the emerald ash borer, there are some discontinuous sections of the M10 highway with an abundance of ash trees that is sufficient for the pest invasion. In these sections (for example, sections 520 and 620 km), further settlement of *A. planipennis* in its natural way is possible. Slightly to the south, 800 m from the M10 highway (section 580 km), there is an insignificant advancement of the ash borer in the northwestern direction from Tver towards St. Petersburg: *A. planipennis* was recorded in the northwestern part of Tver: in the Zavolzhskii District at the Doroshikha Railway Station in 2018 (Peregudova, 2019).

The abundance of ash trees along the M10 highway in the section from Moscow to Tver, where the invasive pest *A. planipennis* is dispersed currently, is uneven. There is a sufficient amount of ash trees for the free flight of the pest in this area. The only exception is a 620 km plot near Tver (Fig. 1). This plot serves as a seemingly serious barrier for *A. planipennis* spread by flight. Proceeding from the speed of the pest's dispersal in the northern regions, it would have covered the distance of about 140 km between the northwestern outskirts of Moscow and Tver by flight in 14 years. This time interval is similar to the time differences between settlement in Moscow (late 1990s) and Tver (2010) (Demidko et al., 2020). However, the speed of the emerald ash borer dispersal is certainly less than 20 km in 2 years, and therefore, most likely, it covered the distance from Moscow to Tver hitchhiking, especially since *A. planipennis* had been recorded 2 years earlier (in 2013) 8 km east of Tver (closer to Moscow) in Emmaus (Straw et al., 2013) and 50 km east of Tver in Konakovo (Orlova-Bienkowskaja, 2013).

CONCLUSION

The introduction of *A. planipennis* from Tver to St. Petersburg by flight is hardly possible due to lack of continuous stands of ash trees in this area, insufficient abundance of food resource (ash trees) along the M10 highway, and large gaps between individual ash trees, groups, and bands of trees along this route, which represent a barrier to the pest's natural spread. At the same time, the emerald ash borer can reach Torzhok by flight, and it has not been done yet. The natural distribution of *A. planipennis* to St. Petersburg, that is 590 km from the northwestern borders of the Moscow invasive enclave (Tver), would take at least 59 years if there was a sufficient food resource supply and if one generation of *A. planipennis* could fully develop in 2 years.

The distribution of the emerald ash borer from Moscow to Tver most likely also occurred due to hitchhiking, as indicated by lack of sufficient abundance of ash trees on one of the 20-km plots, as well as by the distance between these cities, which the pest most probably could not cover by flight during the period between its initial appearance in Moscow and Tver.

Relatively limited and insular distribution of *A. planipennis* to the north from Moscow makes it possible to suggest that the pattern of its dispersal in the north of Western Europe may be the same. This fact gives promise that the spread to the north of Russia and European countries can be prevented by special quarantine measures**,** that should be developed taking into account the gaps between natural ash stands and ash tree belts along the roads. It is also possible to consider the issue of artificially thinning the ash stands (food resource for *A. planipennis*) as a preventive measure averting the invasion of the *A. planipennis*.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest. The authors declare that they have no conflict of interest.

Statement on the welfare of animals. All the applicable international, national, and institutional guidelines for the care and use of animals were followed. All the procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted.

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