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Original article

Improving biodiversity in Central and Eastern European gardens needs regionally scaled strategies

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ABSTRACT

Amid ongoing urbanisation, gardens are expected to play an increasing role in enhancing urban biodiversity by supplementing green areas and improving landscape connectivity. Biodiversity-friendly gardens also improve human well-being and foster connections between nature and people. To study these benefits, we distributed a questionnaire (n = 5255), and used a scoring system to evaluate gardens' ecological value (GAR index), gardeners' attitudes (RES index), and pesticide use habits (PES index). We used machine learning to explore how these indices interact and what sociodemographic factors drive them across Central and Eastern Europe (CEE). Our aim was to explore the ecological values of gardens and gardening practices, identifying characteristics that might contribute to building high biodiversity. We found significant variability within and between countries, with Romania scoring low and Czechia high in all indices. Domestic pesticide use was ubiquitous across CEE and largely unaffected by sociodemographic factors. Increased time spent gardening was associated with the highest pesticide use and a greater potential for fostering high biodiversity. Gardeners aged over 55 tended to uphold longstanding conventional practices and thus lowered both PES and GAR index scores. The local differences highlight the need for regionally tailored biodiversity-friendly gardening guidelines instead of standardised regulations across Europe. Effective environmental education and community programs can be developed based on local biodiversity and the three indices we used. These programs should inform gardeners about the environmental and health impacts of pesticides and provide comprehensive biodiversity-related knowledge. This is especially important in CEE, where such initiatives are currently underrepresented.

1. Introduction

Built-up urban areas in the European Union (EU), which accounted for an average of 4.4 % of its territory in 2015 (Eurostat, 2018), are projected to increase to 7 % by 2030 (Perpiña Castillo et al., 2019). This ongoing urbanisation, together with increasing anthropogenic activities, is a major driver of biodiversity loss (Hagen et al., 2012) and the rapid decline of undisturbed ecosystems (Bengtsson et al., 2000). Most parts of

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Europe are already impoverished in biodiversity, and characterised by small natural areas, broken up by human intervention into a mosaic of agricultural lands and settlements (Jongman, 2002). Thus, it is particularly important to halt, or at least reduce the ongoing degradation and losses of natural habitats in areas heavily modified by human activities, and, as much as possible, maximise biodiversity. However, whilst conservation efforts for maintaining and preserving biodiversity have already been a part of many agricultural systems (Concepción et al., 2020), urban biodiversity rarely gains enough attention (Fischer et al., 2020; Ramalho & Hobbs, 2012). Although, the European Commission (EC) adopted a law to stop the loss of urban green spaces with ecological features by 2030 and subsequently increase them (EC, 2024a), the area of urban green spaces have only increased in some Southern and Western European cities (e.g. Pamplona/Iruña (Spain) and The Hague (Netherlands); EEA, 2022). In Eastern Europe, Czechia, Poland, and Romania are just about to catch up (EEA, 2023; Kabisch & Haase, 2013). Yet, in none of the EU countries, could the amount of re-naturalised areas compensate for what has been lost for urbanisation (EC, 2022).

Urban green infrastructure covers an average of 42 % of the city area in the EU according to the European Environment Agency (EEA, 2022), implying that urban biodiversity can be substantially improved by developing green infrastructure (Baldock, 2020), such as diversifying urban parks and community gardens, establishing pollinator-friendly meadows, creating a network of corridors, and installing green roofs (Lin et al., 2015; Seitz et al., 2022).

Besides public places, private gardens occupy an average of 16–36 % of the total urban area in Europe (Cameron et al., 2012; Goddard et al., 2010), and therefore the role of gardens in preserving and supporting native biodiversity and their contribution to urban sustainability are becoming increasingly important (Hanson et al., 2021). Enhancing environmental quality in domestic gardens also offers a great opportunity to improve human health and well-being (Soga et al., 2017) and alleviate biodiversity loss simultaneously (Freeman et al., 2012; Li et al., 2023).

The biodiversity of domestic gardens varies along a wide spectrum (Home et al., 2019), and their ecological value is determined by multiple environmental factors, such as climate, adjacent landscape mosaic/-characteristics (Braschler et al., 2020), natural vegetation (Borysiak et al., 2017), and soil composition (Tresch et al., 2019). Although these intrinsic attributes are mostly beyond the gardeners' control, the garden's impact on biodiversity primarily depends on their decisions regarding design, use, and management (Quistberg et al., 2016). With appropriate management, even small or highly anthropised gardens can support high biodiversity (Griffiths-Lee et al., 2022). On the other hand, numerous anthropogenic stressors, such as the intensity of cultivation (van der Veen, 2005), mowing frequency (Lerman et al., 2018) or pesticide use (Tassin de Montaigu & Goulson, 2023), often compromise the ecological value of gardens (Varga-Szilay & Pozsgai, 2022). Besides the need to reduction of these stressors (Proske et al., 2022, Tassin de Montaigu & Goulson, 2023), there is an agreement that the potential ecological value of gardens in conservation correlates positively with the microhabitat diversity of gardens (Majewska & Altizer, 2020). Ultimately, garden management is a series of 'tyranny of small decisions' (Dewaelheyns et al., 2016, Kahn, 1966) with mixed motivations (Hruška et al., 2021) and external factors such as demographics, household income, neighbours' expectations, accessibility of information, and education, can influence gardeners' behaviour (Goddard et al., 2013). Hence, evaluating the biodiversity values of gardens necessitates considering the gardeners' management and attitude toward a diverse garden. Yet, the major drivers in management may depend on several societal factors and cultural background.

In Western Europe, leisure opportunities and recreational activities have long been the primary drivers of gardening, promoting well-being (Beumer, 2018) whereas in Central and Eastern Europe (CEE) gardening for food self-provisioning (FSP) still may dominate (Jehlička et al., 2020; Smith & Jehlička, 2013). CEE countries share a historical background in FSP, which is thought to be a coping strategy for economic pressures (Alber & Kohler, 2008). However, the previous differences in gardening motivation between western and eastern Europe are beginning to blur with the emergence of new gardening trends in both regions (Poniży et al., 2021). Indeed, the demand for ensuring food security and quality in Western countries is growing (Glavan et al., 2018; Pourias et al., 2016) and, at the same time, CEE countries are shifting toward wildlife-friendly and recreational activities in gardening (Tóth et al., 2018; Trendov, 2018). Still, due to the limited access to biodiversity-related information in Eastern Europe, lower willingness to change, and the extensive use of pesticides in gardens (Coisnon et al., 2019), CEE appears to be lagging behind in the adoption of biodiversity-friendly practices (for example leave space for wildlife – EC, 2015), and the increasing emphasis on nature conservation across all Europe (Galluzzi et al., 2010) seems to be embraced by CEE countries more slowly than in their Western counterparts (Hruška et al., 2021; Vávra et al., 2018).

Whilst there have been numerous studies investigating the role of gardens in maintaining urban biodiversity in Western Europe since the 1990s (Delahay et al., 2023), in CEE these are scarce (but see Varga-Szilay & Pozsgai, 2022). However, the divide in the applied gardening practices between East and West remains significant, and assessing the ecological value of CEE gardens, therefore, requires consideration of location-specific anthropogenic and environmental variables (Varga-Szilay et al., 2024).

To address this knowledge gap, we investigate how three key variables, a garden diversity indicator (GAR index), an indicator for gardening attitudes of gardeners (RES index), and one for their habits related to pesticide use (PES index) vary across nine CEE countries and how these variables correlate with each other. Using these indices, we also explore the differences between gardens and gardening practices with a potential for maintaining high biodiversity, both between and within countries. Since these factors can fundamentally drive local educational strategies, we particularly aim to pinpoint how sociodemographic parameters and geographical factors best predict gardens' ecological values, as well as the respondents' attitudes towards supporting insect pollinators in their gardens and their pesticide use habits. Hence, understanding the costs and benefits of initiatives to enhance garden diversity is essential for effective planning and management; therefore, we propose educational strategies based on population and local biodiversity (measured via a proxy Bird index) patterns in CEE.

2. Material and methods

2.1. Questionnaire design and data collection

An online questionnaire was distributed in nine CEE countries (Croatia, Czechia, Estonia, Hungary, Latvia, Poland, Romania, Slovakia, and Slovenia), all of which were formerly part of the Eastern Block and are currently members of the EU.

Participants ($n = 5255$; Table 1) could complete the questionnaire in any of ten languages, including Croatian, Czech, Estonian, Hungarian, Latvian, Polish, Romanian, Slovak, Slovenian, and English. The questionnaire gathered information about the location and the main characteristics of the garden, the sociodemographic parameters, the gardeners' gardening attitudes, cultivation habits, pesticide usage, environmental awareness, and pollinator-friendly practices.

Participants had to indicate their gender, their highest level of completed education, and their residency according to the Nomenclature of Territorial Units for Statistics (henceforth NUTS). Because of the large number of NUTS-3 regions in Poland, to simplify the questionnaire, here, residencies were recorded at NUTS-2 levels, while the other eight participating countries were recorded at NUTS-3 levels.

The questionnaire was designed using Google Forms and distributed through gardening-oriented websites, social media platforms, and targeted emails to organisations dedicated to gardening and environmental

Table 1

First and last days of the three months data collection period in the nine participating countries, and the number of respondents.

Country	Country ISO code	Population (Eurostat, 2022)	First day* of the data collection	Last day of the data collection	Number of respondents
Czechia	CZ	10827529	18/01/2023	21/04/2023	648
Estonia	EE	1365884	22/01/2023	25/04/2023	710
Croatia	HR	3850894	27/01/2023	30/04/2023	462
Hungary	HU	9599744	26/10/2022	27/01/2023	1088
Latvia	LV	1892103	23/01/2023	26/04/2023	393
Poland	PL	36753736	14/02/2023	18/05/2023	746
Romania	RO	19054548	16/01/2023	19/04/2023	434
Slovenia	SL	2116972	18/01/2023	21/04/2023	347
Slovakia	SK	5428792	25/01/2023	28/04/2023	427
SUM					**5255**

* The day on which the first questionnaire was completed.

conservation between 26th October 2022 and 18th May 2023, for 90 days in each country (Table 1).

The participation was voluntary, anonymous, and a Data Protection and Privacy Statement was available alongside the questionnaire.

2.2. Definitions

For terminological clarity and consistency, we used '*garden*' as an umbrella term encompassing all garden types, regardless whether they were urban, rural, peri-urban gardens, ornamental or vegetable gardens, or whether they were located within residential plots or community gardens. We used '*gardener(s)*' to refer to any respondent who owned, managed, or otherwise tended and cultivated a garden or allotment, either as a pastime or for a living.

For clarity, we followed Varga-Szilay et al. (2024) in defining '*pesticides*' as 'all synthetic and non-synthetic products that are used to control pests, including 'all commercially available and homemade plant protection products, either those allowed in organic gardening or used in conventional practices' and '*gardening*' as 'all garden work and all garden care practices, such as the cultivation of flowers, fruits, vegetables, and ornamental plants, mowing, and soil management'.

2.3. Data processing

Out of the original 59 questions, we discarded 19 due to their lack of relevance to this study. A total of 5 questions were used to characterise respondents based on geographical and sociodemographic aspects, 3 characterising the gardening engagement, while the remaining 32 questions were utilised to construct the GAR, RES, and PES indices (see Section 2.4).

The original categorical replies of our questionnaire were re-categorised for analytical purposes on a few occasions (see Supplementary Methods 2.1). NUTS polygons, number of inhabitants, the regional gross domestic product (GDP) in purchasing power standards per inhabitant for each NUTS (PPS, henceforth), and the urban-rural typology for each NUTS-3 region were obtained. PPS was only available for NUTS-2 categories. When country capitals with separate NUTS categories were situated within a larger unit, capitals were merged with the largest NUTS surrounding them (CZ, HR, HU, LV, PL, RO). In these cases, for PPS and number of inhabitants, the mean and sum of the merged areas were calculated, respectively. In the case of urban-rural typology data, the originally obtained NUTS-3 categories were merged into NUTS-2 in Poland, and the NUTS polygons of the abovementioned capitals were merged with the surrounding polygons. For this, a weighted mean of the numerised typology index was calculated using the areas of the merged NUTS polygons as weights. The means were rounded to the nearest integer and converted back to categories.

2.4. Scoring system

Since we were unable to collect empirical biodiversity data from the gardens, we could not directly evaluate the association between gardening practices, valuations, and urban biodiversity, only assess the gardens' potential for maintaining high biodiversity through proxy indices. Thus, we rated the potential ecological value of the gardens, the gardeners' attitudes to maintaining/creating a biodiverse garden, and pesticide use habits with an answer-based scoring system. The calculation of each index was based on questions that contributed with different weights.

The **garden (GAR) index** shows what potential a garden has to build high biodiversity, based on 12 questions. This index reflects on the structural diversity of the gardens, including garden size, the area of undisturbed patches and plants covering the garden, and the habitat types of adjacent areas, as well as, the disturbance level and the presence of artificial habitats. The weights were determined by the importance of the components in maintaining high biodiversity (Supplementary Methods 2.1.1).

The **respondent (RES) index** assesses the gardeners' knowledge of garden wildlife and their attitudes to maintaining/creating a biodiversity-friendly garden, based on 10 questions (Supplementary Methods 2.1.2).

The **pesticide (PES) index** shows the degree of pesticide load in gardens by assessing the amount and diversity of pesticides used and the related knowledge of the gardeners, based on 10 questions. Although fertilisers are not pesticides, for simplicity, fertiliser use was also incorporated into this index (Supplementary Methods 2.1.3). The scoring ranged between 0 and 100 points for each index. For the full details of the index calculation process, the reader should consult with the Supplementary Methods 2.1.

2.5. Environmental context

2.5.1. Bird index

Since garden diversity depends on the historical biodiversity of a given area (Dobrovodská et al., 2023) but simplified, human-modified landscapes can achieve moderate levels of ecological benefits more rapidly (Haenke et al., 2009), the efficiency of biodiversity-friendly activities can only be measured in the context of local biodiversity indices. Thus, as a proxy for local biodiversity, we collected a full list of bird species recorded between 2010 and 2023 in each NUTS-3 area (except in Poland, see Section 2.1) from the Global Biodiversity Information Facility (GBIF.org, 2024). To minimise the observer bias, and the effect of rare species, in each NUTS, we only considered relatively common species that had at least five recorded occurrences per year from the particular area. We standardised the collated number of species with the area of the NUTS (i.e. divided the species number with the area of NUTS in km squares). To compensate for observer density (i.e. more species are likely to recorded with higher population density) we also further divided the number of species with the population of the NUTS. Using the same methodology, we also gathered a species list for the whole area of interest (i.e. the nine participating countries) and standardised for bird species per km^2. We then divided the standardised local bird richness with the standardised whole-area bird richness.

2.5.2. Urban-rural typology

The European urban-rural typology data is a qualitative index which classifies grid cells into rural and non-rural grids and establishes three categories (predominantly rural, intermediate, and predominantly urban) of urbanisation based on the percentage of the population living in rural grid cells (Eurostat, 2024). We employed this index to approximate urbanisation. Since the qualitative nature of this index, we also converted our four indices (bird, GAR, RES, PES) to categorical variables by dividing them at their 0.33 and 0.66 quantiles. When calculating the quantiles, only measured values were included and the theoretical minimum and maximum were not considered. NUTS areas with less than five respondents were excluded.

2.6. Statistical analysis

We examined the correlation between the three indices (GAR, RES, PES) with the Spearman correlation test. We used the Kruskal-Wallis method to test if GAR, RES, and PES indices differ among countries. Pairwise differences were investigated using the pairwise Wilcoxon test with Holm-corrected p-values.

To investigate how well sociodemographic parameters (country, gender, age, education level, having children; Supplementary Table 1), gardening engagement (gardening experience, gardening perception and the average time spent gardening; Supplementary Material 2.2), geographical factors (latitude and longitude of the centroids of the NUTS areas as numerical variables), and the PPS (as a numerical variable) predict our three indices we employed Gradient Boosting Machine (GBM) learning processes. Each of the indices were used as response variables in three separate models with the above eleven explanatory variables.

GBM is an ensemble learning method that builds a series of decision trees to improve prediction accuracy and handle complex, non-linear relationships. We selected GBM due to its robustness with mixed data types and strong performance in structured datasets. We randomly divided the datasets into training (70 %) and test (30 %) sets. After an optimisation and tuning process of the model parameters, we built the GBM model using a Gaussian distribution with 5 levels of interaction depth, with 0.3 shrinkage, 0.80 bag fraction, and a 10 fold cross validation on 28, 26, and 10 (for GAR, RES, PES indices, respectively) trees. This method well-suited for capturing complex, non-linear relationships and interactions between predictors. The model fit was evaluated by calculating the R-squared and Root Mean Standard Error (RMSE) values. We used the SHapley Additive exPlanations (SHAP) method to interpret our final models. For the software background and related packages used in modelling and visualization, the reader should consult the Supplementary Methods 2.2.

3. Results

3.1. Sociodemographic characteristics and gardening practices

Altogether 5255 gardeners completed the questionnaire from the 9 participating countries (Supplementary Fig. 1, Table 1), of which 1146 were males (21.80 %), 4094 were females (77.91 %), and 15 were non-binary gender (0.29 %). The majority of respondents were between 36 and 55 years old (n = 2841, 54.06 %). The greatest proportion of gardeners had a postsecondary education (n = 3225, 61.37 %), followed by middle-level education (n = 1466, 27.90 %) and postgraduates (n = 512, 9.74 %), while only 52 respondents had elementary school as the highest level of their education (0.99 %) (Supplementary Table 1).

In all participating countries, most of the respondents considered gardening as their favourite hobby (between 21.05 % and 58.31 %) or a pleasant pastime (between 26.46 % and 62.54 %) (Supplementary Fig. 2).

In most participating countries, mowing several times a month was under 40 % (Supplementary Fig. 3) but in Estonia and Latvia, the majority of gardeners (65.07 % and 63.61 %, respectively) mowed the lawn several times a month, and the proportion of those who did so once a month was also high (27.04 % and 21.88 %). The average pesticide use among the nine countries was 52.60 %, ranging from 38.88 % in Slovakia to 69.59 % in Romania (Supplementary Fig. 4).

3.2. Indices

The mean of the calculated indices was 56.49 (range: 14.97, 91.32), 63.25 (range: 9.25, 96.75), 76.33 (range: 24.87, 100), for GAR, RES, and PES, respectively (Supplementary Table 2). The GAR index with the RES index showed a moderate, positive correlation (Spearman's rho=0.55, $p < 0.001$). The PES index showed an almost negligible, negative correlation with the RES index (Spearman's rho=-0.09, $p < 0.001$). There was no significant correlation between GAR and PES indices ($p = 0.487$).

There were significant differences between the participating countries in all indices (Kruskal-Wallis chi-squared=290.85, 671.51, and 235.13, GAR, RES, PES respectively, $p < 0.001$) (Supplementary Table 3,4), and the index values varied broadly among NUTS areas (Fig. 1). A total of 197 respondents had all three scores below the first quartile of the indices, with those from Romania and Hungary being the lowest, whilst there were a total of 90 respondents in the fourth quartile of all indices, mostly from Czechia and Slovenia (Supplementary Table 2,3).

3.3. GBM outputs

The GBM model for the GAR index explained 12.45 % of the variance for new observations (RMSE=11.29, Supplementary Table 5), with SHAP values indicating the country variable being the best and the average time that gardeners spent gardening being the second-best predictor (SHAP value=2.15, 1.94, respectively) (Fig. 2**A**).

Countries like Romania, Poland, and Croatia shifted the GAR index toward the lower, while Czechia, Estonia, Latvia, Slovenia, and Slovakia to higher values (Fig. 2**C**). The GAR index increased with increasing time spent gardening.

The two age categories over 55 shifted the GAR index toward lower values (particularly the age group of over 65), in contrast, the three age categories between 26 and 55 resulted in higher values. Perceiving gardening as a work or a pleasant pastime both lowered the GAR index values while perceiving it as a favourite hobby increased them. Post-secondary and postgraduate education shifted the index to higher values, while middle-level education to lower ones. Albeit it had a low influence in the model, gardeners who had children separated well from those who did not, with those having children shifting the index to higher values. The GAR index values were increased from the west to the east (Fig. 2**B**).

The GBM model for the RES index explained 24.73 % of the variance for new observations (RMSE=13.13, Supplementary Table 6), with SHAP values indicating the country variable being the best and how gardeners perceived gardening being the second-best predictors (SHAP value=3.80, 2.26, respectively) (Fig. 3**A**). Whilst Hungary and Czechia had the highest SHAP values, and thus the RES index, Poland and Croatia had the lowest ones, with Romania and Latvia also indicating lower values. Only perceiving gardening as a favourite hobby shifted the SHAP values to higher ranges, all other cases lowered them, especially when gardening was perceived as a duty (Fig. 3**C**). SHAP values increased with the time spent gardening. Older age groups predicted lower RES index values, while the 26–35 age group exhibited higher ones. Gender, education, and having children were less important variables. However, SHAP values separated well with gender, with women presenting at higher values. SHAP values increased from west to east, except for a few very eastern locations presenting the highest values on the right side of the axis (Fig. 3**B**).

The GBM model for the PES index explained 0.08 % of the variance for new observations (RMSE=18.19, Supplementary Table 7), with SHAP values indicating the country variable being the best and the average time that gardeners spent gardening being the second best

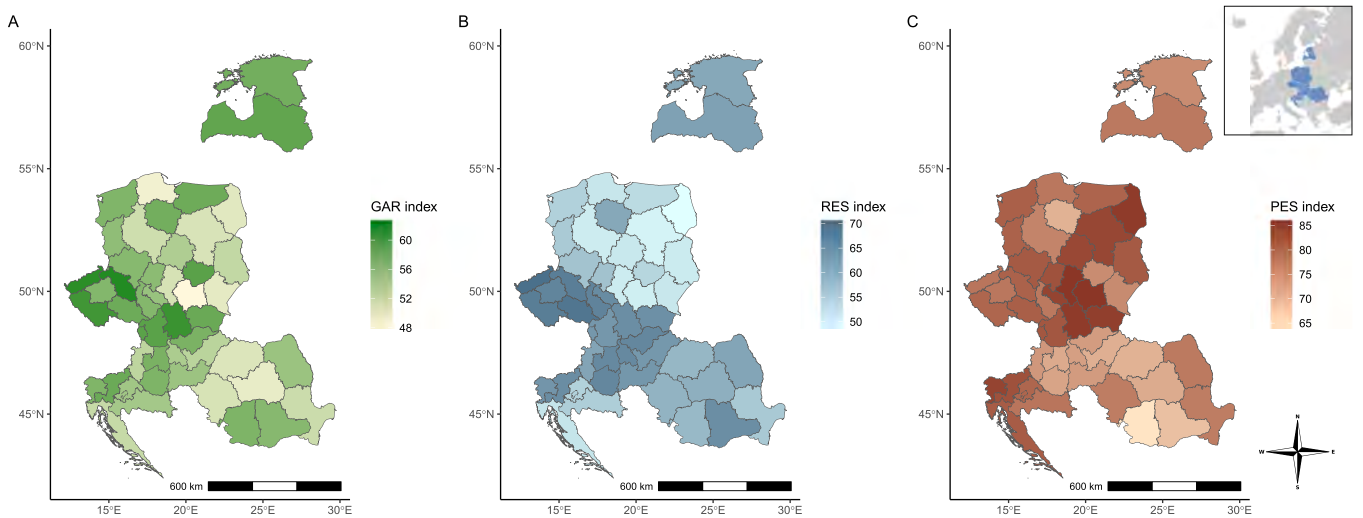

Fig. 1. The garden (A), respondents (B) and pesticide (C) indices in the nine participating countries. The colour depth of the maps indicates the mean of the indices calculated for each NUTS-2 area.

predictors (SHAP value=3.20, 1.56, respectively) (Fig. 4**A**). Romania, Estonia, and Hungary had the lowest SHAP values, whilst Poland, Slovakia, and Slovenia showed the highest ones (Fig. 4**C**). An average of 1–2 h of gardening per day predicted a higher PES index, whilst all other times spent gardening lowered it, with the lowest values associated with those who spent up to 12 h a day gardening. More than 10 years of gardening experience shifted the index to lower values. Perceiving gardening as a pleasant pastime shifted SHAP to higher values, whereas in most other cases, the values decreased equally when gardening was perceived as a duty and a favourite hobby. Women shifted SHAP to higher values, however, gender, age, having children, and education level were not deemed to be important variables. Having children separated positive and negative SHAP values, with those respondents who had children associated with higher values. SHAP values increased both from south to north and east to west (Fig. 4**B**).

3.4. Urbanisation level and indices

When areas within urbanisation levels were cross-referenced with the categorised three indices, different effects of urbanisation levels of the three indices were revealed (Fig. 5). Half of the predominantly urban NUTS areas (3 of 6) were categorised as low GAR values, and half of the NUTS areas typologised (26 of 52) as intermediate reached a medium level on the GAR index. The RES categories were relatively evenly spread both among intermediate and predominantly rural areas but most predominantly urban regions (4 of 6) were categorised as medium RES (Supplementary Table 8). The distribution of PES categories was uniform among predominantly urban and predominantly rural areas, whilst in intermediately urbanised regions intermediate PES category was the most common (22 of 52), followed by the high and low categories (17 and 13 of 52, respectively) (Fig. 5**,** Supplementary Table 8).

Of the NUTS areas typologised as predominantly urban, Czechia, Hungary, Slovakia and Slovenia had those with the highest scores of all calculated indices (bird, GAR, RES, and PES) (e.g. the Plzeň region in Czechia with the highest scores in all variables but the bird index), while Romania had that with the lowest (the Vrancea county in Romania with the lowest scores in all variables). All predominantly urbanised areas were categorised relatively high in all indices with Slovakia having the highest scores (Bratislava region) and Poland and Romania bhaving the lowest scores (Silesian Voivodeship, București-Ilfov region).

4. Discussion

Gardens offer significant opportunities for advancing global biodiversity and sustainability targets. Our work investigated the intertwined relationship between sociodemographic parameters, sustainable garden management, and biodiversity conservation from a highly understudied area of the EU. We found that both cultural background and personal attitudes influenced the potential biodiversity value of gardens significantly, and so did pesticide use. Thus, our results show that merely examining either the structural diversity of private gardens, sociodemographic parameters, gardeners' gardening attitudes, or biodiversity-negative activities (e.g. pesticide use) individually may be insufficient for obtaining a reliable proxy of whether gardens could potentially maintain/build high diversity in human-altered areas.

Although Eastern European countries share similar recent sociopolitical and economic histories, country identity was the strongest factor influencing differences among respondents. Significant differences were observed both among and within countries, regardless of the scale, in all three examined indices, with the smallest differences in GAR and the largest in PES. These variations were confirmed through pairwise comparisons between countries as well as the GMB models. There were countries experiencing either equally low or high values on all indices, such as Romania faring poorly in all indices, whereas Slovakia showing overly high values. Sometimes indices implied counteracting effects, such as a high GAR index, suggesting a great prospect for maintaining high biodiversity in gardens, occurred together with high pesticide use in Hungary. This is mostly in line with Coisnon et al. (2019) who found similar trade-offs in variables influencing sustainable gardening practices such as Hungary in leaving lower spaces for wildlife and scoring very low in avoiding the use of pesticides, yet having been categorised high in selecting plants that provide food for birds and pollinators and avoiding the introduction of potentially invasive plants. Other countries such as Romania generally ranked poorly in both our study and known from the literature (Coisnon et al., 2019). All three indices varied widely, however, indicating the multidimensional nature of factors driving sustainable gardening (see Supplementary Material 3.3 and Supplementary Figures 7–10).

The extensive application of pesticides beyond the agricultural sector, including gardens, and the inter-country disparities in pesticide usage within Europe are critical issues for biodiversity-friendly gardens (Poniży et al., 2021; Varga-Szilay et al., 2024). Our study found substantial differences between countries in this regard, with 20–30 % of respondents in Hungary and Romania thinking that the use of pesticides

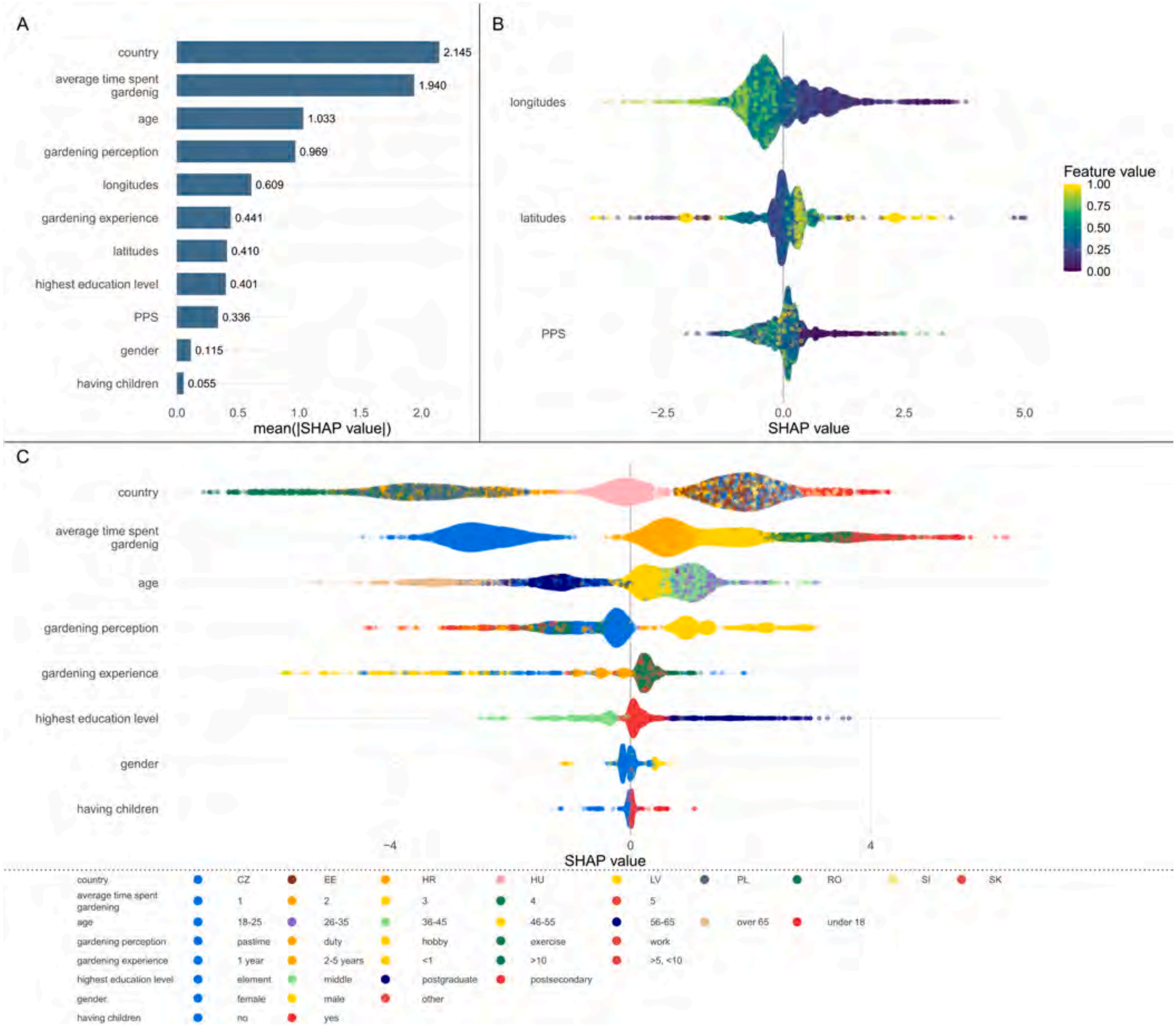

Fig. 2. Global SHAP (SHapley Additive exPlanations) summary plots for the GBM model of the GAR index: (A) variables ordered by their importance based on average absolute SHAP values; (B) beeswarm plots of SHAP values for numerical variables; and (C) beeswarm plots of SHAP values for categorical variables. Each point represents one respondent. For numerical variables, colours indicate variable values, while for categorical variables, they represent distinct category levels. Countries are abbreviated as CZ, EE, HR, HU, LV, PL, RO, SI, and SK, for Czechia, Estonia, Croatia, Hungary, Latvia, Poland, Romania, Slovenia, and Slovakia, respectively. Time spent with gardening is shown in a self-reported scoring system as indicated by the respondents, with 1 representing the lowest ('one to two hours per day') and 5 representing the highest value ('even twelve hours per day').

is either important or crucially important for their gardening, a claim with which only 2 % of those from Slovakia agreed (Supplementary Fig. 5.).

There is a disparity though between pesticide use and the other two indices we measured. Although nearly 70 % of respondents from Romania considered the widespread use of pesticides as one of the most threatening factors to pollinators, their average pesticide use was still the least favourable in our study. Indeed, what gardeners perceive as a biodiversity-friendly garden may not necessarily take into account important details (such as pesticide use and non-native species), suggesting that self-reporting surveys may be misleading in this term.

As found by Larson et al. (2022), those who perceived gardening as a hobby were more inclined to change their gardens to be attractive and beneficial to biodiversity, and we also discovered that gardeners who dedicate more time spent gardening tend to maintain gardens with higher biodiversity potential. Our results corroborate with the findings of both Philpott et al. (2020) and Lin et al. (2017) who indicated that time spent in domestic gardens positively correlates with plant species richness, higher dissimilarity in crop composition, and high levels of nature-relatedness. Moreover, our findings agree with those of Geppert et al. (2024) who reported that the time spent outdoors increased the willingness to pro-pollinator actions. In our study, however, both when gardening was associated with a hobby and more time was allocated for gardening were characterised by increased pesticide use. Therefore, there is a higher possibility for these gardeners to create an ecological trap in these gardens for visiting organisms, especially insects (Varga-Szilay & Pozsgai, 2022). There is, however, a noticeable contrast in behaviour based on gender and parental status (Fig. 4**C**) the pesticide load shifted towards more favourable conditions in gardens where respondents were women or with children.

Although country identity proved to be the most important variable in predicting the potential for maintaining high garden biodiversity, the

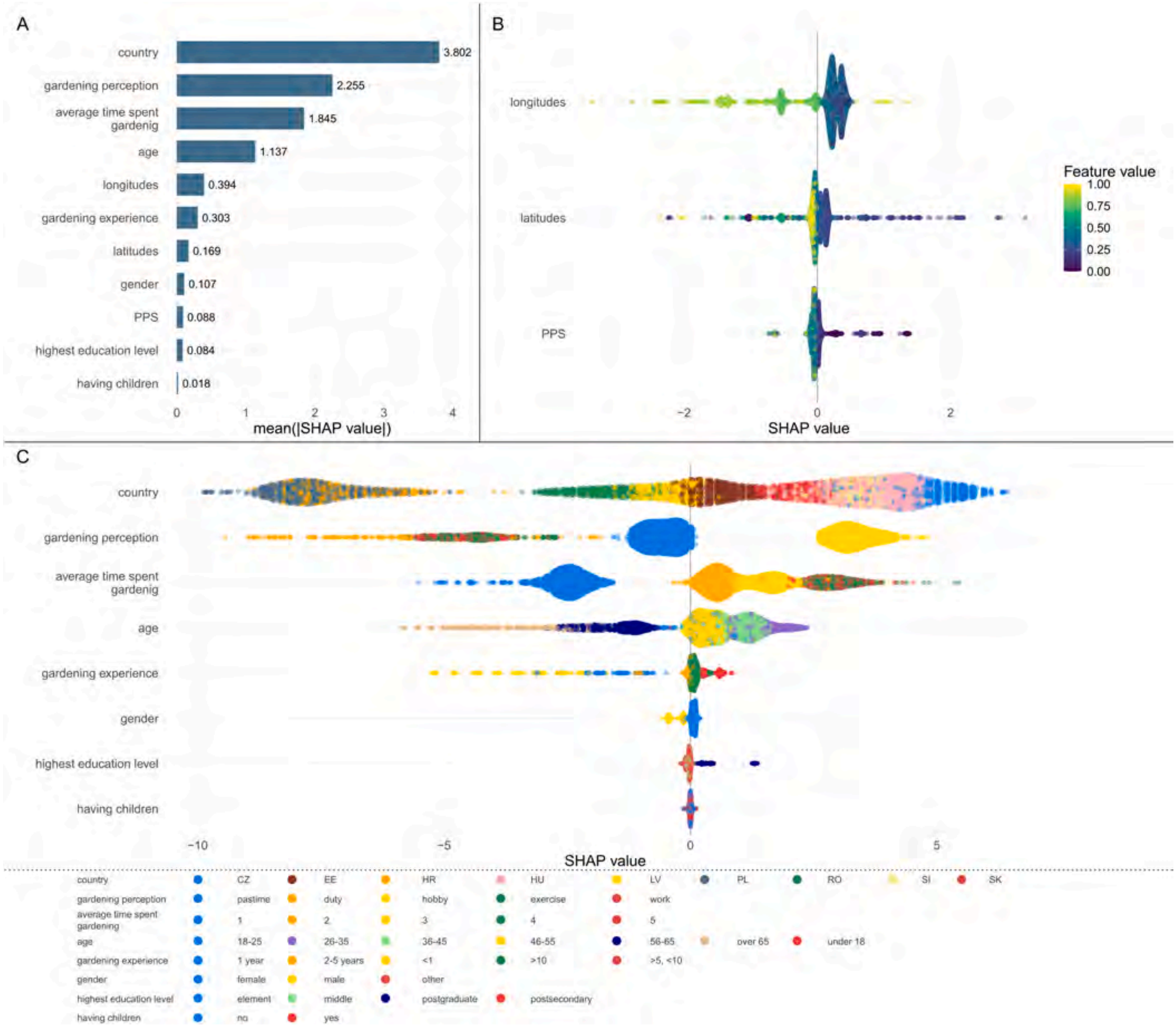

Fig. 3. Global SHAP (SHapley Additive exPlanations) summary plots for the GBM model of the RES index: (A) variables ordered by their importance based on average absolute SHAP values (B) beeswarm plots of SHAP values for numerical variables; and (C) beeswarm plots of SHAP values for categorical variables. Each point represents one respondent. For numerical variables, colours indicate variable values, while for categorical variables, they represent distinct category levels. Time spent with gardening is shown in a self-reported scoring system as indicated by the respondents, with 1 representing the lowest ('one to two hours per day') and 5 representing the highest value ('even twelve hours per day').

respondents' attitudes towards supporting biodiversity in their gardens, pesticide use, gardeners' perception, the long-term gardening experience and daily management also played key roles. Furthermore, nature conservation was the prime aspect that influenced gardening habits in four countries, albeit in three of these this did not mean a lower pesticide use. In Croatia and Poland, over 80 % of respondents felt nature conservation had no impact on their gardening habits (Supplementary Fig. 6). Upon entering the EU, national-level policies and initiatives that may have influenced gardening practices largely aligned with EU policies on nature protection, including the adoption of the Wild Birds and Habitats Directives (EC, 2004b). Most of the countries in question joined the EU in 2004, with the exceptions of Romania (2007) and Croatia (2013) as the last to fully implement all EU nature protection directives. Therefore, differences in gardening practices and environmental attitudes may be shaped more by factors other than environmental policies alone, except maybe for Croatia.

Increasing age (especially that over 65) negatively influenced both the potential of gardens for maintaining high biodiversity and the gardeners' attitudes toward maintaining biodiversity-friendly gardens, which suggests the elderly are more inclined to follow and uphold longstanding conventional practices, regardless of whether or not they are beneficial for ecological sustainability. Whether these decisions are driven either by the difficulties the elderly may have with manoeuvring among the continuous flow of complex ecological issues which were not highlighted during most of their lives, the scarcity of the available information from the more traditional information channels they use, or some alternative explanations is yet to be clarified. Nonetheless, the age-independent pesticide use in our GBM model suggests that even with broad information availability, behavioural change is not guaranteed.

However, gardening practices and their associated sociocultural and economic variables exhibited significant diversity among gardeners and the final outcome for biodiversity-friendliness appeared to be a series of multifactor decisions depending on numerous background drivers (Gifford & Nilsson, 2014). For instance, despite several studies

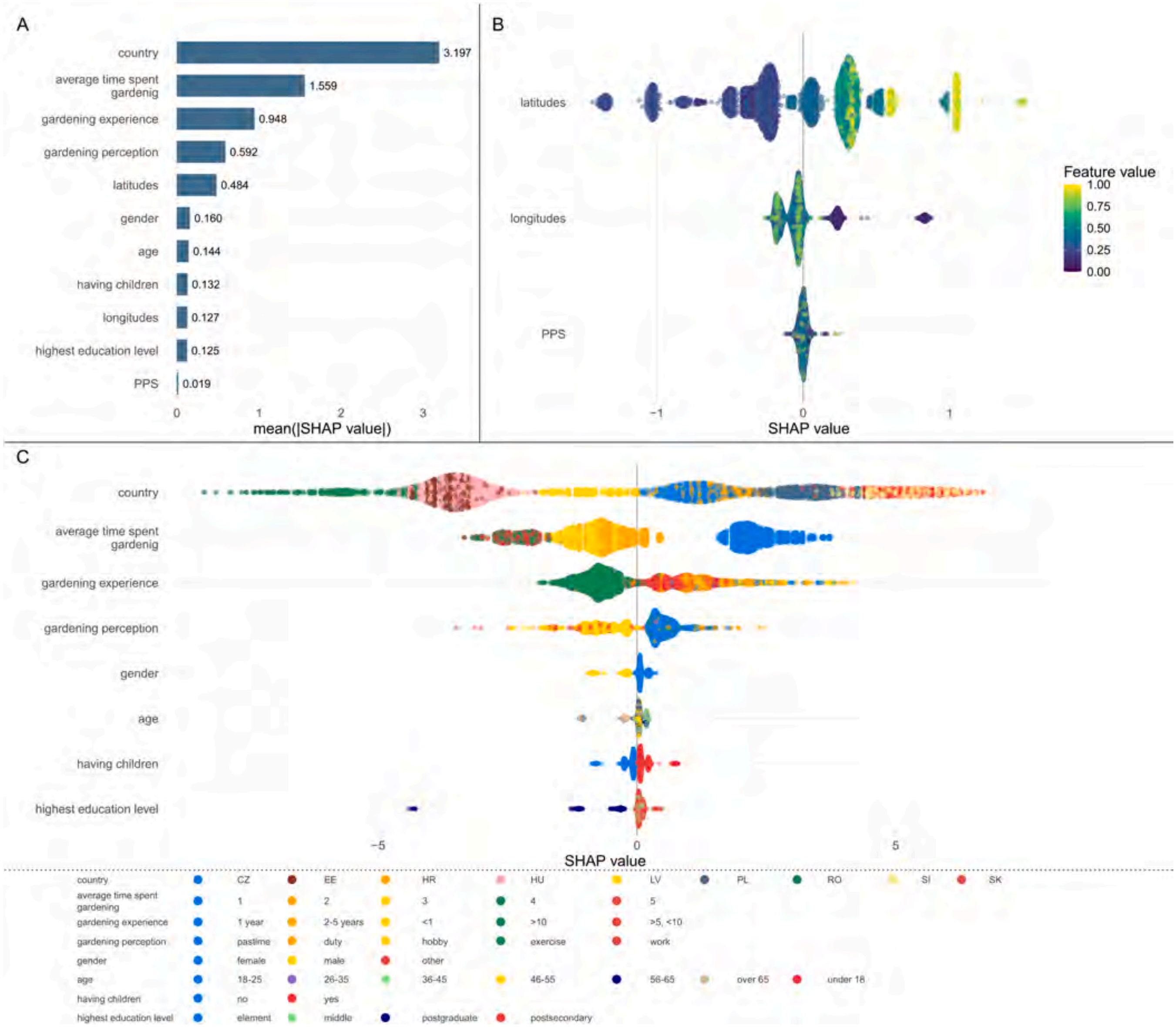

Fig. 4. Global SHAP (SHapley Additive exPlanations) summary plots for the GBM model of the PES index: (A) variables ordered by their importance based on average absolute SHAP values; (B) beeswarm plots of SHAP values for numerical variables; and (C) beeswarm plots of SHAP values for categorical variables. Each point represents one respondent. For numerical variables, colours indicate variable values, while for categorical variables, they represent distinct category levels. Time spent with gardening is shown in a self-reported scoring system as indicated by the respondents, with 1 representing the lowest ('one to two hours per day') and 5 representing the highest value ('even twelve hours per day').

highlighting a substantially positive effect of GDP per capita and household income on sustainable gardening practices and pollinator abundance in domestic gardens (e.g. Baldock et al., 2019), in our GBM model, PPS did not prove to be a significant explanatory variable for any of our indices. The role of agriculture in national economies may influence the perceived need for pesticides to enlarged the yield and profit, and more people involved in agriculture for living have access to pesticides (e.g. detected high pesticide use in gardening in Hungary; Varga-Szilay et al., 2024, Varga-Szilay & Pozsgai, 2022). So, pesticides use can vary depending on the scale of agricultural activity in each country. At the same time, countries like Croatia and Slovenia may place greater value on natural heritage as an asset to their economies, as the tourism play more important role in national GDP than agriculture (Hrvatska narodna banka, 2024, Ministarstvo poljoprivrede, šumarstva i ribarstva, 2024).

Despite the existing differences among the NUTS regions and countries in all three indices, we did not find strong geographical correlations; neither latitude nor longitude had a high explanatory power in our GBM models, which reinforce the cultural rather than climatic or biological effects of countries. Nonetheless, longitude had a higher influence on the GAR index than latitude, which might not be as expected since the north-south gradient exhibits steeper changes in climate and habitats, than the one from east to west. This greater importance of the east-west axis might be explained by the higher impact of Western European countries on how more westerly regions in CEE perceived biodiversity issues after political and societal changes in the 1990s. Conversely, the lower geographic influence on the RES and PES indices could be attributed to the continued strong connection to traditional practices across the studied countries.

The lack of a clear geographical pattern and within-country diversity in all indices suggests that large-scale planning policies might not be appropriate to achieve their targets and strategies must be regionally tailored rather than countrywide and have to be underpinned by interdisciplinary study efforts. Our study can offer fundamental insights to

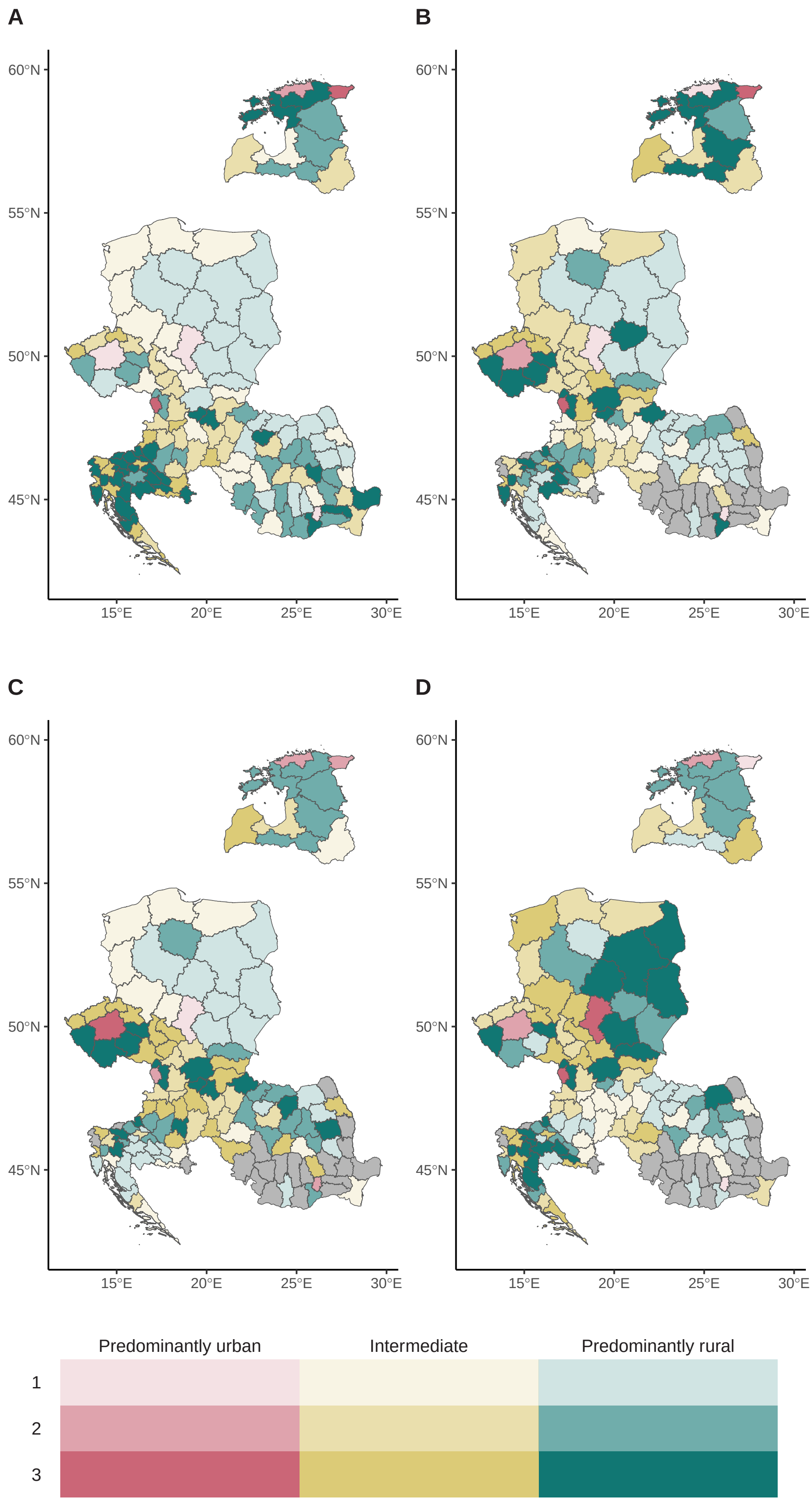

Fig. 5. The relationship of the bird (A), garden (B), respondent (C), and pesticide (D) indices with the urban-rural typology index based on NUTS-3 areas (except for Poland, in which NUTS-2 were used). The colours represent the levels of urban-rural typology, as follows: red–predominantly urban, yellow–intermediate, green–predominantly rural. The transparency of the colour indicates the categorised index value (bird/GAR/RES/PES) on a three-level scale (divided into categorised at the 0.33 and 0.66 quantiles). The grey colour indicates NUTS areas from which we had less than five respondents (n = 20).

identify pathways toward sustainable green infrastructure and to improve the natural value of gardens, as well as to forecast how they can be optimised and where the greatest rewards can be gained.

4.1. Implications for policy and planning

Areas with generally **low urbanisation** and also **low biodiversity** are likely to be agricultural- and farmlands in which gardens with high biodiversity can act as habitat islands, ecological corridors, or stepping stones which facilitate the movement of wildlife through unsuitable agricultural areas. In these areas, improving the structural complexity of the gardens and reducing pesticide use could be the most beneficial for biodiversity. Disseminating knowledge about ecological-friendly practices and sustainable gardening habits would also be key. Indeed, the predominantly rural areas in northeast Poland, where both bird index and urbanisation are low, also suffer from low RES. However, information exchange here may need to rely more on interpersonal relationships or traditional media than online channels (Troumbis, 2021) and overall biodiversity is likely to be more impacted by agricultural rather than garden practices.

Attempting to improve biodiversity value in home gardens in areas with generally **low urbanisation** levels and **high biodiversity** probably is the least beneficial for local biodiversity, yet reducing pesticide use can prohibit degradation and may form garden-level biodiversity islands that increase landscape complexity. Moreover, maintaining and even improving garden diversity in these areas, such as predominantly rural areas in the northern part of Croatia and Slovenia and southern part of Estonia can be particularly important as good examples for environmental education and maintaining source populations of wildlife for adjacent but less favourable areas.

Thus, at low urbanisation levels improving aspects of the RES would be the priority, along with a substantial decrease of pesticide use. With increasing biodiversity, gardens will benefit from improved conservation biological control (Landis et al., 2000), which may further decrease pesticide use.

Biodiversity-friendly activities can achieve fast and great ecological benefits in areas where **urbanisation** is **high** and **biodiversity** is **moderate or low**. Although their biodiversity potential will remain limited, prioritising increasing gardens' structural and plant diversity will enable them to serve as ecological corridors or stepping stones for most wildlife to navigate around highly urbanised areas. Although biodiversity will unlikely increase substantially, the high visibility of biodiversity in densely populated areas has an outstanding educational value. Even though few CEE regions fulfil these criteria (e.g. the central part of Czechia), most Western European areas predominantly classified as urban are likely to fall into this category.

Although **high urbanisation** and **high biodiversity** rarely co-occur, some areas in CEE, such as northern Estonia, exhibit such a phenomenon. This offers an opportunity for the dissemination of activities tied to increasing the RES index (e.g. through campaigns and species identification trainings), as they can quickly reach many individuals and engage them in enhancing garden biodiversity. Additionally, these efforts provide a substantial amount of data for biodiversity monitoring, resulting in additional benefits.

At high urbanisation levels, increasing gardens' structural diversity and other aspects beneficial for maintaining high biodiversity are key but improving gardeners' attitudes towards biodiversity-friendly gardening and reconnecting them to nature are also important. Since the level of urbanisation across Europe is projected to reach 83.7 % by 2025 (United Nations, 2018), this improvement in attitude is necessary to exploit the potential of gardens to mitigate large-scale biodiversity loss. However, due to the ubiquitous use of pesticides in CEE, improving the PES index would be equally necessary in every area, both urban and rural.

Adequate planning, at least, at the regional scale, with the active involvement of gardeners, is crucial for increasing the biodiversity value of gardens at a larger scale. For this, future nature conservation planning strategies and studies should acknowledge the variability of gardeners' attitudes and gardening practices, as well as the gardens' potential for biodiversity conservation (Cameron et al., 2012).

4.2. Limitations

Although we collected over 5255 responses, this represents a small fraction of the focal area of our study. Our dissemination methods likely biased participation toward gardeners with regular Internet access, underrepresenting those in less developed areas, such as parts of Poland and southern Romania. However, countries like Estonia and Hungary had high coverage, likely reflecting common gardening practices in those regions. Partially due to these low-information areas, the deeper interpretation of country-wise differences, based on diverging histories, agricultural traditions, and policies was not feasible.

Although we aimed for one response per garden, maintenance is often shared (e.g. among family members), meaning motivations and attitudes are influenced by multiple people.

4.3. Future perspectives

Involving more participants from the surveyed CEE countries, standardising the questions and expanding the area of interest to all European countries, as well as repeating the same survey within a reasonable time frame would all be highly advantageous. Investigating the distinction between the gardening habits in Western and Central-Eastern European regions, as well as those from the Balkan, such as Serbia and Bulgaria, holds particular potential. While addressing privacy concerns may present challenges, extending our study with measures of biodiversity and landscape configuration from each garden could introduce extra layers of complexity to our exploration.

Further research is needed to explore how national economic conditions influence public attitudes toward gardening and nature conservation. Although not directly examined in the present study, the results indicate a need to investigate how economic factors – following the countries' transition to capitalism – may have influenced gardening practices. This includes considering how national policies and historically embedded traditions could be improved to promote more environmentally friendly gardening, particularly in relation to the use of synthetic pesticides.

Furthermore, a direct link between garden diversity, and the potential of thereof, and biodiversity conservation should be established and implemented into urban green space management.

5. Conclusions

While gardens may not replace undisturbed natural habitats, it is imperative to reconsider maintaining high levels of urban and rural biodiversity as valuable complements for increasing the area of semi-natural habitat patches and creating a network of ecological corridors and stepping stones (Beninde et al., 2015). In our study, however, we show that the potential of gardens for maintaining high biodiversity varies widely among CEE regions, as does their conservation value. Therefore, to maximise this value improving several aspects of CEE gardening practices in concert is necessary. The variability both between and within participating countries, underscores the need for approaches tailored to regional circumstances rather than unified regulations across European countries.

Although some differences have been observed along the north-south gradient, ideas about promoting biodiversity and nature conservation appear to be spreading primarily from the west to east. This trend should be supported through future efforts, particularly targeting eastern countries. In addition to raising awareness of biodiversity, specific agricultural measures and practices should be promoted and made accessible to gardeners to encourage more rapid, in situ changes as many gardeners still tend to follow more traditional approaches.

Nature-friendly practices appear to be more strongly supported by individuals with higher levels of education, and those influenced by age or parental status. These findings could inform more targeted initiatives that promote gardening as a tool for nature conservation in this region of Europe.

On the other hand, to ensure that gardens truly contribute positively to sustainable urban environments, the multifaceted issue of pesticide usage that permeates various aspects of gardening, from food production in allotments to the care of ornamental plants and flea treatments for pets, needs to be uniformly addressed across all EU countries. Similarly, information for providing a comprehensive understanding among the public regarding the potential environmental and human health impacts of pesticides should also be made broadly available.

Biodiversity-friendly gardens also improve human health and well-being (Samus et al., 2022) and provide urban residents with the opportunity to reconnect to the natural world (Cameron et al., 2012). Thus, while increasing the diversity of gardens alone may not solve the biodiversity crisis, by creating ecological corridors of these gardens can contribute to conservation, foster a shift in human attitudes towards preserving natural areas, and enhance the ecological quality of urban environments. To fully exploit all benefits of gardens and to increase people's knowledge concerning the environment, population-wide, regular, and high-quality education and community programs which, shape people's attitudes, willingness to take action, and interest, are needed (Shwartz et al., 2012; Sturm et al., 2021; Tikka et al., 2000). Similar programs have been running for decades in Western European countries but they are still scarce in CEE (EC, 2015; Jehlička & Jacobsson, 2021). Yet, the need for improving the ecological quality of gardens is not unique to Western Europe, where it gets the most emphasis, but is also present in CEE. Hence, local strategies for environmental education emphasising the importance of biodiversity-friendly gardening should be developed for CEE countries as well. These, however, should be tailored to local needs and provide access to biodiversity-related information through a broad variety of channels to reach all strata of society.

Besides serving as a proxy to indicate gardens' environmental quality, our study also can help in accessing these gardens' potential in designing eco-networks of biodiversity-friendly gardens. It also can act as a tool for facilitating the decision for optimal strategies to maximise the environmental benefits of gardens.

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CRediT authorship contribution statement

Zsófia Varga-Szilay: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Szovenyi Gergely:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Pozsgai Gabor:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Viluments Silva:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Fetyko Kinga Gabriela:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Seric Jelaska Lucija:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Eve Veromann:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Kristin Anton:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Ruzickova Jana:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Danilo Bevk:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Agata Jojczyk:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Barsevskis Arvids:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Benedek Klara:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Code Availability

The data and the underlying code is available through the GitHub repository: https://github.com/zsvargaszilay/domestic_gardens_in_CEE.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.129074.

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