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Modeling Current and Future Distribution of *Cochlodina laminata* in Eastern Europe under Climate Change

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Abstract: In this study, we focused on the eastern part of the *Cochlodina laminata* range. Although this door snail is widespread in Europe, even a widespread species may lose habitats if future climate change projections are realized. The range shift is one of the consequences of climate change. We applied SDM methods to model the current potential range of *C. laminata* and the range shift after 40 and after 80 years. We used climatic parameters as predictors. The annual mean temperature has the greatest impact on the modeling results (about 30–60% among models). The precipitation of the warmest quarter also had a high relative importance (about 15–40% among models). For future projections, we considered two shared socio-economic pathways (ssp245 and ssp585). We applied three algorithms: the generalized additive model (GAM), support vector machine (SVM) and multilayer perceptron (MLP) and ensemble prediction. Our projections showed a decrease in habitable area in the eastern part of the range of *C. laminata* in 40 and in 80 years. According to the forecast, the habitat suitable area will become more fragmented. The range shift with new suitable areas is expected toward the east direction.

Keywords: ecological modeling; SDM; climate change; species distribution; Clausiliidae

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1. Introduction

The climate change impact on distribution and range shifts has been shown for many animal species [1,2]. Research often focuses on endangered species on the one hand or potentially invasive species on the other [3–5]. The same trend is also observed in molluscan studies [6–8]. This is explained by the need to develop protective measures to conserve biodiversity and prevent damage to native ecosystems and humans [9–11]. The loss of habitats of rare, endangered species or the spread of invasive species (sometimes these events are associated) is the most obvious application for ecological modeling and environmental management [3–11]. However, species that are currently widely distributed over large areas may also be subject to range changes in the future. Such transformations also may affect ecosystems [12,13]. This effect will be especially noticeable if the changes affect large areas.

The object of our study is *Cochlodina laminata* Montagu, 1803. This snail of the family Clausiliidae (Gastropoda: Pulmonata) is widely distributed in Europe. Clausiliidae are often of interest for research due to their ecological features, high species diversity, and wide geographic distribution [14–17]. Although there are many stenobiont species in this family, *C. laminata* is one of the "most eurybiont" European clausilids. The species inhabits the entire range of forest biotopes: from forest edges to floodplain and ravine forests [18]. The snail inhabits forest biotopes and lives in forest litter, decaying wood and stumps. *C. laminata* is widespread in Europe, including eastern Europe [19]. According to Likharev [17], the range of *C. laminata* on the East European Plain has the shape of a wedge that extends deep into the continent. The range of the species covers the territory of several natural zones, and it is especially interesting that *C. laminata* lives in the forest-steppe and even locally in the steppe zone [20]. In this part of its range, *C. laminata* inhabits both regions with high and low diversity of malacofauna. The species is distributed in the Balkans and Carpathians, regions with high species richness, including endemic door snails [15,21–24]. At the same time, on the territory of the Central Russian Upland, Middle Volga region, where the malacofauna is not so rich, the species is also often found [25–29]. *C. laminata* also inhabits the mountainous Crimea and is found in the Caucasus [17,30,31]. We should note that by "Caucasus" we mean the territory within the physical–geographical boundaries of the Caucasus, so from the north it extends southward from the lowlands of the Kuma and Manych river basins. Perhaps due to the large territory, there is a problem of lack of species occurrence data of the eastern part of the species range. In other words, the range of the species in eastern Europe is not completely clear for the current time.

In this part of the species range, as well as in others, the effects of climate change are already manifesting, and it is expected that they will intensify [32]. It can be assumed that climate change will also affect the distribution of snails in this territory, including *C. laminata*. SDM methods are often used to predict range shifts due to climate change [33–35]. Different models of climate change and different socio-economic scenarios are used for forecasts [36,37]. Now, the most relevant is the Phase 6 of the Coupled Model Intercomparison Project (CMIP6) climate model set [38–40]. Like the previous sets of climate models, CMIP6 shows a warming climate and, in addition, an increase in climate extremes [41,42].

In our study, we focused specifically on the territory of eastern Europe (up to the Urals); we were especially interested in the border areas of the range. At the first stage of the research, we modeled the distribution of the species at the current time. We evaluate the habitat suitability of different parts of eastern Europe for *C. laminata*. At the second stage, we investigate the projected future range shift after 40 (2041–2060) and 80 years (2081–2100). For the future modeling, we used two socio-economic climate change scenarios, including the most pessimistic.

2. Materials and Methods

2.1. Species Data and Study Area

We used the following data sources of *C. laminata* occurrences: the authors' field collections (49 points), literature searches (96 points) [18,26,28,29,43–54]; the GBIF repository, from which iNaturalist data were previously excluded (4034 points) [55–63]; data from the collection of the Malacology Laboratory of the State Museum of Natural History of the National Academy of Sciences of Ukraine (3 points, www.pip-mollusca.org (accessed on 25 April 2022)); and the catalogs of the Zoological Institute of the Russian Academy of Sciences and the Zoological Museum of Moscow State University (117 and 25 points, respectively).

Occurrence data preprocessing included deduplication and spatial thinning. For GBIF data, the thinning distance was 20 km; for data from other sources, it was 10 km. The choice of thinning distance is determined by the initial spatial distribution of present points: such a distance made it possible to minimize the effect of sampling bias but at the same time not to remove an excessive number of present points. As a result, after the thinning procedure, 131 points from the GBIF and 210 points from the other sources were included in the models (Figure 1; Table S1). Four hundred background points were randomly generated as pseudo-absence points.

The study area covered the territory of eastern Europe from 66° N to 40° N and from 20° E to 60° E.

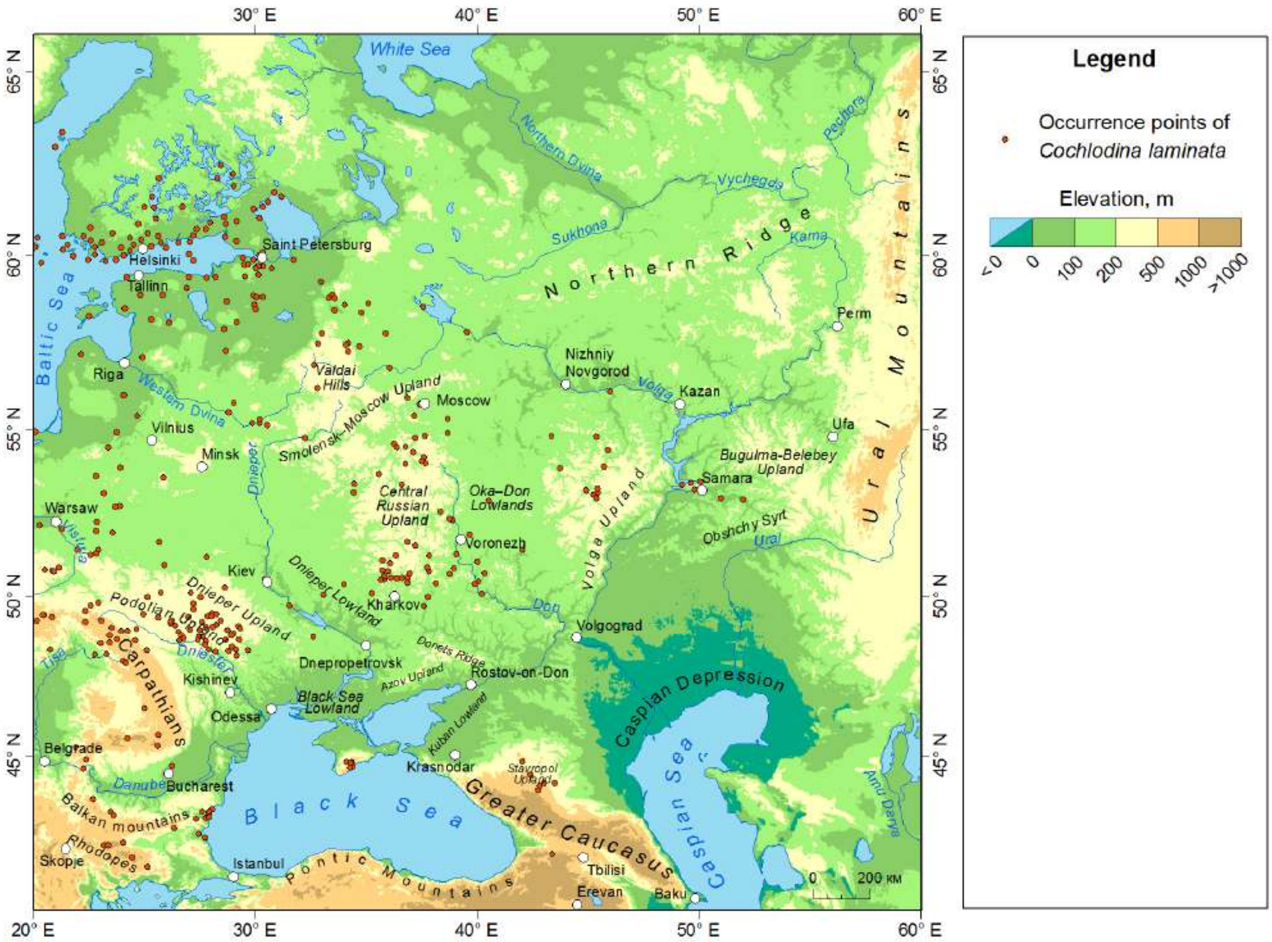

Figure 1. *Cochlodina laminata* occurrences.

2.2. Environmental Predictors

In our study, we used bioclimatic data from the WorldClim.org (accessed on 25 April 2022) database with a 2.5 min spatial resolution [64]. We tested 19 bioclimatic variables for multicollinearity using the variance inflation factor (VIF) [65]. We selected eight of them based on the test results after excluding the highly correlated variables from the set. So, the following climatic parameters were included in the species distribution models: 'bio1' (Annual Mean Temperature), 'bio2' (Mean Diurnal Range), 'bio4' (Temperature Seasonality), 'bio8' (Mean Temperature of Wettest Quarter), 'bio9' (Mean Temperature of Driest Quarter), 'bio15' (Precipitation Seasonality), 'bio18' (Precipitation of Warmest Quarter), and 'bio19' (Precipitation of Coldest Quarter). The relative contribution of each predictor in the model was calculated.

In addition to the VIF test results, the ecology of the species was also considered in the selection of variables. For the study area, the ecology of the species was described in the most detail by Likharev [17], and the breeding ecology was also described by Mamatkulov for the middle part of the East European Plain [18]. Since the territory is quite extensive, the limiting factors in the northern and southern parts may differ. In the north and northeast, the range boundary is largely determined by the duration of the frost-free period as well as by snow cover. In the south and southeast, the range boundary is more dependent on summer temperature and precipitation. Given the result of the multicollinearity test, we believe that these factors are reflected in the bioclimatic variables bio2, bio4, bio8, bio9, and bio18. The annual mean temperature should also affect the distribution of the species over such a vast territory, since if we generalize information about the ecology of the species, its distribution is largely limited by cold continental–arctic air masses from the northeast and continental–subtropical masses from the southeast.

To predict the distribution of the species after 40 years (2041–2060 period) and after 80 years (2081–2100 period), we used data from CMIP6 (Coupled Model Intercomparison Project Phase 6) future climate projections from the WorldClim.org database. For future modeling, we chose the same climate predictors with a spatial resolution of 2.5 min that have been used in the current distribution species modeling.

Predictions based on different climate models differ; for this reason, the common practice is using different models and generalizing the result [66–68]. For the future projection, we used four models from the CMIP6: HadGEM3-GC31-LL (Hadley Global Environmental Model—Earth System version 3) [69], ACCESS-ESM 1.5 (Australian Community Climate and Earth System Simulator—Earth System Model 1.5) [70], CanESM5 (Canadian Earth System Model version 5) [71], and BCC-CSM2-MR (medium-resolution version of Beijing Climate Center Climate System Model) [72].

We chose these models because there are variations in model predictions in different climatic zones, in forecasting annual maxima, and in accounting for the carbon cycle and vegetation change [42,73–75].

For each of these climate models, we took two Shared Socio-economic Pathways (SSPs): SSP2-4.5 and SSP5-8.5. When measuring habitat suitability, modeling different SSPs, as well as different Representative Concentration Pathways (RCPs), helps to consider different climate change scenarios depending on climate policies [36,37].

Our forecast is based on climatic factors, since the region of our study is a large area. For this area, unfortunately, there are no other suitable predictors for future modeling of sufficient spatial resolution. For small areas (as in some regions), there are, for instance, land cover models [76–78]. Such predictors add detail and accuracy to the models. But we suppose that in order to show the potential changes in the range of a wide spread of terrestrial molluscs over a large area across decades, our approach can be applied.

2.3. Species Distribution Modeling

The following algorithms were used for current and future modeling: the generalized additive model (GAM), support vector machine (SVM) and multilayer perceptron (MLP). We used a fivefold cross-validation method with 25% test and 75% training sets of occurrence points. The models' evaluation was tested using the area under the receiver operating characteristic curve (AUC) [79–81]. We derived one ensemble prediction on the weighted results of all models [82]. We evaluated the suitability scores of habitats from 0 to 1.

We also found threshold values for habitat suitability. For these aims, we applied a sensitivity–specificity sum maximization approach [83]. Furthermore, the territory was divided into areas of potential presence (1) and absence of the species (0): above the threshold value and below it. Presence/absence type maps were made based on ensemble models considering the threshold value. The areas of the range were calculated according to the results of the ensemble model for the present and for the future. For calculating the area, we vectorized the result of the ensemble prediction. We calculated the mean results for all climate projections for each time period and SSP separately. We also calculated the standard deviation to determine the uncertainty [67,84]. We performed these operations in the spatstat package [85].

Modeling, analysis and the main part of the data preprocessing were carried out in the R version 4.1.2 using packages sdm [86,87]. The spatial thinning procedure was carried out using the spThin package in the R environment [88]. To work in the sdm package, we also used the following packages: maptools, sp, raster, rgbif, rgeos, dismo, rgdal [89–96]. The code file is in Supplementary Table S2. The processing of raster images with predictors, as well as the preparation of the resulting maps, calculating the area of the range was performed in ArcGIS version 10.7.

3. Results

3.1. Current Distribution Modeling

At the first stage, we obtained models of habitat suitability for the study area at the current time using three algorithms with a fivefold cross-validation (Figure 2).

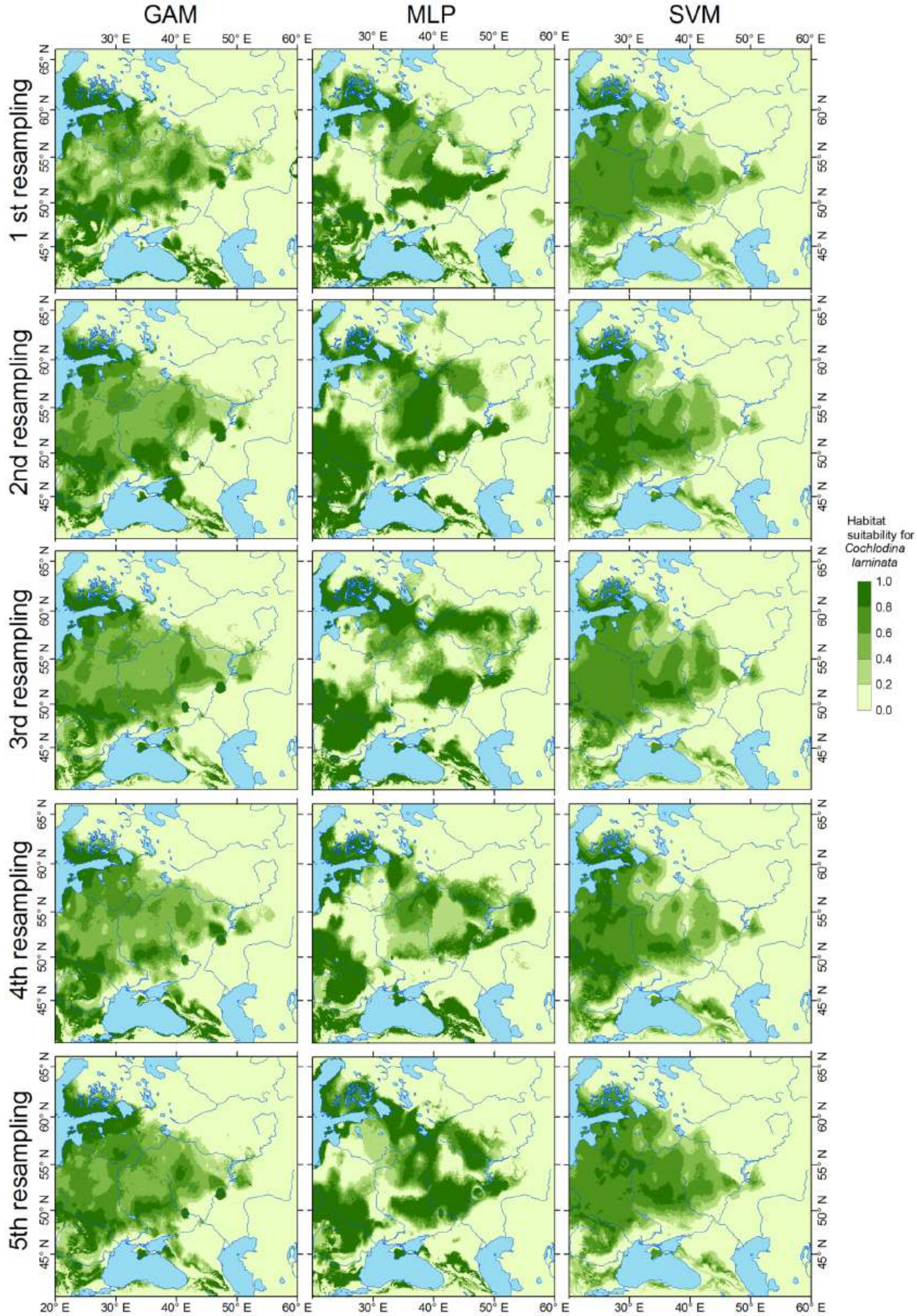

Figure 2. *Cochlodina laminata* current habitat suitability according to tested three model types.

The resulting prediction varied depending on the applied algorithms. The GAM and MLP algorithms give, on the one hand, a more fragmented picture, but, on the other hand, the area suitable for *C. laminata* habitation in these models is larger than in SVM. The SVM shows a more “filled” area, including those areas where no points of occurrence were noted due to lack of data. In particular, this applies to the territory of Belarus. In all cases, the potential range extends to the Cis-Urals (in all models) or even reaches the Urals (in GAM and MLP models).

An AUC score has comparable and rather high values (0.86-0.88) for all models. This characterizes the good performance in predicting the *C. laminata* distribution (Figure 3).

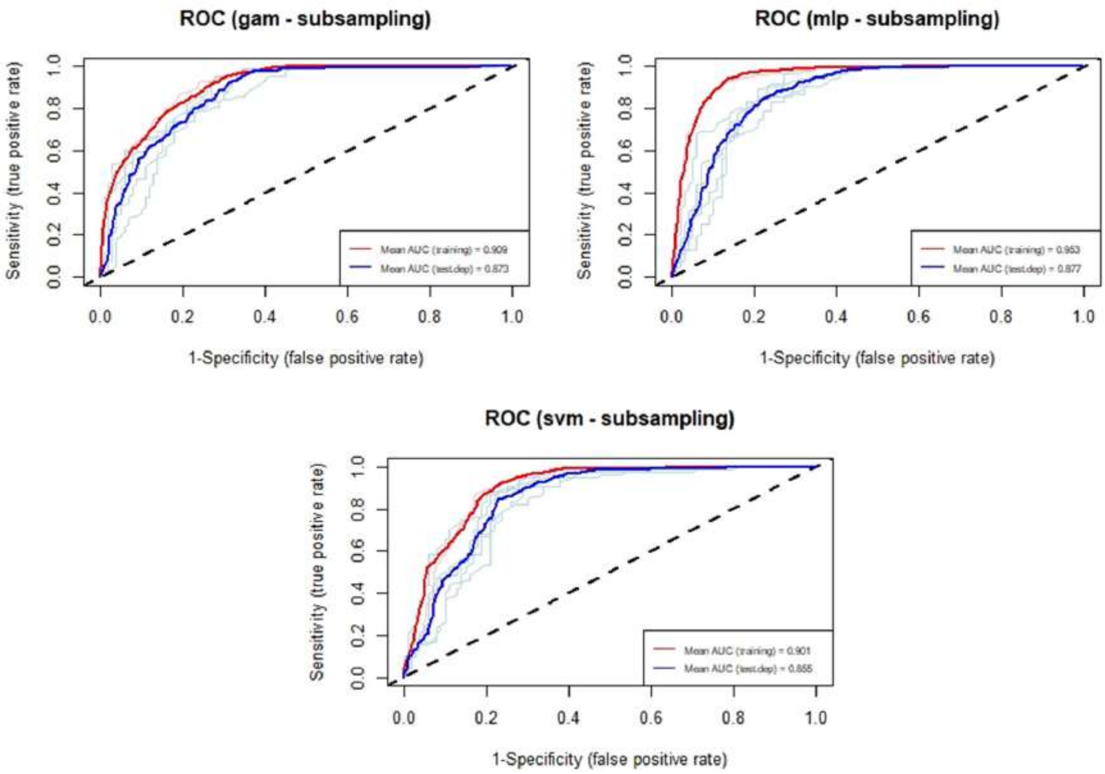

Figure 3. Receiver operator curves (ROC) and area under curve (AUC) values for different models. Red curve represents the model performance for a training set, pale blue lines—for testing sets and individual models, dark blue line—overall performance among all models.

The ensemble forecast shows the average result for all models (Figure 4). Territories with different degrees of suitability are shown in Figure 4A. The habitat suitability threshold is 0.349. Based on this value, we divided the territory into suitable and unsuitable for the species (“presence/absence”). This version of the *C. laminata* distribution prediction map is shown in Figure 4B.

The ensemble model also showed that the potential range reaches the Cis-Urals in the eastern part: the Obshchy Syrt and part of the Bugulma–Belebeev Upland.

In the southern part (in the forest-steppe and partly in the steppe zone), the potential range includes the south of the Central Russian Upland to the southeast of the Donetsk Ridge. Suitable habitat territory is also located in the south of the Dnieper Upland and the Black Sea Lowland. The southernmost part of the *C. laminata* range includes the territories of the Black Sea region: the mountainous part of the Crimean Peninsula, Ciscaucasia, some part of the Caucasus, the Pontic Mountains, and the Balkans. The total area of habitable territory in the study region is 2,814,972.024 km^2 according to the ensemble model for the current time. We emphasize that our forecast is based on climate predictors; that is, we are talking about the climatic niche of the *C. laminata*. Therefore, for the current time, our model shows the wide distribution of the snail in eastern Europe without details inside the “wedge”.

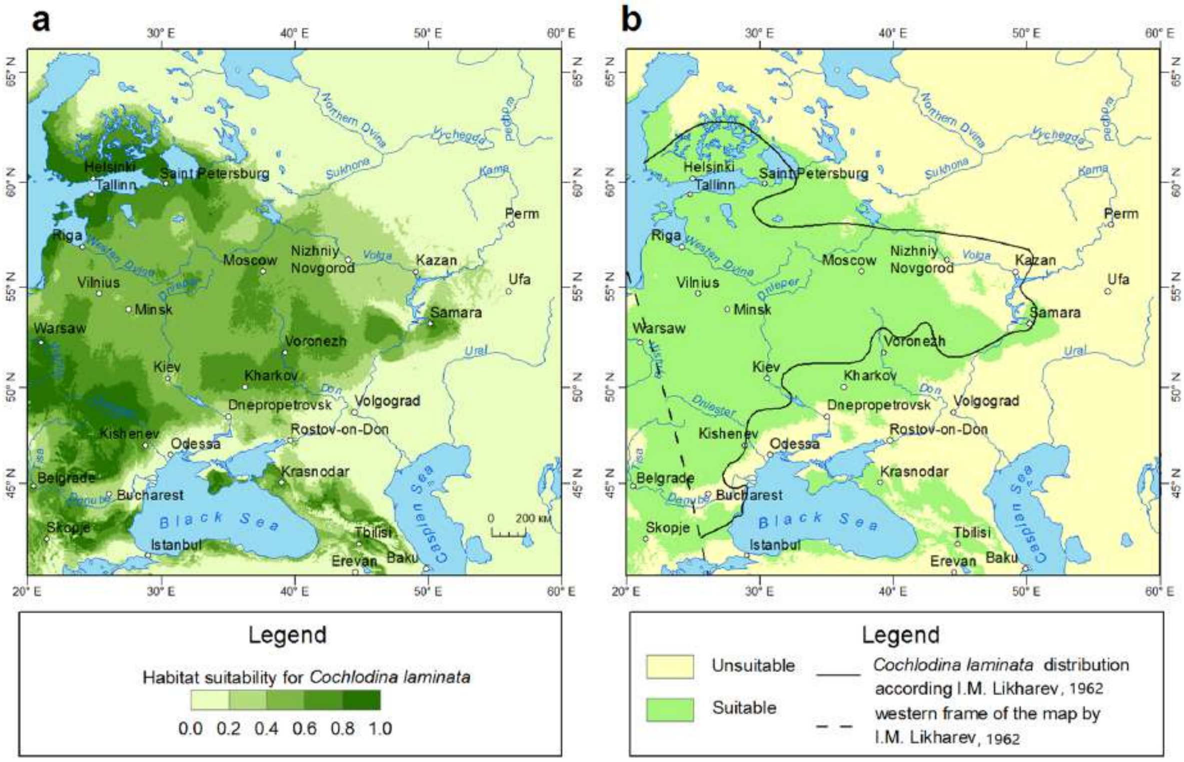

Figure 4. *Cochlodina laminata* current habitat suitability according to the ensemble model: (**A**) quantitative background format; (**B**) thresholded format [17].

3.2. Future Distribution Modeling

Prediction maps of the *C. laminata* future distribution based on all used climate models and SSPs are presented in Figures S1 and S2. Of the four climate projections that we used in modeling, three showed a reduction and fragmentation of the species range. The BCC-CSM2-MR-based model turned out to be an exception: for both SSPs, the forecast showed a future expansion of the range mainly in a northeasterly direction.

Thus, according to the projection based on the BCC-CSM2-MR, by 2060, the habitat suitable area will increase by 64.6 and 9.1% (for SSP 245 and 585, respectively) compared to the current one. By 2100, the range area will be 72.5% and 67.1% larger than the current one for SSP 245 and 585, respectively.

However, other forecasts showed a significant reduction in the area of the range: to 29.2–42.4% of the current one by 2060 and to 16.6–43.6% of the current one by 2100.

The average forecast also showed a reduction in the habitat suitable area by 2060 (Figure 5) and by 2100 (Figure 6). The averaged projection showed a trend toward a reduction in the range: a decrease by 35.1–36.6% for 2041–2060 and by 56.3–72.2% for 2081–2100. All models also showed that new territories become suitable for *C. laminata* in the east part of the range. But these new suitable territories are very highly fragmented and small. A more noticeable shift to the east was obtained for SSP 585. Prediction uncertainty is also shown in Figures 5 and 6. Expectedly, higher projection uncertainty is observed on the range periphery, so the range shift in its periphery is less predictable.

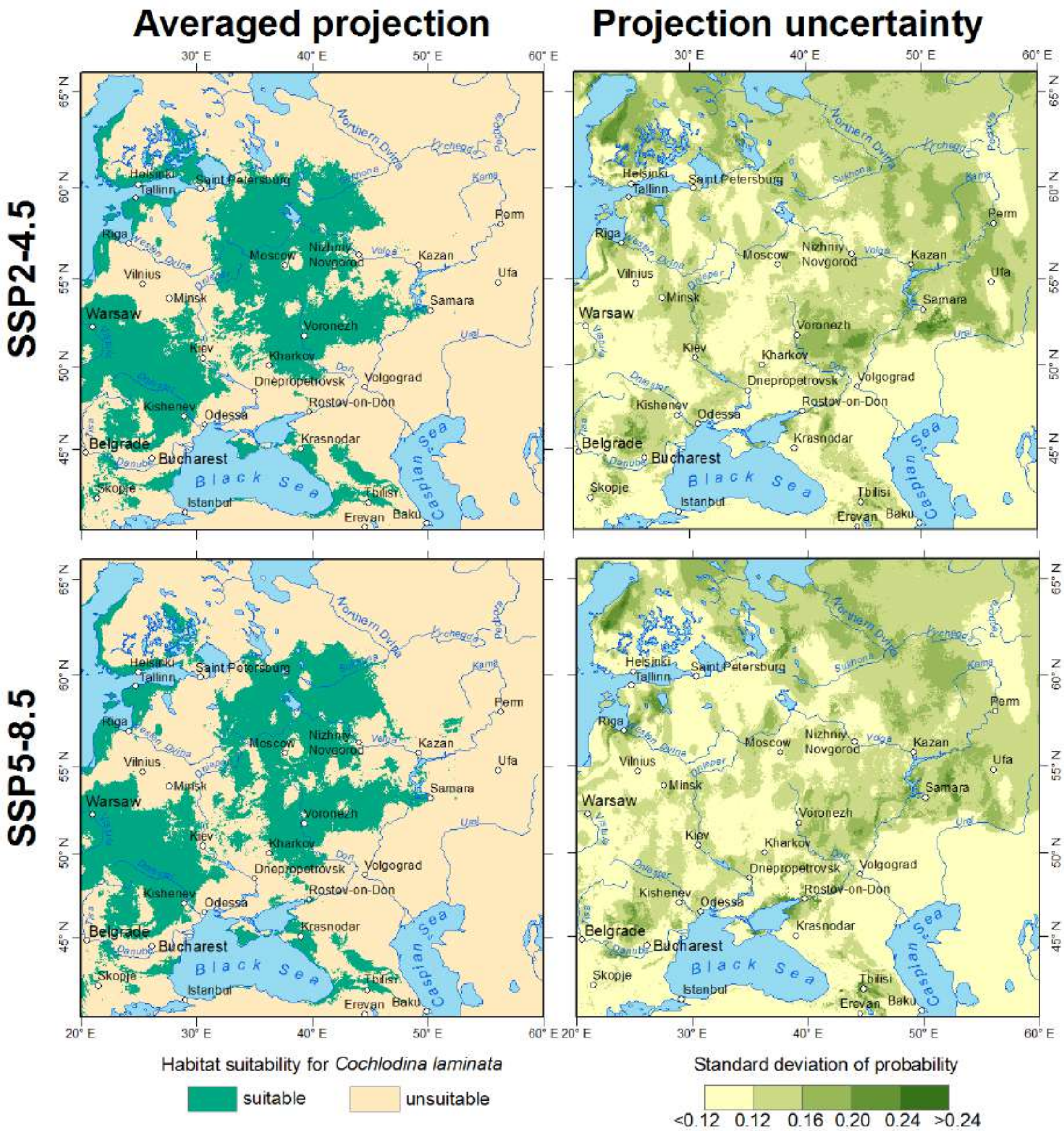

Figure 5. Averaged projection and projection uncertainty in *Cochlodina laminata* habitat suitability in 2041–2060.

3.3. Variable Importance

The annual mean temperature (Bio1) has the largest contribution in all models (Figure 7).

In addition to Bio1, precipitation of the warmest quarter (Bio18) made the largest relative contribution to the GAM models, while temperature seasonality (Bio4) made the largest relative contribution to the SVM models. The contribution of all other variables in all models was relatively equal. For MLP, the value of all variables was relatively equal, although Bio1 made the greatest contribution to these models as well. The least significant variable for all models was the mean temperature of the driest quarter (Bio9).

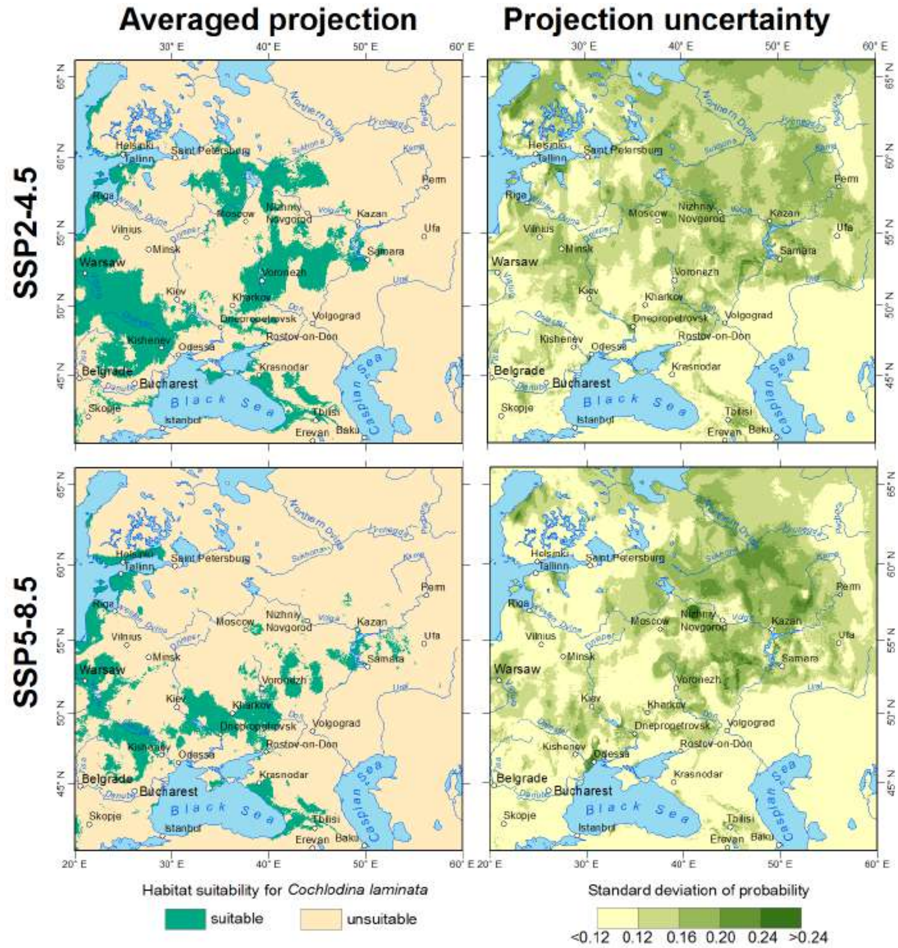

Figure 6. Averaged projection and projection uncertainty in *Cochlodina laminata* habitat suitability in in 2081–2100.

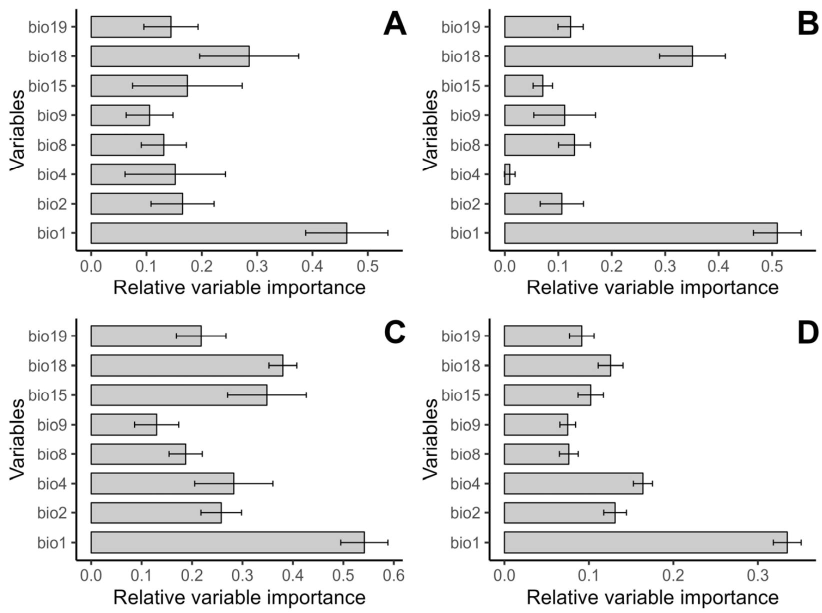

Figure 7. Relative importance (from 0 to 1) of SDM variables for different models: (**A**) ensemble; (**B**) GAM; (**C**) MLP; (**D**) SVM.

4. Discussion

The SDM result represents the potential range of the species and shows the area suitable for its habitat [97,98]. In other words, the prediction based on SDM cannot be taken as an unambiguous answer to the question about the boundaries of the species range. However, the result of SDM allows us to see which areas contain the most optimal conditions for the species habitat as well as the boundaries of the suitable habitat area. We will mainly focus on the ensemble projection result, since it gives an average result over the models [82].

I.M. Likharev showed in his monograph a map of the *C. laminata* distribution in the eastern part of the range [17]. For the most part, our prediction for the current species distribution in eastern Europe coincides with Likharev's scheme. Namely, the central part of the clinal range exactly coincides, the limitation of which Likharev determined by a combination of temperature and humidity. However, according to our models, the *C. laminata* range turns out to be wider in the southeast direction and apart in the Black Sea region and the Caucasus. There are also some differences in the northeastern part of the range: a small area (39° E, 62° N) is marked in the forecast as habitable for the species, which goes beyond the boundaries outlined by Likharev. At the same time, there are also areas that, on the contrary, in Likharev's map are designated as part of the range, while in our current projection, they are shown as unsuitable for habitation. The main reason for this discrepancy is most likely the lack of species occurrence data. This applies to a part of the Mari lowland and the north of the Volga Upland (the confluence of the Sura River into the Volga).

If we focus on the southeastern part of the *C. laminata* range, which was of most interest to us, we can distinguish the territories of the forest-steppe and mountain ecosystems that are included in the potential range of the species. Areas suitable for the species habitat in the southern part of the potential range are located in the Caucasus, the Pontic Mountains and in the Crimean Mountains. According to I.I. Puzanov [30], the species inhabits the entire zone of beech forests on the Crimean Peninsula. And according to A.A. Bajdashnikov [31], the distribution of *C. laminata* in the Crimea is limited by the forests of the northern slopes. There is very little information about the distribution of *C. laminata* in the Caucasus and the Pontic Mountains except for data from the north Caucasus which we used in our occurrence data set. However, both in the Crimea and in the Caucasus, the diversity of clausilids species is quite high, including endemic species [17,99–101]. And if the ecological features of different clausilids species and their local habitats are quite well known for the Crimea [31,102–104], then additional studies are needed to accurately describe the ecological niche *of C. laminata* in the ecosystems of the Caucasus.

The southern part of the eastern wedge of the *C. laminata* range passes through the zone of forest-steppe and steppe. The territory of the potential range belongs to the Don basin and from the Central Russian Upland continues to the Volga Upland, a little, not reaching the Obshchy Syrt. If we take into account not only the ensemble forecast but also the MLP and GAM models, then the current range runs even further east to the Urals. The distribution of *C. laminata* on the Central Russian Upland is mostly confined to ravine and upland oak forests, which is described in the work of V.A. Nikolaev for the main part of this territory [105] and is also described for the Dvurechansky National Park [27]. In addition to oak forests, *C. laminata* is found in floodplain forests, which was also noted on the territory of the Donetsk Ridge [25]. On the Volga Upland, the species occurs in oak forests, mixed forests, aspen forests [28,29,48,49]. Unfortunately, there are no descriptions of *C. laminata* occurrences in the easternmost part of its potential range yet. However, according to our models, areas of the Bugulma–Belebey Upland are territories are potentially suitable for the species.

Our projections based on future climate change models showed a significant reduction in habitat suitable area. Moreover, we can see the dynamics: the area of habitable territories will be reduced by more than one-third after 40 years, and in the next 40 years, one-half or a little more than one-quarter of the current territory of the snail's range will remain due to the average scenario. This negative prognosis is not surprising. Possible changes in biomes due to climate change are also consistent with such expectations. Thus, forecasts based on CMIP6 show a change in biomes on one-fifth or one-third of the land area by 2100 according to the RCP4.5 or RCP8.5 scenario, respectively [1]. Moreover, this study showed a northward shift of biomes with an increase in the proportion of treeless biomes in the northern hemisphere. Such changes undoubtedly affect vegetation and biodiversity. Based on CMIP6 climate models, deforestation in the 21st century has been shown [38]. It can be expected that the habitat suitability for land snails that inhabit forest biotopes will be reduced. Predictions of future changes in the distribution are modeled for different animal species, including molluscs belonging to different ecological groups. In many cases, these forecasts are pessimistic, although this is not an absolute trend. There are many examples of such studies for tropical species, which is explained by the high interest in the biodiversity of the tropical region and the threat of its decline. For example, it has been shown that the reduction in forests in South America in the future will lead to the "savanization" of the mammalian fauna [106]. A meta-analysis of the potential distribution of neotropical birds has shown a reduction in habitats of 25.7% to 44.5% from current ones in a number of species [2]. Modeling changes in the distribution of 17 genera of freshwater molluscs in northwest and central Europe based on climate change scenarios also provides dramatic predictions [107]. Another example of the land snail *Megalobulimus sanctipauli* Ihering & Pilsbry, 1900 inhabiting the tropical forests of South America shows a range shift but only a slight reduction [6].

In our forecasts for 2041–2060, there is a noticeable reduction in suitable areas in the central and in the northwest part of the *C. laminata* range on the East European Plain. By 2100, the potential range may look not like a wedge but rather like a series of fragments or like a band: wider in the western part and narrowing to the east. Separately habitable areas will be located in the southern part (the Black Sea region, the Caucasus). Interestingly, this picture is very similar to the prediction of soil surface moisture in the warm season based on the SSP5-8.5 in the CMIP6 ensemble modeled by Cook et al. [39]. This is a forecast of changes in climate parameters by 2100. Unfortunately, due to the low resolution for the models, these data cannot be directly used as predictors in our projections. But we consider this similarity interesting. Moreover, the correlated indicator, precipitation of warmest quarter (Bio18), was included in our models. Another process is the replacement of native tree species with alien ones. The invasive process can often progress under the influence of climate change. According to predictions based on bioclimatic variables, many indigenous tree species are expected to be replaced by non-indigenous species in Europe in the next 60 years [108]. This shift may entail changes in the soil and microclimate; for this reason, the impact of invasive plant species replacing native ones on fauna deserves additional research.

We believe that it is quite difficult to isolate any single factor (or even several) as the main limiting one. But in general, the combination of temperature and humidity as well as precipitation in the warm and cold seasons determines the distribution of many species of snails, especially clausilids [17]. Molluscs of the Clausiliidae family have increased requirements for temperature and moisture even compared to other land snails [17]. Clausilids have poor protection against drying out. These snails are most active at a temperature of 17–20 °C and a humidity of more than 90% [109]. The limiting factor of precipitation is especially important in the southern and southeastern parts of the range. Here, the protective role of forests in avoiding drying out is significant for *C. laminata*. We presume that the climate shift toward continentality in the study area, and the possible reduction in forests, in our opinion, most likely explains such a reduction in habitat suitable areas for the species.

If we consider the features of the species biology, the most vulnerable is the reproduction and survival of juvenile individuals [18]. *C. laminata* is an oviparous species, and with a decrease in soil moisture, death at the juvenile stage increases. In the conditions of the middle part of the East European Plain, snails of this species begin to lay eggs early (maybe in March), which lasts until the end of July [18]. But at the same time, in the case of snow melting and an anomalous increase in winter temperature, the individuals did not lay eggs. Mamatkulov suggests that the length of daylight hours and the need for exposure to low temperatures after the breeding season, as well as precipitation, also have an effect on oviposition. This is also shown in other species of the family. The presence of snow cover is also important, which protects all land snails, not only clausilids, from freezing during the cold season [20].

The question remains: will this species be able to adapt quickly enough to changing environmental conditions? For example, it has been shown that in the laboratory, *C. laminata* reproduced throughout the year [110], although the problem of the survival of egg clutches and juveniles, with a change in soil moisture conditions, can greatly affect the reproduction of the species. That is, the question of species adaptation is still difficult to solve, although it is one of the key ones for understanding the perspective of the species in a particular territory. It is also difficult to predict the change in forest area, which will certainly affect the species distribution. However, some works investigate this area, and we see the potential in this direction for using such forecasts in SDM [111].

5. Conclusions

The current potential range of the most widespread door snail in Europe, *C. laminata*, reaches the Cis-Urals. In the southeastern part, the potentially suitable area covers not only the Balkans, the mountainous Crimea, but also a part of the Caucasus and the Pontic Mountains. In fact, the forest-steppe zone and some areas in the steppe zone in the eastern part of the *C. laminata* range are suitable for the species habitat. The annual mean temperature made the greatest contribution in all models, and also the precipitation of the warmest quarter had a high contribution. All other factors had approximately equal influence on the models. All the models we applied predict a large reduction and fragmentation of the potential range of the species after 40 and 80 years. Despite the general decline in suitable habitats, in some areas previously unsuitable for the species, such habitats may appear. This also applies to the easternmost regions of the potential range. The results of our projection can be used for conservation purposes and for more detailed field studies of the eastern part of the *C. laminata* range.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/d15111155/s1, Table S1: Occurrence data after spatial thinning; Table S2: Program code; Figure S1: *C. laminata* future habitat suitability according to tested three algorithms' types based on four climate models for 2041–2060; Figure S2: *C. laminata* future habitat suitability according to tested three algorithms' types based on four climate models for 2081–2100.

Author Contributions: Conceptualization, V.V.A.; methodology, V.V.A.; software, V.V.A. and P.A.U.; validation, V.V.A. and P.A.U.; formal analysis, V.V.A.; data curation, V.V.A.; writing—original draft preparation, V.V.A.; writing—review and editing, V.V.A.; visualization, P.A.U. All authors have read and agreed to the published version of the manuscript.

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