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

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Abbreviations
CEE: Central and Eastern Europe
CZ, EE, HR, HU, LV, PL, RO, SI, SK: Czechia, Estonia, Croatia, Hungary, Latvia, Poland, Romania, Slovenia, Slovakia
NUTS: The Nomenclature of Territorial Units for Statistics
PPS: purchasing power standards per inhabitant
GAR, RES, PES index: garden-, respondent-, pesticide index
NMMc: No Mow May campaign

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Abstract

Amid ongoing urbanisation and increasing anthropogenic activities, domestic gardens, while cannot replace natural habitats, play a crucial role in enhancing urban biodiversity by supporting green areas and as parts of ecological corridors. Moreover, these biodiversity-friendly gardens also improve human well-being and foster a connection between nature and people. We circulated an online questionnaire between 2022 and 2023 to investigate how the garden parameters, the gardening motivation of garden owners, and their pesticide use habits depend on each other in nine Central- and Eastern European (CEE) countries. Moreover, we aimed to explore the differences and similarities between gardens and gardening practices with a potential for maintaining high biodiversity. To achieve this, we assessed the ecological value of the gardens, the motivation of garden owners, and their pesticide use habits using an answer-based scoring system. Our findings reveal significant variability both among participating countries and within them on a smaller and larger scale, across all three indices, highlighting the need for region-specific circumstances rather than unified regulations across European countries to maximize the conservation value examined. Our study underscores the potential of domestic gardens in designing eco-networks and informs strategies to optimize their environmental benefits. However, due to the ubiquitous domestic use of pesticides in CEE, informing garden owners about the environmental and human health effects of pesticides would be equally necessary in every area, both urban and rural. Additionally, our findings suggest that effective environmental educational programs and tailored strategies should be developed to meet local needs rather than overarching but too general international targets. At the same time, these programs should provide comprehensive biodiversity-related information, reaching all strata of society. This is especially important in CEE, where such initiatives are currently under-emphasized.

Keywords: rural-urban gradient; urban ecosystems; environmental consciousness; sustainable gardening; environmental sensitivity; urbanisation

1. Introduction

Built-up urban areas will cover 7% of the European Union (EU) by 2030 (Perpiña Castillo et al., 2019) and this ongoing urbanisation and increasing anthropogenic activities, in turn, contribute to biodiversity loss (Hagen et al., 2012) and the rapid decline of natural ecosystems (Bengtsson et al., 2000). Most parts of Europe are already impoverished, and characterised by small natural areas, broken up by human intervention into a mosaic of agricultural lands and settlements (European Environment Agency, 2012; Eurostat, 2022b; Jongman, 2002; Perpiña Castillo et al., 2019). Thus, it is particularly important to halt, or at least reduce losses in human-managed areas 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; van Elsen, 2000), urban biodiversity rarely gains enough attention (Fischer et al., 2020; Ramalho & Hobbs, 2012). Although, the European Commission proposed a law to stop the loss of green urban spaces by 2030, and gain 5% by 2050 with a minimum tree canopy cover (European Commission, 2022) the area of urban green spaces has only increased in some Southern and Western European cities (e.g. Pamplona/Iruña (Spain) and Hague (Netherlands)). From Eastern Europe, Czechia, Poland, and Romania are just about to catch up (European Environment Agency, 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 urbanization (European Commission, 2022).

Urban green infrastructure covers an average of 42% of the city area according to the European Environment Agency (EEA) (European Environment Agency, 2022), implying that urban biodiversity can be substantially improved by developing green infrastructure (Baldock, 2020; Baldock et al., 2019; Heidt & Neef, 2008; Liang et al., 2023), such as diversifying city/urban parks and community gardens, rooftop gardens, establishing bee-friendly meadows, creating a network of corridors, and installing green roofs (Aguilera et al., 2019; Beninde et al., 2015; Lin et al., 2015; Seitz et al., 2022). Besides public places, however, private domestic gardens occupy an average of 16-36% of urban green areas in Europe, and therefore the role of domestic gardens in preserving and supporting native biodiversity and their contribution to urban sustainability are becoming increasingly important (Cameron et al., 2012; Fontaine et al., 2016; Goddard et al., 2010; Hanson et al., 2021). Indeed, enhancing environmental quality in domestic gardens offers a great opportunity to improve human well-being (Camps-Calvet et al., 2016; Krols et al., 2022; Marques et al., 2021) and alleviate biodiversity loss simultaneously (Li et al., 2023). The biodiversity of domestic gardens varies along a wide spectrum (Home et al., 2019; Lindemann-Matthies & Marty, 2013), 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; Prendergast et al., 2022), and soil composition (Tresch et al., 2018, 2019). Although these intrinsic attributes are beyond owners' control, the impact of domestic gardens on biodiversity primarily depends on the decisions of garden owners, which dictates design, use, and management (Quistberg et al., 2016). With appropriate management, even small or highly anthropized domestic gardens can support high biodiversity (Donkersley et al., 2023; Griffiths-Lee et al., 2022; Muratet & Fontaine, 2015). On the other hand, numerous anthropogenic stressors (Varga-Szilay et al., 2024) and a series of 'tyranny of small decisions' (Dewaelheyns et al., 2016), 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). There is an agreement that the potential ecological value of gardens in conservation correlates positively with the structural diversity of gardens (Majewska & Altizer, 2020), reduced pesticide usage (Tassin de Montaigu & Goulson, 2023), and reduced mowing frequency (Chollet et al., 2018; Lerman et al., 2018; Proske et al., 2022). Ultimately, however, garden management is a series of decisions with mixed motivations (Hruška et al., 2021) and external factors such as demographics, household income, neighbours' expectations, accessibility of information, and education, can influence owners' behaviour (Goddard et al., 2013; Varga-Szilay et al., 2024). Hence, considering all factors, evaluating the biodiversity values of gardens necessitates considering the garden owners' management and attitude toward a diverse garden. The major drivers in management may depend on several societal factors.

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, 2021; 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; Jehlička et al., 2021). However, the previous differences in gardening motivation are gradually beginning to blur with the emergence of new gardening trends (e.g. wildlife-friendly gardening) in both Western and Central- and Eastern Europe (Keshavarz et al., 2016; Poniży et al., 2021) as the demand for ensuring food security and quality in Western countries grows (Church et al., 2015; Glavan et al., 2018; Pourias et al., 2016). At the same time, gardening in CEE countries shifts toward recreational activities (Petzke et al., 2021; Tóth et al., 2018; Trendov, 2018). Yet, the increasing emphasis on nature conservation across all of Europe, (Galluzzi et al., 2010; Muller et al., 2010; Vávra et al., 2014), seems to be embraced by CEE countries slower than in their Western counterparts (Hruška et al., 2021; Vávra et al., 2018).

Thus, the divide in the applied gardening practices between East and West remains significant. Indeed, due to the limited access to biodiversity-related information (Coisnon et al., 2019; European Commission, Directorate-General for Communication, 2015), lower willingness to change to environmentally friendly practices, and the extensive use of pesticides (European Commission, Directorate-General for Communication, 2015), CEE appears to be lagging behind in the adoption of biodiversity-friendly practices (for example leave space for wildlife) (European Commission, Directorate-General for Communication, 2015).

As differences between East and West remain, assessing the ecological value of domestic gardens, therefore, requires consideration of location-specific anthropogenic and environmental variables (Varga-Szilay et al., 2024). 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 et al., (2024) and Varga-Szilay & Pozsgai (2022).

To address this knowledge gap, here, we seek to investigate how the garden parameters, the gardening motivation of garden owners, and their pesticide use habits depend on each other in nine Central- and Eastern European countries and explore the differences and similarities between gardens and gardening practices with a potential for maintaining high biodiversity. Since these can fundamentally drive local educational strategies, we particularly aim to pinpoint how geographical differences and sociodemographic parameters best predict domestic gardens' ecological values, the respondents' attitudes towards supporting insect pollinators in their gardens, and their pesticide use habits.

Since the efficiency of biodiversity-friendly activities depends on the historical biodiversity of a given area (Dobrovodská et al., 2023) and these activities can achieve faster and greater ecological benefits in simplified and heavily human-modified landscapes (Haenke et al., 2009), a map of the potential impact of improving the ecological value of domestic gardens can be drawn. Hence, insight into the costs and benefits of initiatives for increasing garden diversities is essential for effective planning and management, our imperative is to highlight those areas in CEE where these programs can yield the greatest rewards (e.g. densely populated regions originally hosting high biodiversity).

2. Material and methods

2.1 Questionnaire design and data collection

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

The questionnaire was translated from Hungarian to English and then from English to Croatian, Czech, Estonian, Latvian, Polish, Romanian, Slovak, and Slovenian. The participants could choose the language in which they wanted to complete the questionnaire. It was mandatory to respond to 55 of the total 59 questions, organised into nine sections, which took a maximum of 15 minutes to complete. The questionnaire gathered information about the location and the main characteristics of the garden, the socio-demographic parameters, the garden owners' motivations, cultivation habits, pesticide usage, environmental awareness, and pollinator-friendly practices. Although participants had to indicate their gender (male, female, other), their highest level of completed education (elementary, middle, postsecondary, postgraduate), and their residency according to the Nomenclature of Territorial Units for Statistics (henceforth NUTS, (Eurostat, 2021)), all responses were otherwise anonymously recorded. Because of the large number of NUTS-3 regions in Poland, to simplify the questionnaire, here, residencies were recorded at NUTS-2 levels, while for the other eight participating countries were recorded at NUTS-3 levels.

The questionnaire was designed using Google Forms and was actively distributed between 26th October 2022 and 18th May 2023, for 90 days in each of the nine participating countries (**SM Table 1**). The questionnaire was disseminated through channels such as gardening-oriented websites, and various online social media platforms (for instance Facebook and Instagram) where QR codes and hashtags were used to increase the sharing efficiency. Moreover, through targeted email distributions, outreach efforts extended to professional associations, nongovernmental organizations, foundations, and societies dedicated to domestic gardening and environmental conservation.

2.2 Definitions

Not all respondents are, actually, the owners of the gardens they reported on in the questionnaire but, for simplicity, we refer to everyone as a 'garden owner'. For terminological clarity, we used the definitions of 'pesticides' and 'gardening' as given by (Varga-Szilay et al., 2024). Pesticides were defined 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'. Gardening was defined as 'all garden work and all garden care practices, such as the cultivation of flowers, fruits, vegetables, and ornamental plants, mowing, and soil management' (Varga-Szilay et al., 2024, p. 2).

2.3 Data processing

For the analysis, we used 43 questions relevant to our aims of the original 59 ones. The original categorical replies of our questionnaire were re-categorised for analytical purposes on a few occasions (see **Supplementary Methods**). 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 from ArcGIS Data and Maps (2022a, 2022b) and Eurostat (2022a, 2024), respectively. 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 PSS 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 above mentioned capitals were merged with the surrounding polygons. For this, a weighted mean of the numerized 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. Spatial and polygon calculations were conducted using the 'sf' (Pebesma, 2018) R package.

2.4 Answer-based scoring system

We rated the potential ecological value of the gardens, the garden owners' motivation for gardening, and pesticide use habits with an answer-based scoring system. For this, we used a total of 32 questions from the original 59. The garden (GAR) index shows what potential a domestic garden has to maintain high biodiversity. 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 calculation of this index was based on 12 questions and consisted of 10 components, which contributed with different weights. The weights were determined by the importance of the components in maintaining high biodiversity. The respondent (RES) index assesses the garden owners' knowledge on garden wildlife and their attitudes to maintaining/creating a biodiversity-friendly garden. The RES index was based on 10 questions and consisted of 10 components, including both theoretical (e.g. 'Do you think…?'/'Can you imagine…?') and practical (e.g. 'How do you…?') questions/question groups, which contributed to the index with different weights. 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 garden owners. It was based on 10 questions and consisted of 11 components, which were contributed to the index with different weights. All indices were scaled between 0 (as the lowest) and 100 (as the highest) points. For the full details of the index calculation process, the reader should consult with the **Supplementary Methods**.

2.5 Bird index

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 above) 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 species that had more than 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). 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. For collecting bird data we used the 'rgbif' (Chamberlain et al., 2024) and for spatial calculations the 'sf' (Pebesma, 2018) R packages.

2.6 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 urbanization 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 indices 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. For calculating the correlation matrix the 'psych' (Revelle, 2021) R package was used.

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.

The three indices were used as response variables in three separate Gradient Boosting Machine (GBM) learning processes. Seven socio-demographic variables (gender, age, education level, having children, gardening experience, gardening perception and the average time spent gardening), the PPS, latitude and longitude were also included in the model as numerical explanatory variables. 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 (for GAR index), 26 (for RES index), and 10 (for PES index) trees. 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 GBM models with the 'shapviz' (Mayer & Stando, 2023) and 'kernelshap' (Mayer et al., 2023) R packages. The SHAP assesses individual variable contributions, accounts for variable interactions, assigns importance values, and facilitates the comparison between all possible variable orders (Lundberg & Lee, 2017). Since GBM predicted the country identity as the most influential variable on all three indices, we examined the relationship between GAR and PES indices (the two non-correlating ones) separately for each country and explored how the other important variables grouped within this data cloud.

For modelling and the visualization of model results, we used the 'gbm' (Greenwell et al., 2022) and 'caret' (Kuhn et al., 2023) packages in an R environment (R Core Team, 2021). Preliminary data clean-up was done in a Python (Python Software Foundation, 2019) environment, with the help of 'NumPy' (Harris et al., 2020) and 'Pandas' (The pandas development team, 2022) libraries.

3. Results

3.1 Garden owners' socio-demographic characteristics

Altogether 5,255 garden owners completed the questionnaire from the 9 participating countries (**SM Figure 1, SM 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 garden owners had a postsecondary education level (n=3225, 61.37%), followed by the middle education level (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%) (**SM Table 2**).

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%) (**SM Figure 2**). In most participating countries, mowing several times a month was under 40% (**SM Figure 3**) but in Estonia and Latvia, the majority of garden owners (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 (**SM Figure 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 (**SM Table 3**). The GAR index with the RES index showed a strong, 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 three indices (GAR, RES, PES) (Kruskal-Wallis chi-squared = 290.85, 671.51, and 235.13, respectively, $p < 0.001$) (**SM Table 4, 5**), and the index values varied broadly among NUTS areas (**Figure 1**). A total of 197 respondents had all three scores below the first quartile of the indices, with those from Romania and Hungary faring the worst, whilst there were a total of 90 respondents in the third quartile of all indices, mostly from Czechia and Slovenia (**SM Table 3**).

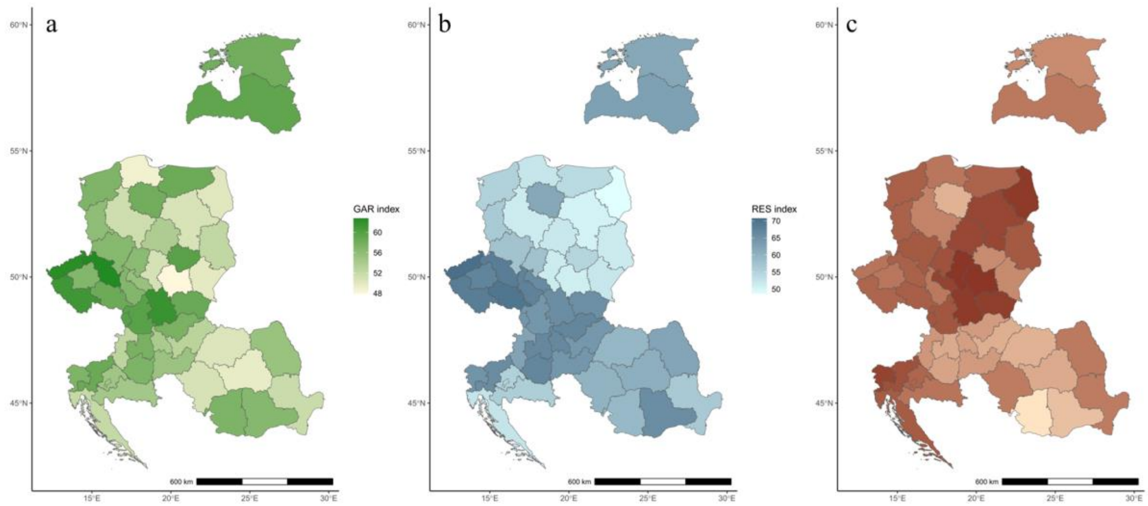


Figure 1: The garden (a), respondents (b) and pesticide (c) indices in the nine participating countries. The colour depth of the maps indicates the mean of the indices calculated for each NUTS-2 area.

3.3 GBM outputs

GAR index

The GBM model for the GAR index explained 12.45% of the variance for new observations (RMSE =11.29), with SHAP values indicating the country variable being the best and the average time that garden owners spent with gardening being the second-best predictors (SHAP value = 2.15, 1.94, respectively) (**Figure 2a**).

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

Age over 56 shifted the GAR index toward lower values (particularly the age group of over 65), in contrast with the age under 55 resulting 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. Postsecondary 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, garden owners 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 (**Figure 2b**).

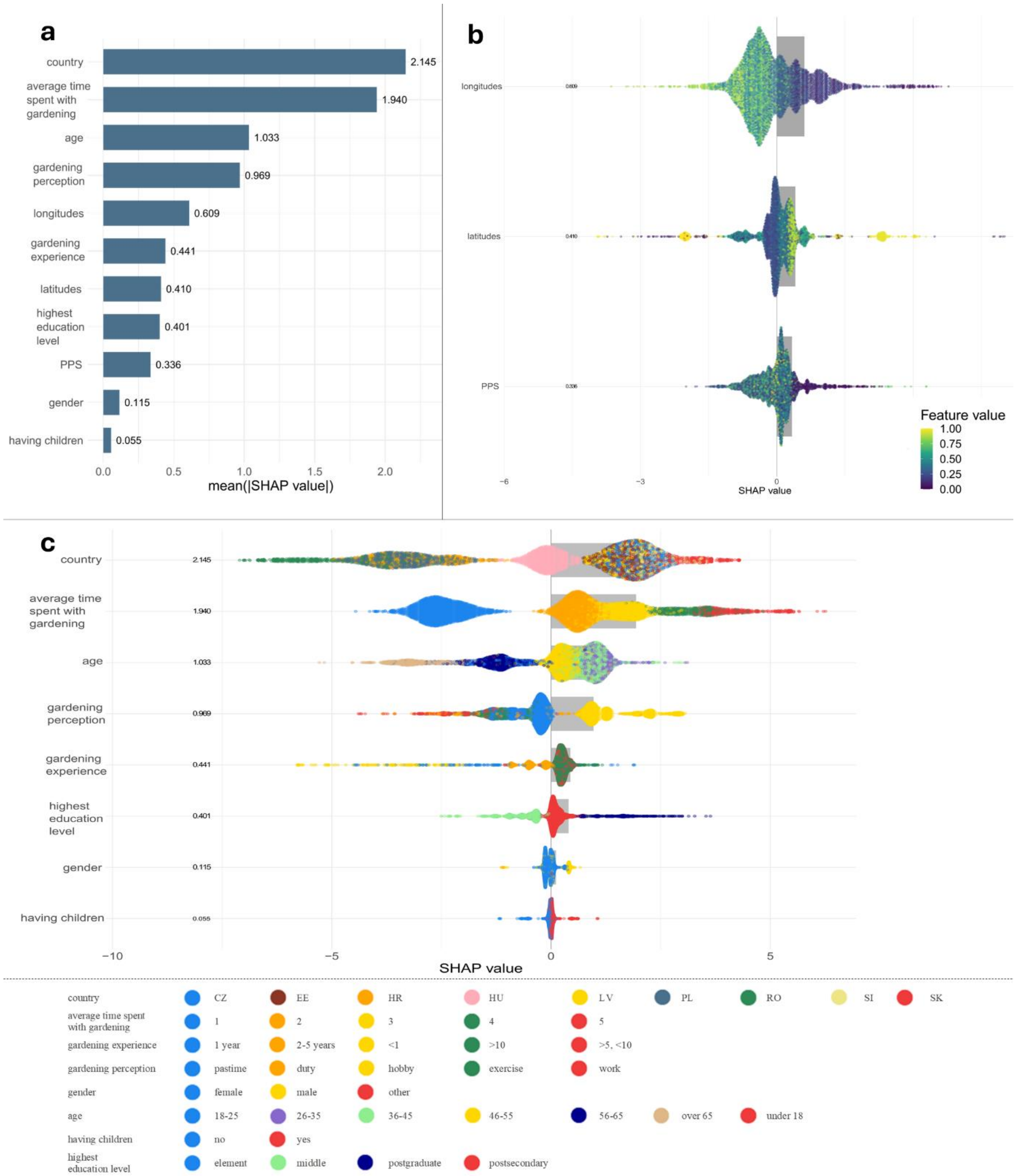


Figure 2: Global SHAP (SHapley Additive exPlanations) summary plots for the GBM model of the GAR index. Variables ordered by their (a) importance based on average absolute SHAP values. Beeswarm plots of SHAP values of (b) numerical and (c) categorical variables. Each point represents one respondent. For numerical variables, colours indicate variable values, while for categorical variables, they represent distinct category levels.

RES index

The GBM model for the RES index explained 24.73% of the variance for new observations (RMSE =13.13), with SHAP values indicating the country variable being the best and how garden owners perceived gardening being the second-best predictors (SHAP value = 3.80, 2.26, respectively) (**Figure 3a**). 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 values, all other cases lowered them, especially when gardening was perceived as a duty (**Figure 3c**). SHAP values increased with the time spent with gardening. Older age groups predicted lower RES index values, while the 26-35 age group had higher ones. Gender, education, and having a child 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 (**Figure 3b**).

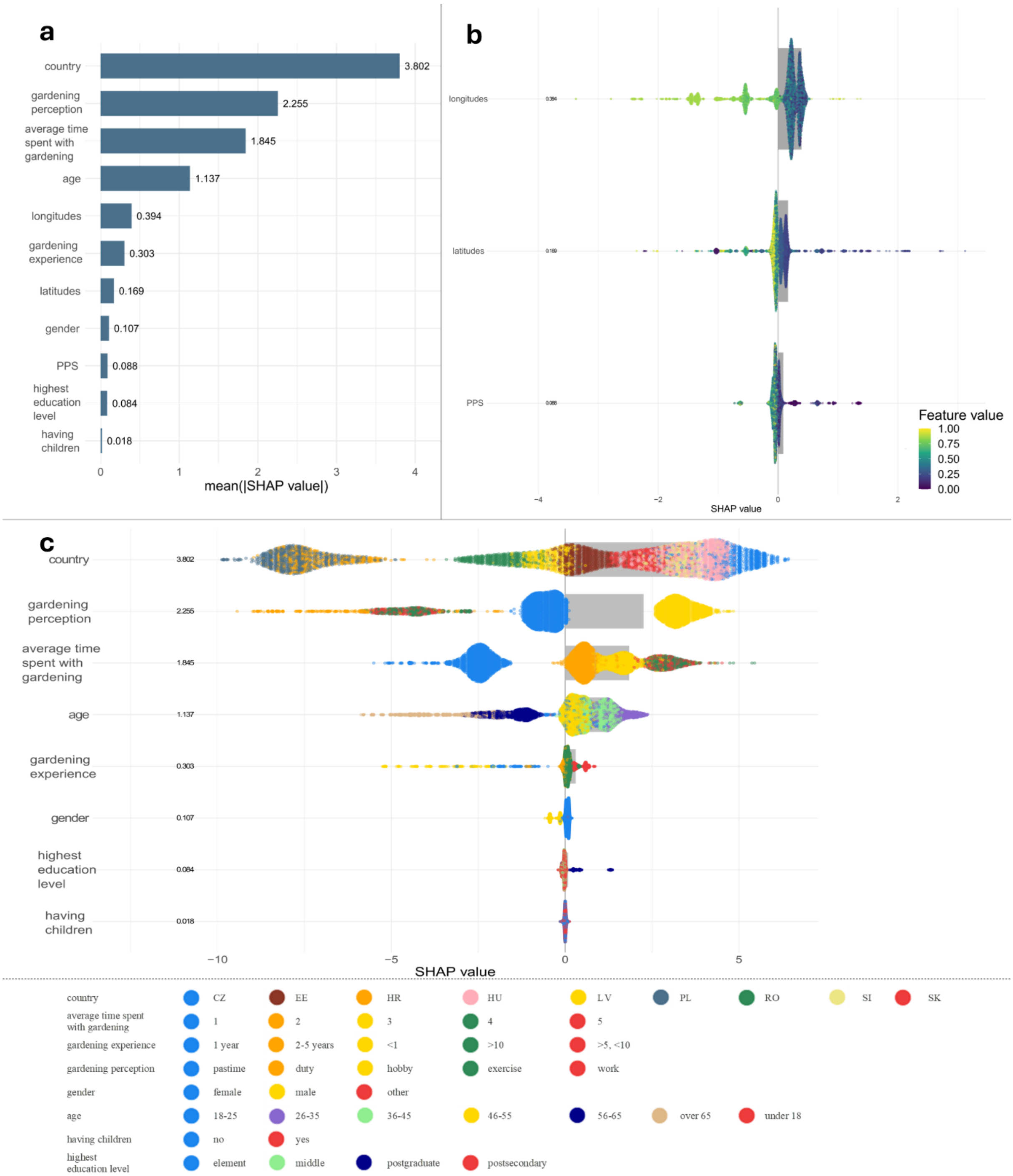


Figure 3: Global SHAP (SHapley Additive exPlanations) summary plots for the GBM model of the RES index. Variables ordered by their (a) importance based on average absolute SHAP values. Beeswarm plots of SHAP values of numerical (b) and categorical (c) variables. Each point represents one respondent. For numerical variables, colours indicate variable values, while for categorical variables, they represent distinct category levels.

PES index

The GBM model for the PES index explained 0.08% of the variance for new observations (RMSE =18.19), with SHAP values indicating the country variable being the best and the average time that garden owners spent with gardening being the second best predictors (SHAP value = 3.20, 1.56, respectively) (**Figure 4a**). Romania, Estonia, and Hungary had the lowest SHAP values, whilst Poland, Slovakia, and Slovenia showed the highest ones (**Figure 4c**). An average of 1–2 hours of gardening per day predicted a higher PES index, whilst all other times spent with gardening lowered it, with the lowest values associated with those who spent up to 12 hours a day with 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 (**Figure 4b**).

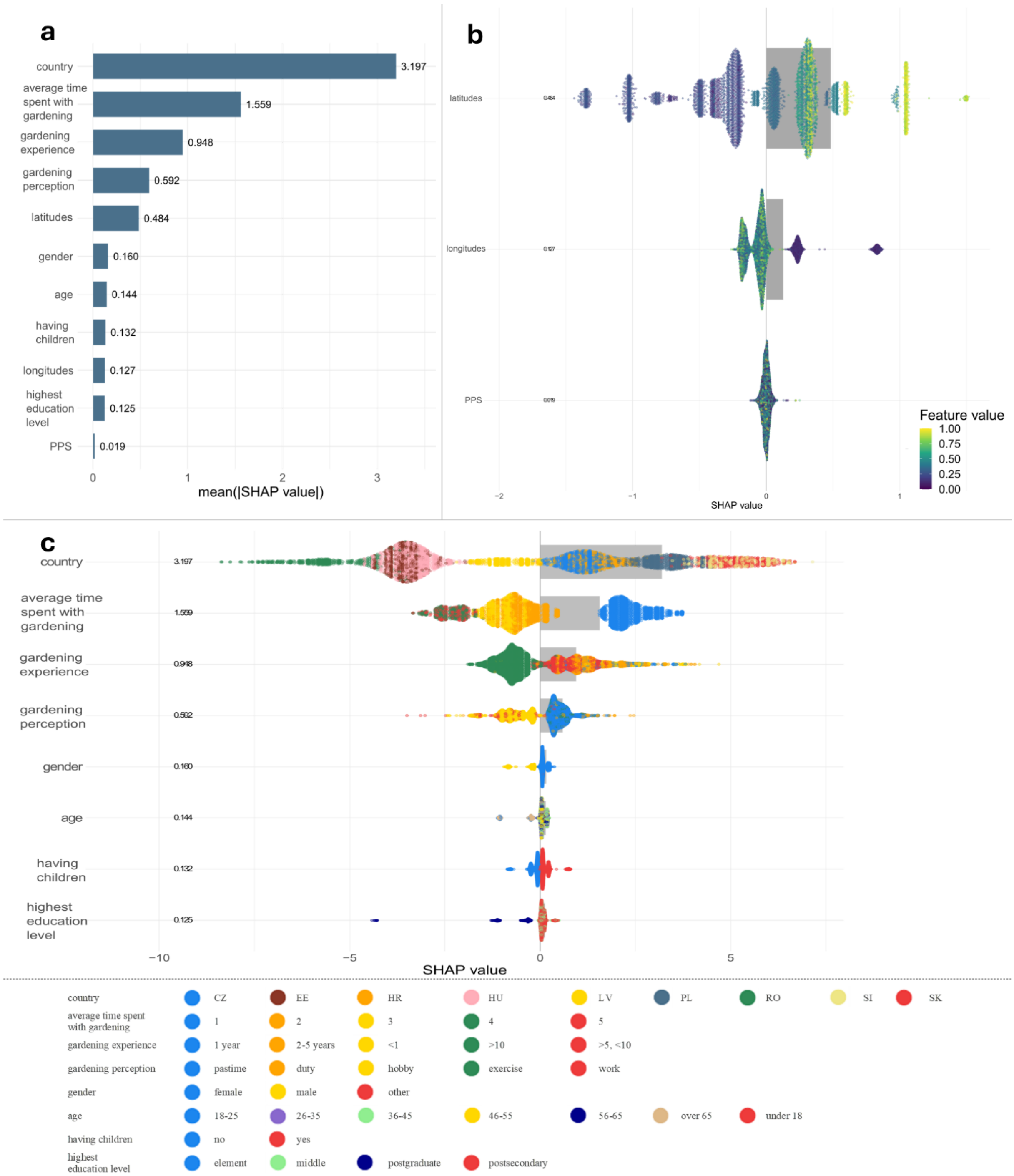


Figure 4: Global SHAP (SHapley Additive exPlanations) summary plots for the GBM model of the PES index. Variables ordered by their (a) importance based on average absolute SHAP values. Beeswarm plots of SHAP values of numerical (b) and categorical (c) variables. Each point represents one respondent. For numerical variables, colours indicate variable values, while for categorical variables, they represent distinct category levels.

The GAR index as a function of the PES index

In our investigation into the influence of country, GAR index, and PES index on the grouping of gardening experience lengths, we found that respondents who had been gardening for more than 2 years were characterized by a greater potential for maintaining high biodiversity and more intensive pesticide use. In Estonia, Latvia and Slovakia, those who had been gardening for less than a year grouped around low pesticide input (high PES index values). On the other hand, in Slovenia, among those who had been gardening for a year or less, there was no one who did not use pesticides at all. In the case of Hungary and Estonia, gardeners who have been gardening for less than one year scored lower in the GAR index but were also characterised by lower PES index values. (**SM Figure 5**).

In Hungary, Poland, Romania, and Slovenia for those garden owners who considered gardening as their favourite hobby the GAR index was greater than in other countries and they also scored lower in the PES index (**SM Figure 6**).

In all participating countries, except Slovakia, the GAR index was the lowest and the pesticide index the highest among garden owners who spent less than 1-2 hours with gardening (**SM Figure 7**).

In all countries but Croatia older age negatively influenced the GAR index. Indeed in Romania, garden owners over the age of 65 fared poorly with the GAR index and all of them used pesticides. In contrast in Croatia, this age group had the highest GAR index values (**SM Figure 8**).

3.4 Areas with a potential for improvement

When areas within urbanization levels were cross-referenced with the categorised three indices, different effects of urbanization levels of the three indices were revealed (**Figure 5**). Half of the predominantly urban NUTS areas (n = 3) were categorised as low GAR values, and half of the

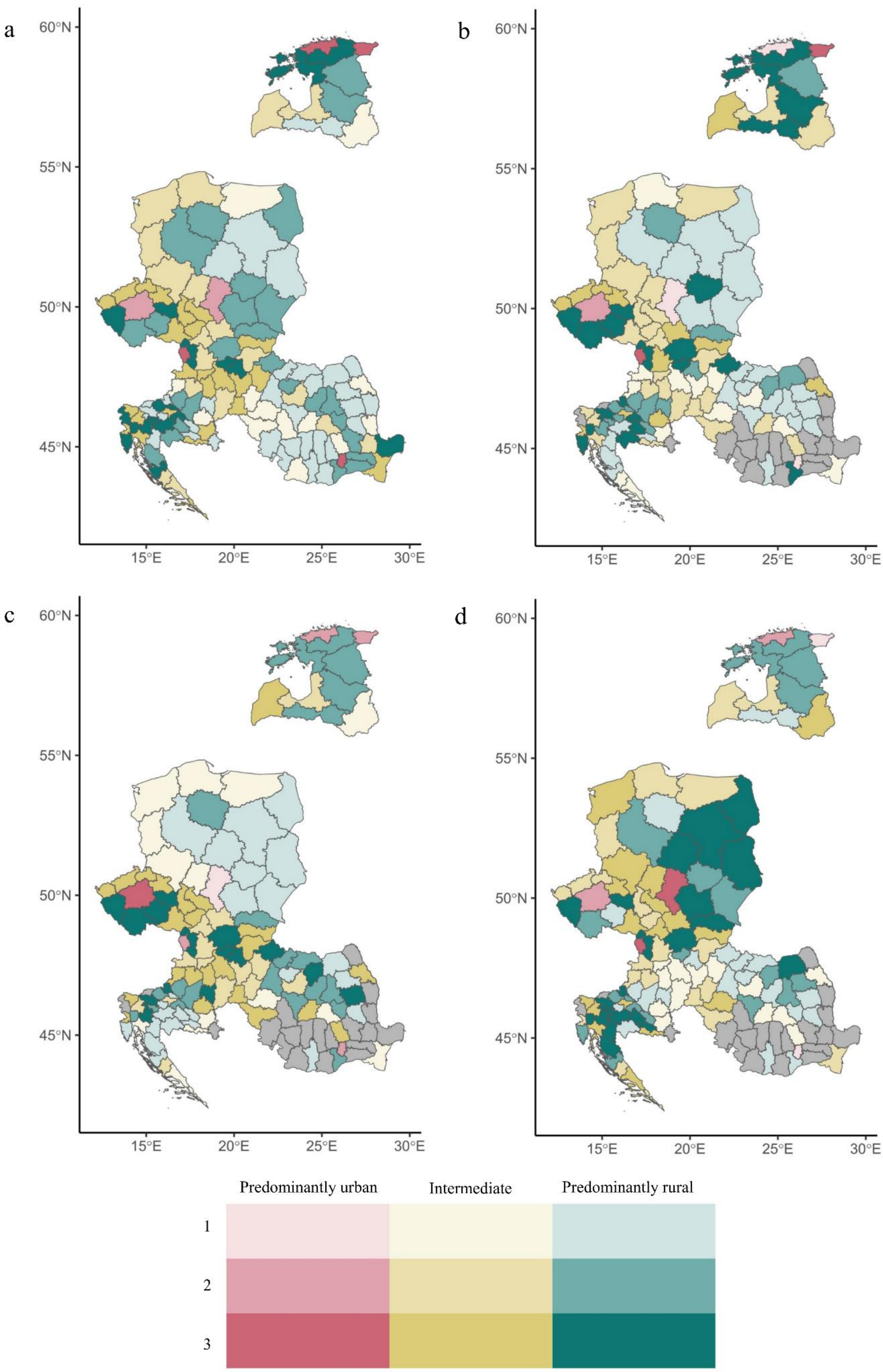
NUTS areas typologised (n = 26) as intermediate reached a medium level on the GAR index. The RES categories were relatively evenly spread both among intermediate and predominantly rural areas but most predominantly urban regions (n = 4) were categorised as medium RES (**Table 1**). The distribution of PES categories was uniform among predominantly urban and predominantly rural areas, whilst in intermediately urbanised regions intermediate PES category was the most common (n = 22), followed by the high and low categories (n = 17 and 13, respectively) (**Table 1, Figure 5**).

Table 1: Contingency tables of urban-rural typology categories and categorised index values of bird, GAR, RES, and PES indices, as expressed by the number of NUTS areas. Values are shown as percentages of the columns.

	Urban-rural typology		
Bird	Predominantly urban (n = 6)	Intermediate (n = 56)	Predominantly rural (n = 77)
Low (n = 46)	0	23.21	42.86
Moderate (n = 44)	33.33	32.14	33.77
High (n = 47)	66.67	44.64	23.38
GAR*	Predominantly urban (n = 6)	Intermediate (n = 52)	Predominantly rural (n = 61)
Low (n = 41)	50.00	26.92	39.34
Moderate (n = 42)	16.67	50.00	24.59
High (n = 36)	33.33	23.08	36.07
RES*	Predominantly urban (n = 6)	Intermediate (n = 52)	Predominantly rural (n = 61)
Low (n = 41)	16.67	28.85	39.34
Moderate (n = 42)	66.67	26.92	34.43
High (n = 36)	16.67	44.23	26.23
PES*	Predominantly urban (n = 6)	Intermediate (n = 52)	Predominantly rural (n = 61)
Low (n = 41)	33.33	25.00	32.79
Moderate (n = 42)	33.33	42.31	31.15
High (n = 36)	33.33	32.69	36.07

*Represents a total of 119 areas from which we had at least 5 respondents.

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 reached the best categories in all variables but the bird index), while Romania had that with the lowest (the Vrancea county in Romania fall into the worst categories in all variables). All predominantly urbanised areas were categorised relatively high in all indices with Slovakia being the best (Bratislava region) and Poland and Romania being the worst (Silesian Voivodeship, București-Ilfov region).



a
b
c
d
60°N
55°N
50°N
45°N
15°E
20°E
25°E
30°E
Predominantly urban
Intermediate
Predominantly rural
1
2
3

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Figure 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).

4. Discussion

Domestic gardens offer significant opportunities for advancing global biodiversity and sustainability targets. Our work investigates the intertwined relationship between socio-demographic parameters, sustainable garden management, and biodiversity conservation from a highly understudied region of the EU and highlights that there are significant differences among countries, and even within countries on a smaller and larger scale in the examined parameters.

Indeed, the participating countries differed in all three examined indices, with having the least differences in GAR and the most in PES, and these differences were supported by both the pairwise comparisons between countries and the GMB model. There were countries experiencing equally low or high values on all indices, such as Romania faring poorly in all indices, whereas Slovakia showed overly high values. Sometimes indices implied counteracting effects, such as a high GAR index, suggesting a great prospect for maintaining high biodiversity in domestic 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 scoring the worst in leaving spaces for wildlife and avoiding the use of pesticides, yet having been categorised as the best 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.

The extensive application of pesticides beyond the agricultural sector, including domestic 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; Varga-Szilay & Pozsgai, 2022). Our study found substantial differences between countries, with 20–30% of respondents in Hungary and Romania thinking that the use of pesticides is either important or crucially important for their gardening, a claim with which only 2% of those from Slovakia agreed (**SM Figure 9**.).

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 align with its real biodiversity potential, suggesting that self-reporting surveys may be misleading in this term, unless gardens are examined from multiple aspects, including socio-demographic or cultural factors.

Indeed, in line with 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 garden owners who dedicate more time spent with 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. In our study, however, both when gardening was associated with a hobby and more time was allocated for gardening were characterized 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 (**Figure 4c**) where women and respondents with children improve the outcome of the PES index, whilst this separation was unclear with the other two indices.

Although the country identity proved to be the most important variable in predicting the potential for maintaining high garden biodiversity, the respondents' attitudes towards supporting biodiversity (especially pollinators) in their gardens, pesticide use, owners' perception, the long-term gardening experience and daily management also proved to be important factors. Furthermore, nature conservation was the prime aspect that influenced gardening habits in four participating countries, albeit in three of these this did not mean a lower pesticide use, and only Croatia and Poland were the ones where more than 80% of the respondents felt that nature conservation does not affect their gardening habits at all (**SM Figure 10**).

Increasing age (especially that over 65) negatively influenced both the potential of gardens for maintaining high biodiversity and the owners' 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. Yet, the age-independent pesticide use we observed in the GBM model suggests that even when information is broadly available behavioural change is not granted.

However, gardening practices and their associated socio-demographic variables exhibited significant diversity among garden owners and the final outcome for biodiversity-friendliness appeared to be a series of multifactor decisions depending on numerous background drivers. For instance, despite several studies 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; Coisnon et al., 2019), in our GBM model PPS did not prove to be a significant explanatory variable for any of our indices.

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 model.

Our results show that merely examining the structural diversity of private gardens, socio-demographic parameters, garden owners' gardening motivation, or biodiversity-negative activities (e.g. pesticide use) individually may be insufficient for obtaining a reliable proxy of whether domestic gardens could potentially maintain high diversity in human-altered areas. Moreover, the lack of a clear geographical pattern and within-country diversity in all indices suggests that regionally tailored rather than countrywide strategies are needed to identify pathways toward sustainable green infrastructure and to improve the natural value of domestic gardens. Since these strategies must be underpinned by interdisciplinary study efforts, our study can offer fundamental insight into how they can be optimised and where the greatest rewards can be gained. Indeed, despite the dominance of moderate values of our indices on the map, local strategies can still be developed based on the preliminary classification.

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 northern 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 areas with generally **low urbanisation** levels and **high biodiversity** probably has the least merit, 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, can be particularly important as good examples for environmental education and maintaining source populations 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 (Lacey et al., 2015; Landis et al., 2000; Quesada-Moraga et al., 2022), 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 **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 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 training), 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.

Thus, at high urbanisation levels, increasing gardens' structural diversity and other aspects beneficial for maintaining high biodiversity is key but improving garden owners' attitudes towards biodiversity-friendly gardening and reconnecting them to nature are also important. Since the level of urbanization across Europe is projected to reach 83.7% by 2025 (United Nations, 2018), this improvement in attitude is necessary to exploit the potential of domestic 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 garden owners, is crucial for increasing the biodiversity value of domestic gardens at a larger scale. For this, future nature conservation planning strategies and studies should acknowledge the variability of domestic garden owners' attitudes and gardening practices, as well as the domestic gardens' potential for biodiversity conservation (Cameron et al., 2012).

4.1 Study limits

Although in our work we collected over 5,255 responses, this only represents a small fraction of the inhabitants and gardeners of the focal area of our study. Moreover, the dissemination channels we used do not allow random respondent selection and our selection process is most likely to be biased towards those who had regular access to the Internet, whilst those living in infrastructurally less developed parts of the countries had a lower chance to learn about our call. Indeed, parts of Poland and the Southern part of Romania are highly underrepresented. Yet, several countries like Estonia and Hungary, have a high coverage which likely portrays faithfully the common gardening behaviours in the regions and trends in garden management among domestic garden owners in the participating CEE countries.

In an effort to engage a broad audience in several languages, we often compromised completeness for simplicity and brevity. Whilst we believe this did not affect the interpretability of our questionnaire, it definitely sets limits on the use of scientific terminology and how detailed information we could gain with some questions.

Although our questionnaire aimed for the response of only one person (the garden owner) for each domestic garden, these gardens are probably cared for by more than one person (e.g. family members), and thus, they are not only influenced by one person's motivation but by severals'.

4.2 Future perspectives

Whilst 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. Especially 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.

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

5. Conclusion

While gardens may not replace 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 (Beninde et al., 2015). In our study, we, however, show that the potential of domestic gardens for maintaining high biodiversity varies widely among CEE regions, and along with it 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.

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, must 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 broadly available.

Biodiversity-friendly gardens also improve human 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 domestic gardens alone may not solve the biodiversity crisis by creating ecological corridors it can contribute to conservation, foster a shift in human attitudes towards preserving natural areas, and enhance the ecological quality of urban environments. To maximally exploit all benefits of domestic gardens, population-wide, regular, and high-quality educational programs which, shape people's attitudes, willingness to take action, and interest, are needed (Shwartz et al., 2012). Similar educational programs have been running for decades in Western European countries but they are still scarce in CEE (European Commission, Directorate-General for Communication, 2015; Jehlička & Jacobsson, 2021). Yet, the need for improving the ecological quality of domestic 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 domestic gardens.

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Declarations

Conflict of interest

The authors declare no competing interests.

Code availability

The underlying computer code is available in the GitHub repository https://github.com/zsvargaszilay/domestic_gardens_in_CEE

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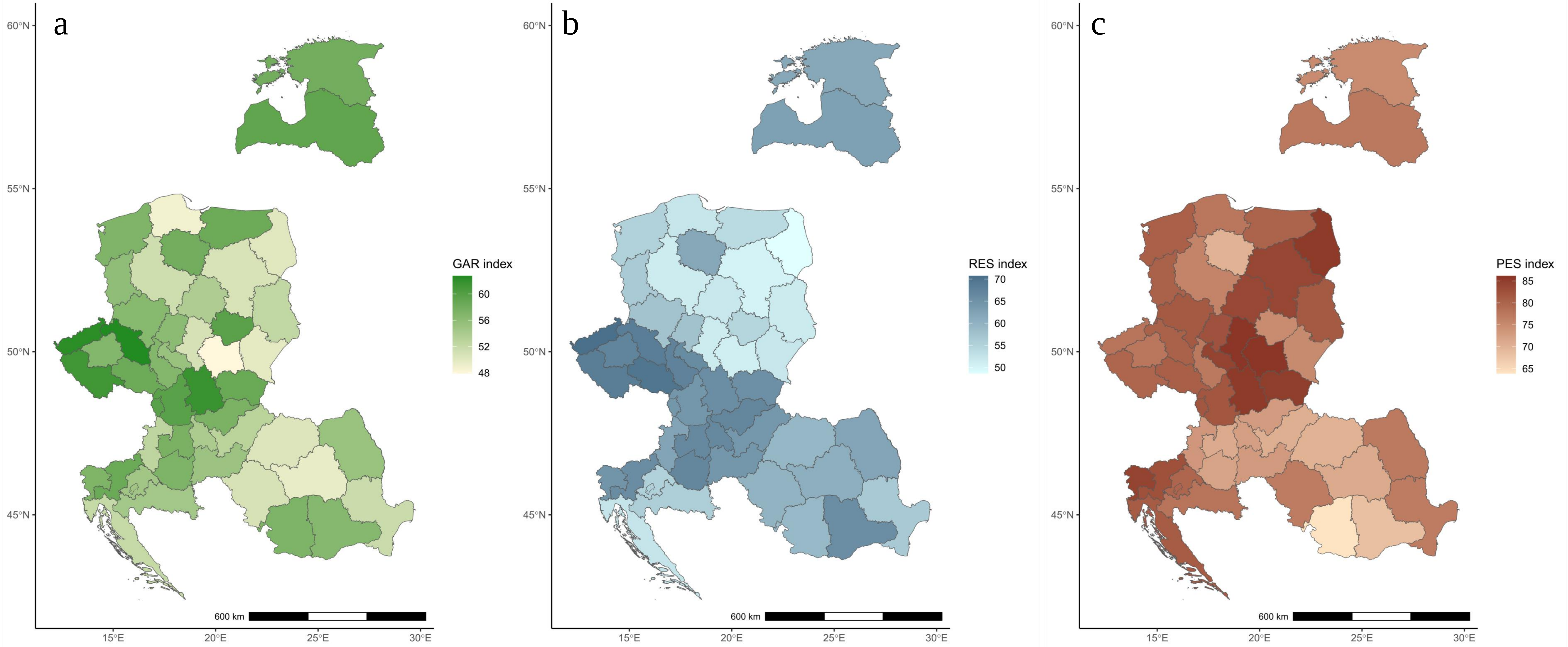

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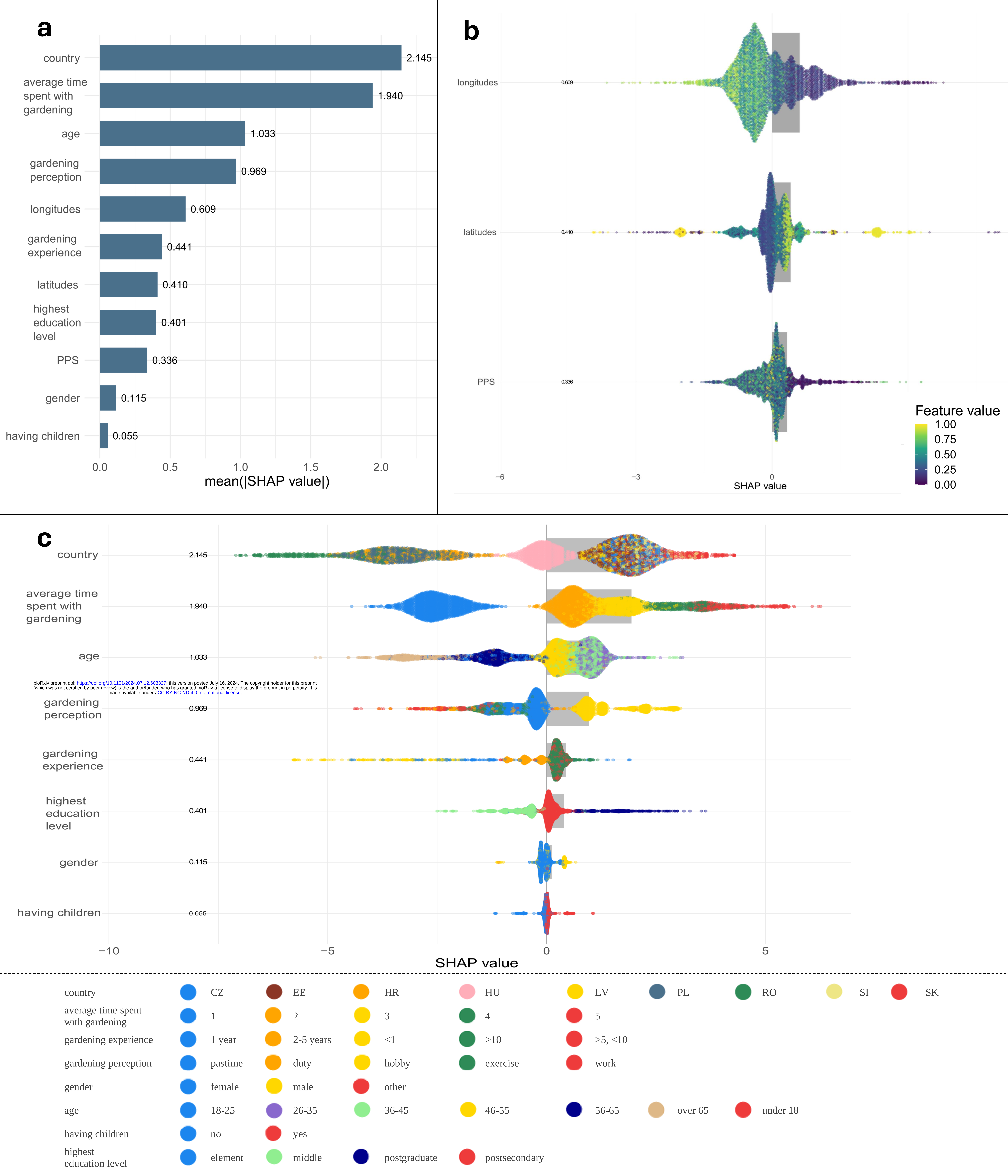
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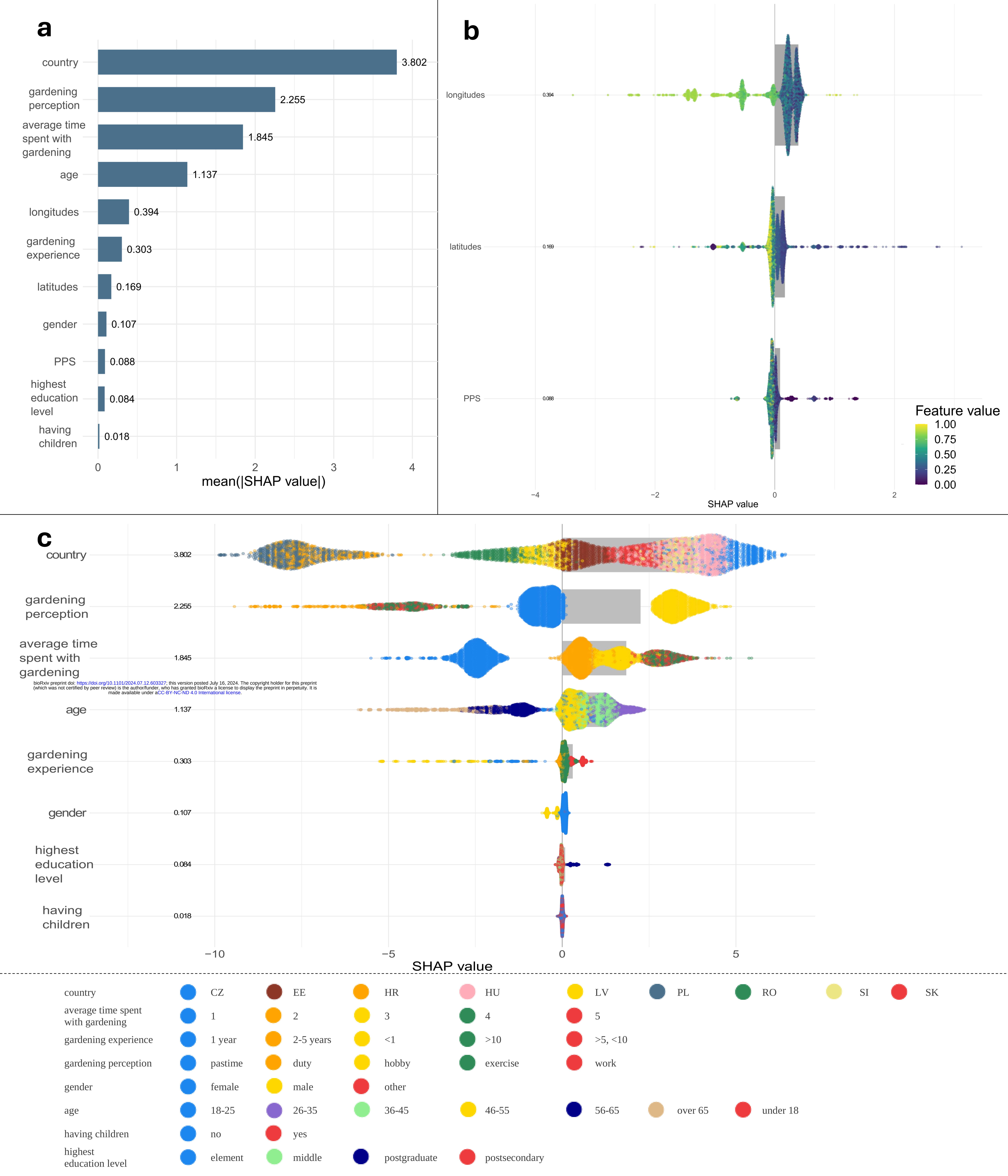
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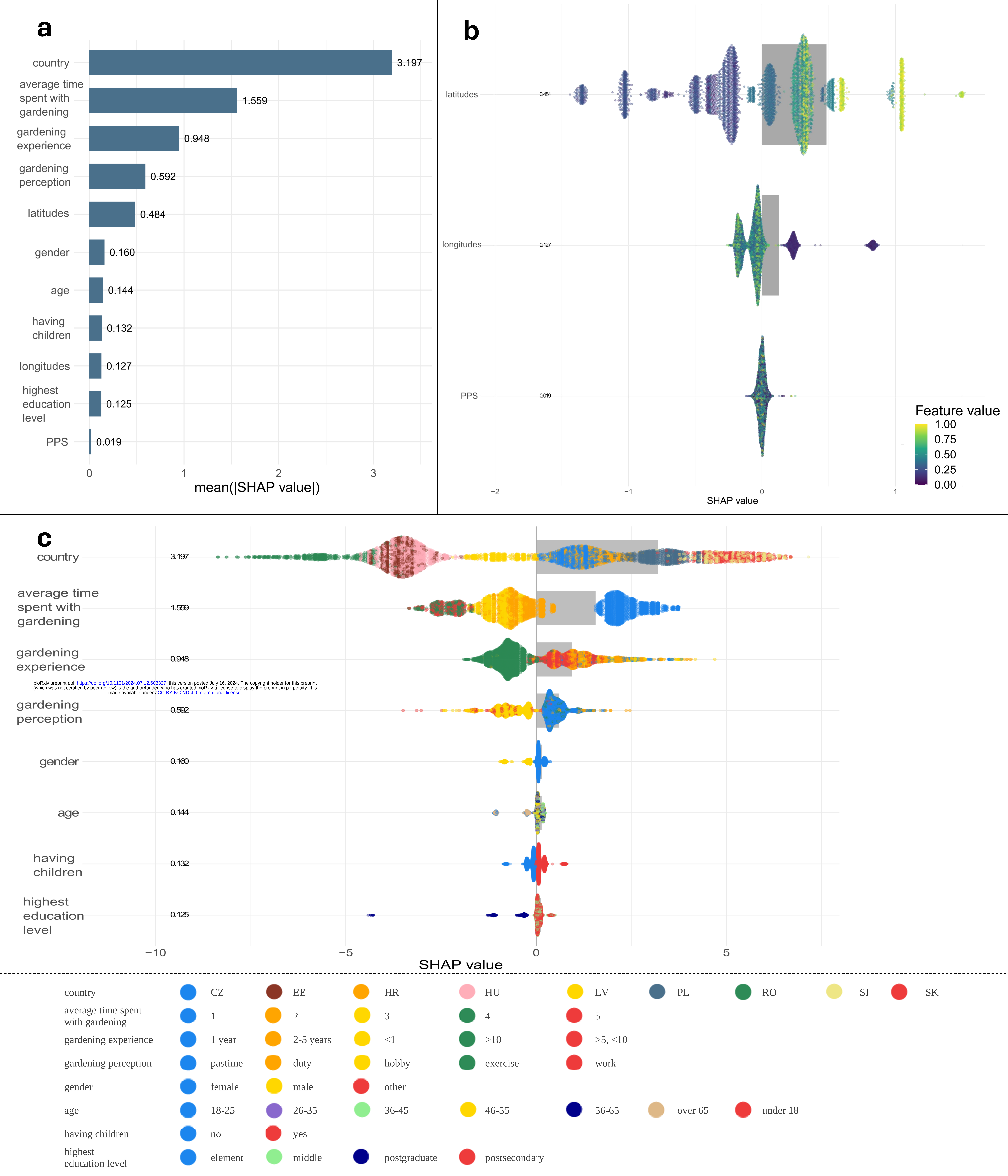

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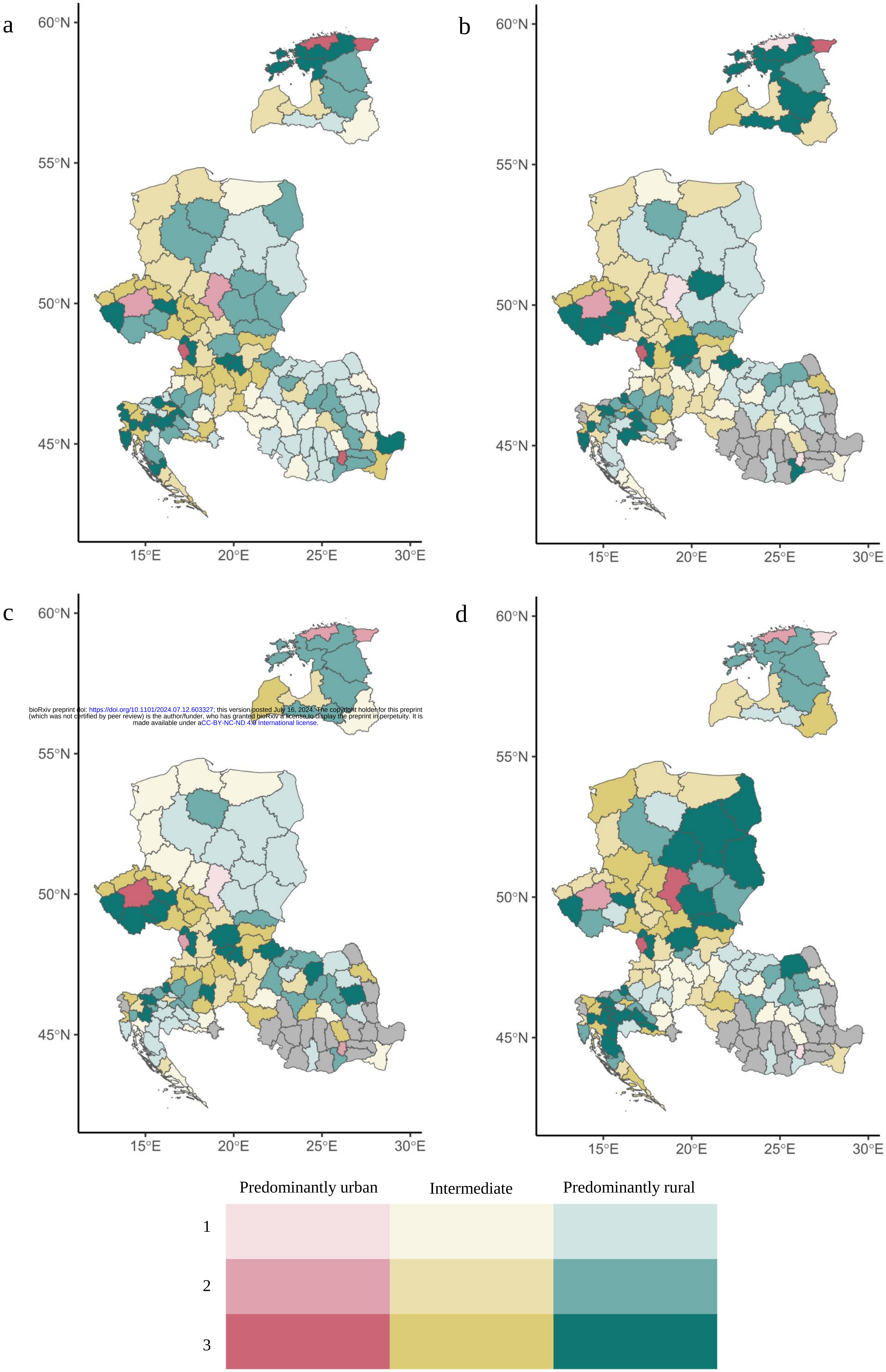
46-55
56-65
over 65
under 18
having children
no
yes
highest education level
element
middle
postgraduate
postsecondary


a
b
c
d
60°N
55°N
50°N
45°N
15°E
20°E
25°E
30°E
Predominantly urban
Intermediate
Predominantly rural
1
2
3