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BESTMAP
BEHAVIOURAL, ECOLOGICAL & SOCIO-ECONOMIC TOOLS FOR MODELLING AGRICULTURAL POLICY

Analysis of the representativeness of Case Studies in the EU context

Deliverable D5.1

31 December 2023

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BESTMAP

Behavioural, Ecological and Socio-economic Tools for Modelling Agricultural Policy

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Preface

This Deliverable provides a report on the methods and data used for assessing the representativeness of BESTMAP case studies in the EU context, developed as part of the Work Package 5 (WP5) - Upscaling. Specifically, the Deliverable explains the research goals, followed by a detailed account of the methods used to assess the potential of ecosystem service models, developed for BESTMAP case studies, to be transferred to other regions across the EU. This Deliverable is closely linked to Deliverable 5.2 - “InVEST Models at the European-scale”, as it uses outputs from the meta-modelling of ecosystem services described in detail in D5.2. Both Deliverables should, therefore, be read in conjunction.

Summary

Insights into potential policy outcomes may be biased if based on an unrepresentative selection of case study information. As case studies are a central element of the BESTMAP project, evaluating their representativeness in the wider EU context is one of the major tasks of WP5 - Upscaling. In this Deliverable, we first briefly describe the principles of meta-models of ecosystem services and biodiversity that were developed as part of Task 5.2 to upscale predictions of ecosystem services beyond case studies. Second, we report on the development of a distance metric used to determine case study representativeness, i.e. the degree of similarity in conditions between BESTMAP case studies and NUTS3 regions across Europe. Third, we describe the transferability diagrams that we used to obtain the relationship between the predictive power of the meta-models and the distance metric, which were then used to determine the threshold within the distance metric (similarity of conditions) that corresponds to a model prediction that we considered reliable (R^2>0.5). Fourth, for each ecosystem service and biodiversity, we present a series of transferability maps based on the set threshold to identify the transferability potential of BESTMAP models to NUTS3 regions across Europe. Finally, we discuss the limitations and challenges of our approach used to determine case study representativeness and the transferability potential of ecosystem service models.

Introduction

Modelling ecosystem services using a set of predictors is a common practice in environmental sciences and has wide application potential in decision-making by stakeholders and policymakers at local to global scales. Modelled results typically include estimates of key ecosystem services such as food production rates, carbon sequestration potential, water quality and biodiversity status.

Knowing what factors can significantly affect food production is essential for understanding and maintaining food security. Similarly, a better understanding of the processes and aspects affecting carbon sequestration, water quality, and the presence of certain species can help mitigate other negative consequences of human actions, such as climate change and habitat loss.

Environmental influences, encompassing both natural and human-induced factors, alter the provision of ecosystem services across different scales. Models serve as potent instruments for navigating such complex systems, enabling the evaluation and prediction of how driving predictors affect ecosystems. At the simplest level, a single ecosystem service can be modelled across a small region, at a single time period. The result would provide estimates based on a set of variables that are considered to significantly affect the focal ecosystem service. However, repeating this method across larger scales, diverse regions, across different time periods, or where there is a scarcity of data poses greater challenges. Among these difficulties is the increased associated resource cost required for data collection and larger analysis.

To overcome the resource limitations, ideally, one might apply models developed and parameterised for one or a few areas to other areas; i.e. **'upscale' models to larger geographies**. This is often a key objective for policymakers, like the European Commission, who try to determine what is 'best' for different regions based on data or models that are limited in scope. Such an upscaling technique raises questions about the data and parameters, as changing the parameters of a model, or trying to model a totally separate place, can lead to a less accurate model or less reliable results. Therefore, quantification of its transfer feasibility and accuracy is required to successfully reuse knowledge from a source model or dataset to target a similar, or dissimilar, region. This leads to two questions:
1) How does one assess the potential to transfer ecosystem service models among regions?
2) How representative is any studied region of any other region in the domain of interest?

In this context, we define **'representativeness'** to mean how closely one region mirrors the characteristics of another region, and **'transferability'** to mean how well a model in one region can accurately predict the results of other regions. Therefore, in theory, If both representativeness and transferability are high, the chance of obtaining reliable results when upscaling a model across wider areas would also be high. However, this needed testing.

In this Deliverable, we address the analysis of representativeness and transferability. First, we provide a conceptual overview of ecosystem service (ESS) and biodiversity meta-models and variable selection and then develop so-called transferability diagrams and maps. Consequently, we discuss not only the possibilities and limitations of our approach but also

identify blind spots in the European Union and more widely across Europe, i.e. areas where BESTMAP results as they stand are not transferable and where new research is needed.

1. BESTMAP context

This Deliverable details the work undertaken as part of Task 5.1 - ‘Upscaling from regional Case Studies’. It builds upon previous BESTMAP work, specifically the creation and running of biophysical models (BPMs) to model food production, carbon sequestration, water quality and biodiversity at the case study level; and also the creation of ESS meta-models across NUTS3 regions. The flowchart of related works can be seen in Fig. 1, of which the work in this Deliverable is outlined in the lowest section.

The case study-level ESS models work is described in detail in D3.3 - ‘Ecosystem service, biodiversity and socio-economic models for each case study’ (Cord et al., 2023). In brief, the considered ESS were modelled in five BESTMAP sub-national case studies (CS) across Europe. The CS comprised the Humber region in the United Kingdom (UK), the Mulde river basin in Germany (DE), Catalonia in Spain (ES), South Moravia in the Czech Republic (CZ) and the Bačka region in Serbia (RS). The outputs of the CS models were ESS and biodiversity estimates at the farm level. For the purposes of ease of reading this document, biodiversity will be also considered an ESS. Among other information, the values for environmental variables, economic variables, and the application of Agri-environmental Schemes (AES) were also obtained at the farm level. However, due to data protection, the data were provided in a tabular form, with all spatial information (except the NUTS3 region) removed.

The creation of meta-models across NUTS3 regions is described in detail in D5.2 - ‘InVEST Models at the European scale’. That step involved creating meta-models of the CS BPM estimates, to determine how well they could predict the ESS results of other NUTS3 regions. In brief, ESS were used as dependent variables in statistical models that fitted variables that were identified as potentially relevant, and ultimately those that emerged as significant during the variable selection process.

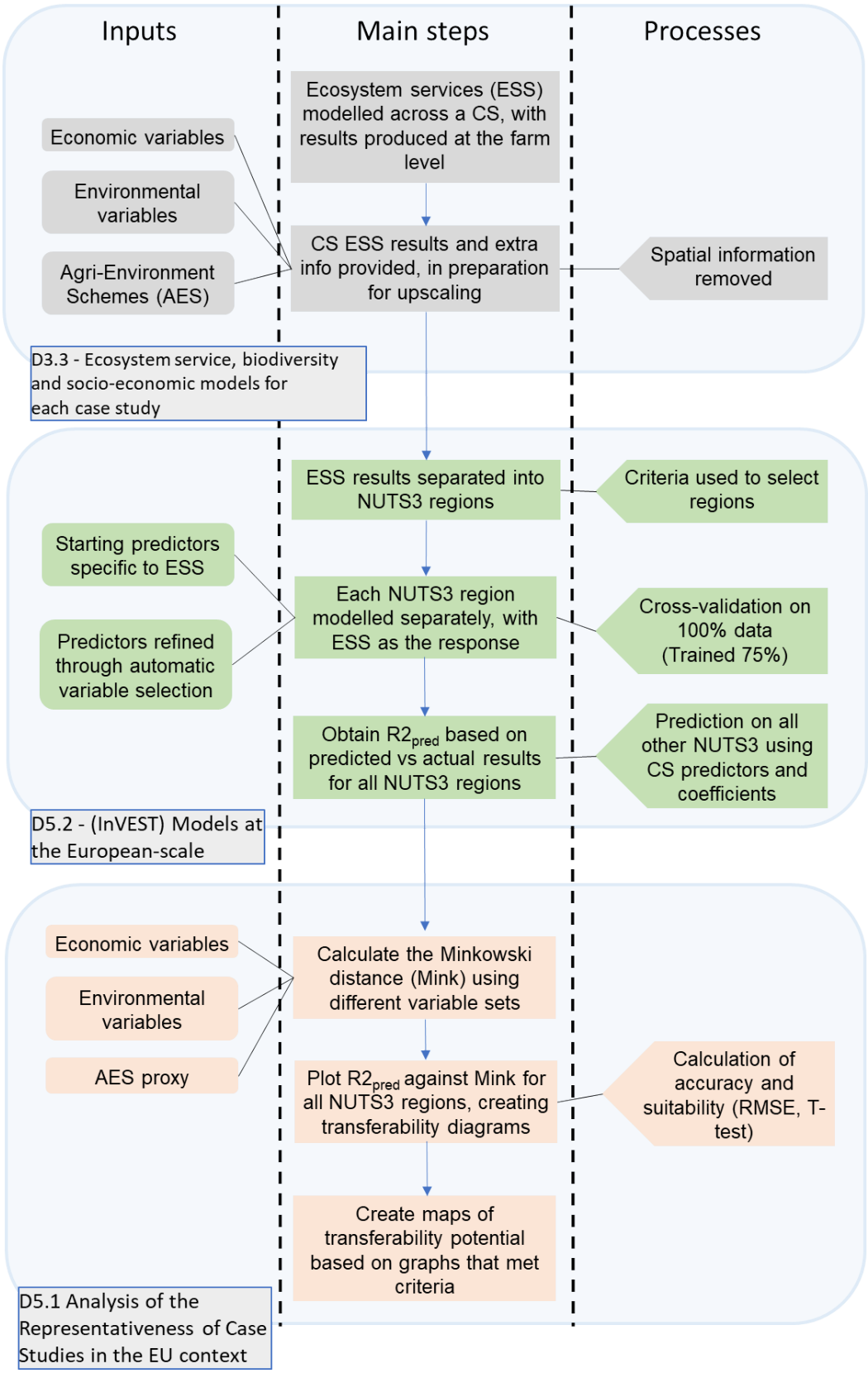

Figure 1: *Flowchart showing where the work described in this Deliverable fits in context to the other work and associated Deliverables of BESTMAP.*

2. Distance metric - CS representativeness

The degree of similarity in conditions between regions (and thus their representativeness for a wider area) can be described by a distance metric, where distance refers to distance in multivariate space rather than geographic distance. From the many specific varieties available, we calculated the Minkowski distance, which is a common measure of similarity between two points in N-dimensional space (Grant Hokit, 2010) and has been used in previous projects to assess the representativeness of regional CS (Václavík et al., 2016). The Minkowski distance is a single value (ranging from 0 to infinity) that indicates the similarity between regions in terms of variables that can describe a location's ecological, environmental, social and economic characteristics, for example. Calculating the distance metric for all possible combinations of existing NUTS3 regions provides a distance matrix (Table 1; Figure 2) that is useful for understanding the environmental and/or socioeconomic similarity between multiple regions, with lower distance values signifying higher similarity of conditions. Calculation of the Minkowski distance (D) for multivariate (not geographical) space on the example data can be described as follows. Suppose we have two points in a two-dimensional space (i.e., with different values for two variables), $X = (3, 4)$ and $Y = (6, 8)$. The distance (D) between these two points is calculated using the formula

$$D(X, Y) = \sqrt{(3 - 6)^2 + (4 - 8)^2}$$

$$D(X, Y) = 5$$

Table 1: *Example of Minkowski distance matrix output for randomly selected NUTS3 regions in Europe – two in the Czech Republic (CZ), two in Norway (NO), one in Croatia (HR), and one in Germany (DE). For example, the difference in environmental conditions between the Czech Republic (CZ064) and Germany (DE21A) is relatively low (D=0.86) compared to Croatia (HR064; D=3.17). Distance is calculated based on environmental variables described below and in Table 2.*

	CZ064	CZ072	NO0B2	NO0B1	HR064	DE21A
CZ064	-	0.1	3.83	3.84	3.17	0.86
CZ072		-	3.77	3.77	3.24	0.91
NO0B2			-	0.43	6.99	4.66
NO0B1				-	6.99	4.65
HR064					-	2.37
DE21A						-

Here, we used a set of environmental, economic and AES variables (Table 2) to calculate the Minkowski distance from each NUTS3 region in our CS to all the other NUTS3 regions in Europe (see example in Figure 2). To capture changes in central tendency and variability, most variables included in the calculation of the distance metric are represented by mean

and standard deviation. These two parameters are calculated from all data points (cells) included in a given NUTS3, i.e. the so-called area average. Because some variables were not appropriate to express in mean and standard deviation, we used relative proportions (e.g., specific land use to total area) (Table 2).

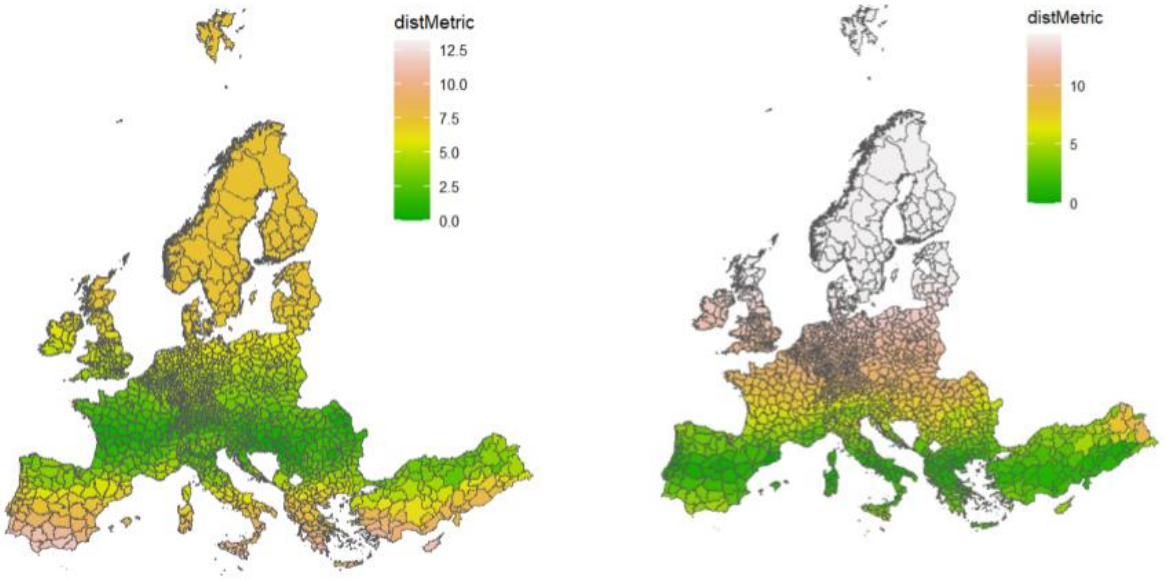

Figure 2: *Example of Minkowski distance values between each European NUTS3 region and Serbia (RS121; left) and Spain (ES511; right). Distance is calculated based on environmental variables described below and in Table 2.*

This set of variables encompassed a total of 84 predictors selected with respect to the four ESS models (food, carbon, nutrient, biodiversity). These variables were previously identified as relevant for the calculation of the selected ESS (see D3.3 on biophysical modelling). The nutrient model was split into a simulation (sub-models) of nitrogen and phosphorus availability and the biodiversity model was represented by five sub-models, each estimating the potential occurrence/habitat suitability of indicator bird species: *Alauda arvensis*, *Carduelis cannabina*, *Emberiza citrinella*, *Sylvia communis*, *Vanellus vanellus*. Food and carbon models and nutrient sub-models had two versions of the Minkowski distance, i.e. one that calculated distances based on all potentially relevant variables and one that accounted only for those variables that came out as significant in the ESS meta-model for at least one NUTS3 region. A binary response of presence or absence for each species was used for the biodiversity sub-models (See D5.2 for details).

Means, standard deviations and/or relative areas of all relevant environmental variables (see D3.2 - 'European Base Layer' for data sources and description) in European NUTS3 regions were calculated in QGIS (QGIS, 2023) using zonal statistics and related functions. The subsequent process, which involved the compilation, selection and standardization of variables together with the calculation of Minkowski distance, was performed in the R software (R Core Team, 2021) using multiple packages including *rgdal, sf, raster, terra, plyr, dplyr*.

Economic variables for most of the EU countries were obtained from the Thünen Institute (Johann Heinrich von Thünen Institute, 2020), where the data represent the exact number of farms, allowing all variables to be standardized per farm. For the UK, which was not covered by the Thünen dataset, economic data were extracted from the Farm Accountancy Data Network (FADN; Anon, 2019), where only the relative proportion (weights) using NUTS2-level data of the value of a given variable is available (European Commission, 2019). The spatial coverage of these combined datasets, i.e. NUTS2 for the UK, and NUTS3 for non-UK countries, is shown in Figure 3. The economic data from Thunen/FADN include Total Utilised Agricultural Area (ha; SE025), Economic size of a farm (€1000; SE005) and Agri-environment and animal welfare payments Value (€; SAEAWSUB_V), which represent farm size, economic size and extent of agri-environmental schemes/practices, respectively. In order to describe different farming systems, we grouped the original farming type 'Type of farming' (TF8) into our own classification of farm specializations (for details see D3.5 - 'Farming System Archetypes for each CS'; Langerwisch et al., 2023; Václavík et al., in revision), including general cropping (P1), permanent crops (P3), livestock grazing (P4) and mixed agriculture. We then averaged all data over the available 2014-2017 period, and aggregated them per farm and NUTS3 region. As not all NUTS3 regions in Europe provided data, we were able to extract information from 1257 NUTS3 regions, resulting in a 17% reduction of the original dataset (1517 NUTS3 regions).

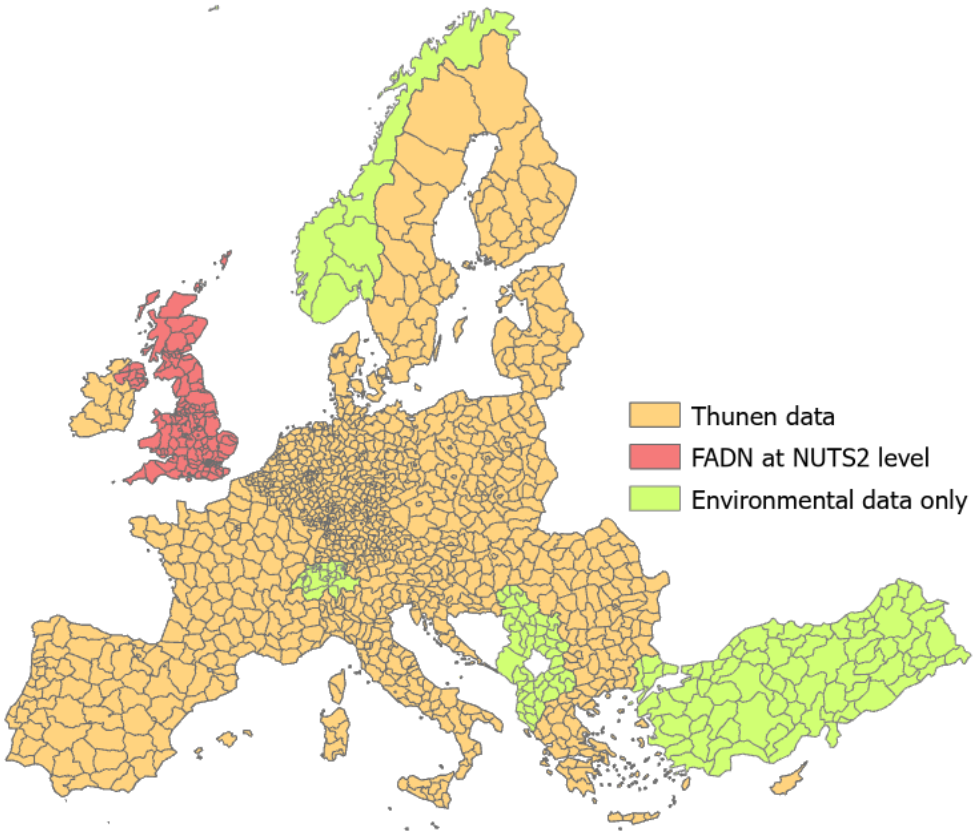

Figure 3: *Spatial coverage of NUTS3 regions with the Thunen and FADN data.*

Table 2: *ESS model variables used to calculate the Minkowski distance metrics. The check mark indicates all variables identified as relevant for the prediction of a given ESS. Abbreviations: x̄=mean, σ=standard deviation, %=relative proportion, MAM=Mar-Apr-May, JJA=Jun-Jul-Aug, SON=Sep-Oct-Nov, DJF=Dec-Jan-Feb. P1=general cropping, P2=horticulture, P3=permanent crops, P4=livestock grazing, mixed=mixed farming.*

Ecosystem service	**Food**			**Carbon**			**Nutrient**			**Biodiver.**		
Parameter	x̄	σ	%	x̄	σ	%	x̄	σ	%	x̄	σ	%
Available water capacity [volume fraction]	✓	✓	-	-	-	-	-	-	-	-	-	-
Seasonal means maximum temperature [°C] MAM JJA SON DJF	✓	✓	-	✓	✓	-	✓	✓	-	✓	✓	-
Seasonal means minimum temperature [°C] MAM JJA SON DJF	✓	✓	-	✓	✓	-	✓	✓	-	✓	✓	-
Seasonal sums precipitation [mm] MAM JJA SON DJF	✓	✓	-	✓	✓	-	✓	✓	-	✓	✓	-
Seasonal means solar radiation [W/m2] MAM JJA SON DJF	✓	✓	-	-	-	-	-	-	-	✓	✓	-
Seasonal means evapotranspir. [kg/m2/month] MAM JJA SON DJF	✓	✓	-	-	-	-	✓	✓	-	✓	✓	-
Land Cover [%] Trees Bogs Arable Shrubs Artificial Natural	-	-	✓	-	-	✓	-	-	✓	-	-	✓
Small woody features [%]	-	-	-	-	-	-	✓	✓	-	✓	✓	-
Seasonal means of soil moisture [% content] MAM JJA SON DJF	✓	✓	-	✓	✓	-	✓	✓	-	-	-	-
Bulk density [g.cm-3]	✓	✓	-	✓	✓	-	-	-	-	-	-	-
Clay content [g.kg-1]	✓	✓	-	✓	✓	-	✓	✓	-	-	-	-
Depth available to roots [cm]	✓	✓	-	-	-	-	-	-	-	-	-	-
Digital elevation model [m]	✓	✓	-	-	-	-	✓	✓	-	✓	✓	-
Hydrologic soil type [%] hsg.b hsg.c hsg.10plus hsg.a hsg.d	-	-	✓	-	-	✓	-	-	✓	-	-	-
Topsoil organic carbon [% content]	✓	✓	-	✓	✓	-	-	-	-	-	-	-
pH [x 10]	✓	✓	-	✓	✓	-	-	-	-	-	-	-
Farm size (Total Utilized Agricultural Area) [ha]	✓	-	-	✓	-	-	✓	-	-	✓	-	-
Economic size (Economic size of a farm) [€]	✓	-	-	✓	-	-	✓	-	-	✓	-	-
Farm specialization P1 P2 P3 P4 mixed	-	-	✓	-	-	✓	-	-	✓	-	-	✓

AES proxy (Agri-environment and animal welfare payments Value) [%]	✓	-	-	✓	-	-	✓	-	-	✓	-	-

3. Transferability diagrams

We hypothesise that the Minkowski distance, being a measure of the similarity of conditions between regions, serves as a robust predictor for the accuracy of a meta-model developed for one region in predicting the ESS values in another region. In other words, higher environmental and socio-economic similarity implies higher model transferability, i.e. enhanced suitability of the meta-model for application in a different but sufficiently similar region.

To test this hypothesis, we devise so-called 'transferability diagrams' to examine the correlation between the accuracy of the meta-models outlined in D5.2 and the Minkowski distance. For this, we use data at the NUTS3 level, using those NUTS3 regions that overlap with our five CS and meet an *a priori* defined set of criteria, i.e. a total of 19 NUTS3 regions (see D5.2 - section 3.2 for details). If the Minkowksi distance is a reliable predictor of model transferability, the relationship should follow a negative linear function. The estimation of this relationship is then used to establish a threshold within the distance metric that corresponds to a reliable model prediction.

More precisely, the transferability diagrams depict the strength of the meta-models (R^2) on the Y-axis, determined by applying the model developed for a given NUTS3 region '1' to all other NUTS3 regions (2-19). Simultaneously, the X-axis represents the Minkowski distance, measuring the similarity between the given NUTS3 region '1' and all the remaining regions. Data points are fitted with a linear trend and evaluated using the root mean square error (RMSE) to understand the transferability function and its significance (see Appendix 1 and Figure 4 with an extended legend for the full description of how to read the transferability diagrams - Figures 4-39).

The transferability diagrams were fitted using alternative sets of variables to calculate the Minkowski distance. As mentioned in section 2, we used all variables identified as potentially relevant for the ecosystem service based on expert judgment and also only those variables that were significant in the ESS meta-model in at least one NUTS3 region. In addition, transferability diagrams for some ESS produced better results (i.e. showing a clearer relationship between the strength of the meta-model and the Minkowski distance) when calculated only from environmental variables, therefore, we present results (transferability diagrams and maps) separately for versions based on (1) environmental variables only and (2) environmental and socioeconomic variables.

3.1 Setting the transferability threshold

Following the development of the transferability diagrams and careful analysis of the associated statistics, we established a transferability threshold (a value above which a model transferability is considered adequate) on the Y-axis of R^2 = 0.5 based on expert judgment carried out during our internal discussions and panel meetings. Although there is no absolute rule for selecting an appropriate threshold because it depends on the purpose of the study and the quality of the data, we argue that for upscaling purposes when working with at least 100 points, this threshold is acceptable. Furthermore, the ecological and ecosystem modelling community considers models with R^2 greater than 0.5 to be reliable models (Johnson and Omland, 2004).

The fitted linear trend in the transferability diagrams is then used to determine the value of Minkowksi distance (degree of similarity) that corresponds to the selected R^2 of 0.5. We then calculate the Minkowski distance between all ~1,500 NUTS3 regions across Europe and apply the selected threshold to identify all those regions to which our ESS models can be transferred with acceptable accuracy. These maps of transferability potential for each ESS are presented in section 4. For final maps, only those transferability diagrams with a significant downward trend (assessed by t-test) are included.

3.2 Transferability diagrams based on all environmental variables

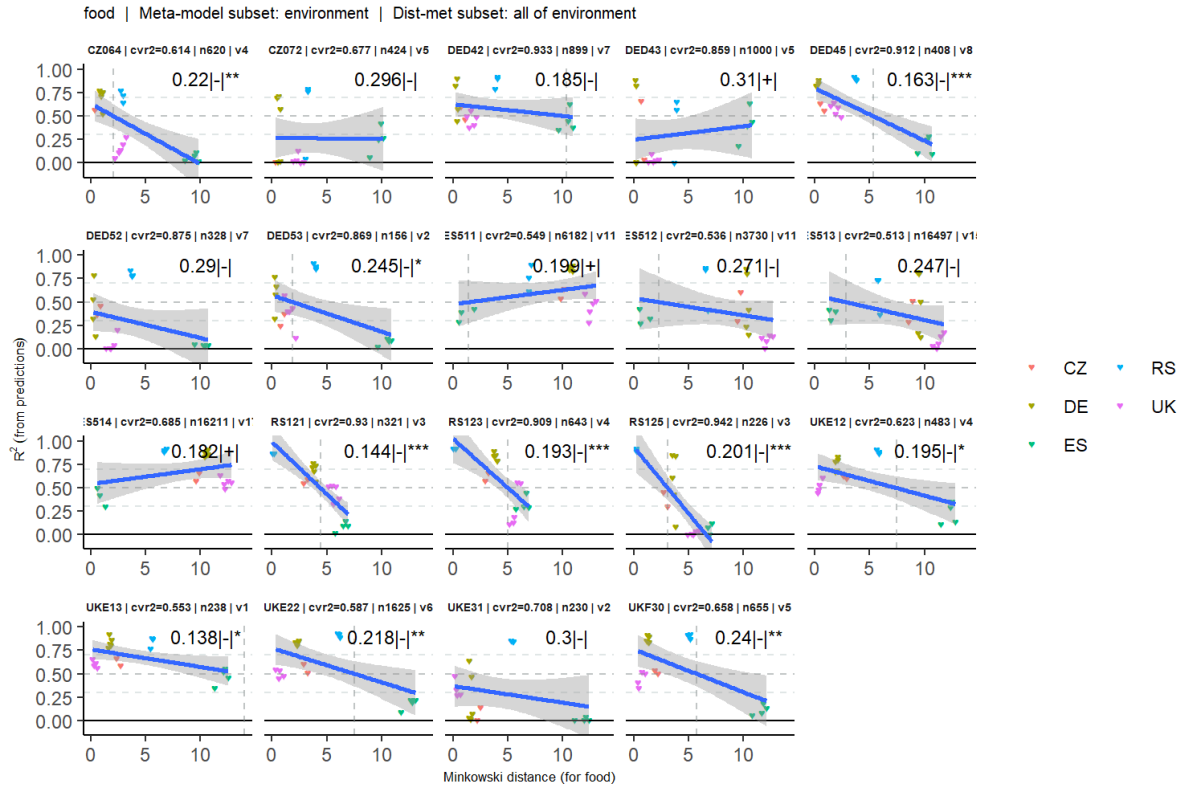

Figure 4: *Transferability diagrams for the* ***food*** *ecosystem service. These are based on* ***all environmental*** *variables that were identified as potentially relevant for the ecosystem service prior to the analyses based on expert judgment (see Table 3). The Y-axis shows the*

coefficient of determination (R^2) that resulted from applying the meta-model from a given NUTS3 region (top left code) to all remaining regions, plotted as triangles coloured by the case studies. On the X-axis is the Minkowski distance between the given and all remaining NUTS3 regions. Data points are fitted with a linear trend and evaluated using the root mean square error (which is the value reported at the top-right corner in each data box) to understand the transferability function and its increasing (+) or decreasing (-) significance (0.90, ** 0.95, *** 0.99). Linear trends are supplemented with grey error bars showing 95% confidence intervals. The Cvr2 value indicates cross-validation R^2 (i.e. within the NUTS3 region for which the meta-model was developed), CvAUC indicates cross-validation Area Under the Curve (AUC) value (only for biodiversity models), n represents the number of farms used to create the meta-model, and v represents the number of variables used in the final meta-model. The vertical dashed line shows the value of Minkowski distance which corresponds to the selected R^2 threshold of 0.5 on the Y-axis and is thus considered suitable for transferability. For more information on the symbols see Appendix 1.*

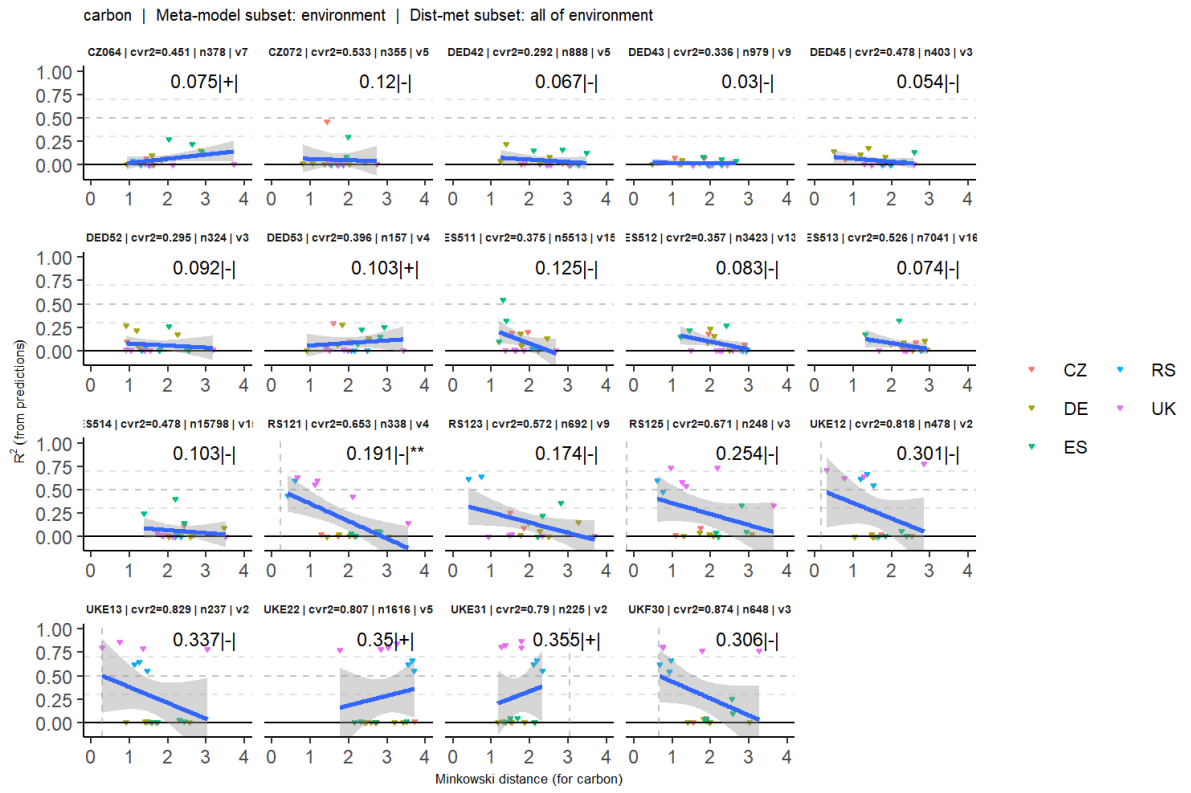

Figure 5: *Transferability diagrams for the* ***carbon*** *ecosystem service based on* ***all environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

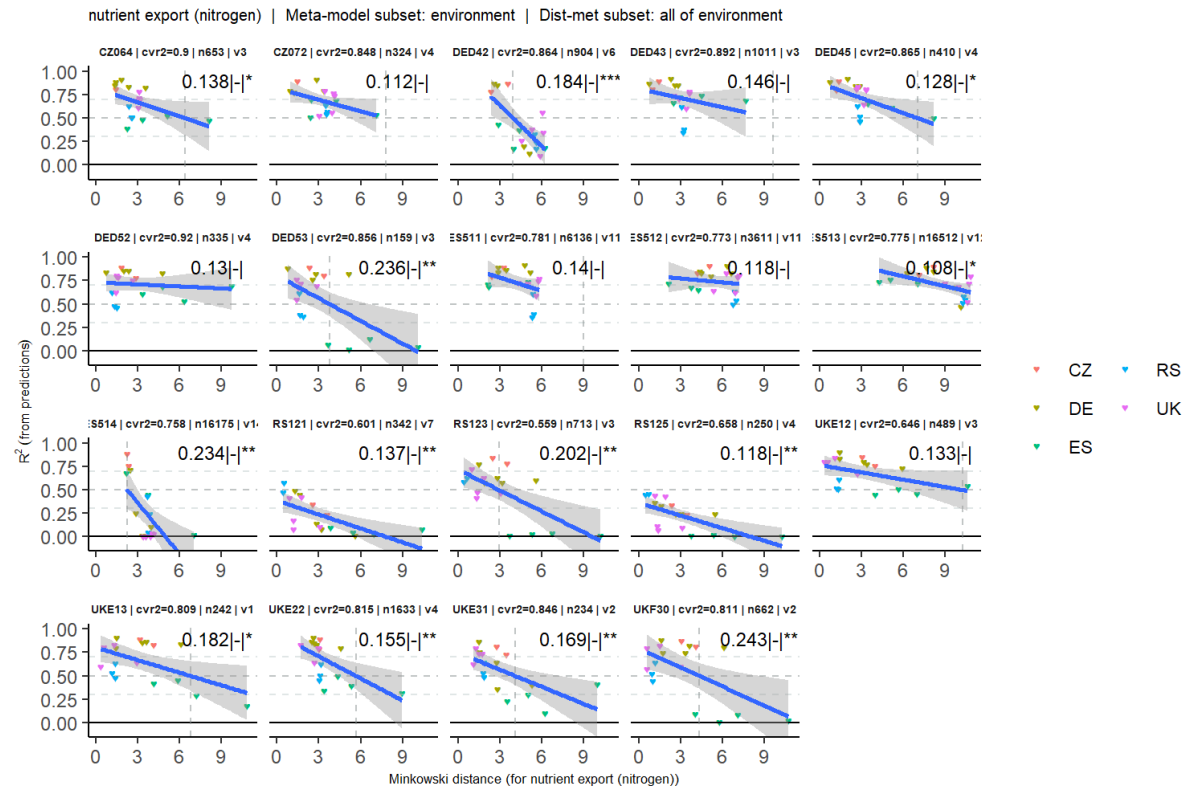

Figure 6: *Transferability diagrams for the* ***nutrient (nitrogen)*** *ecosystem service based on* ***all environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

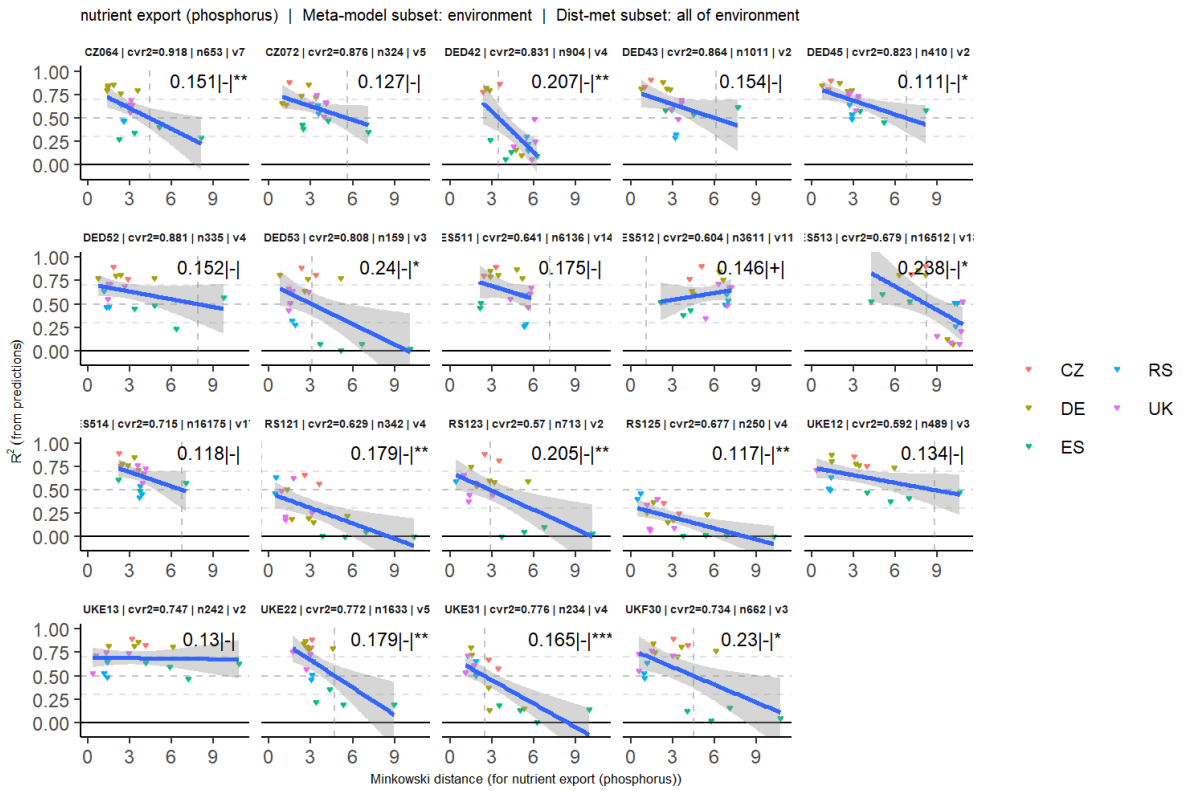

Figure 7: *Transferability diagrams for the* ***nutrient (phosphorus)*** *ecosystem service based on* ***all environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

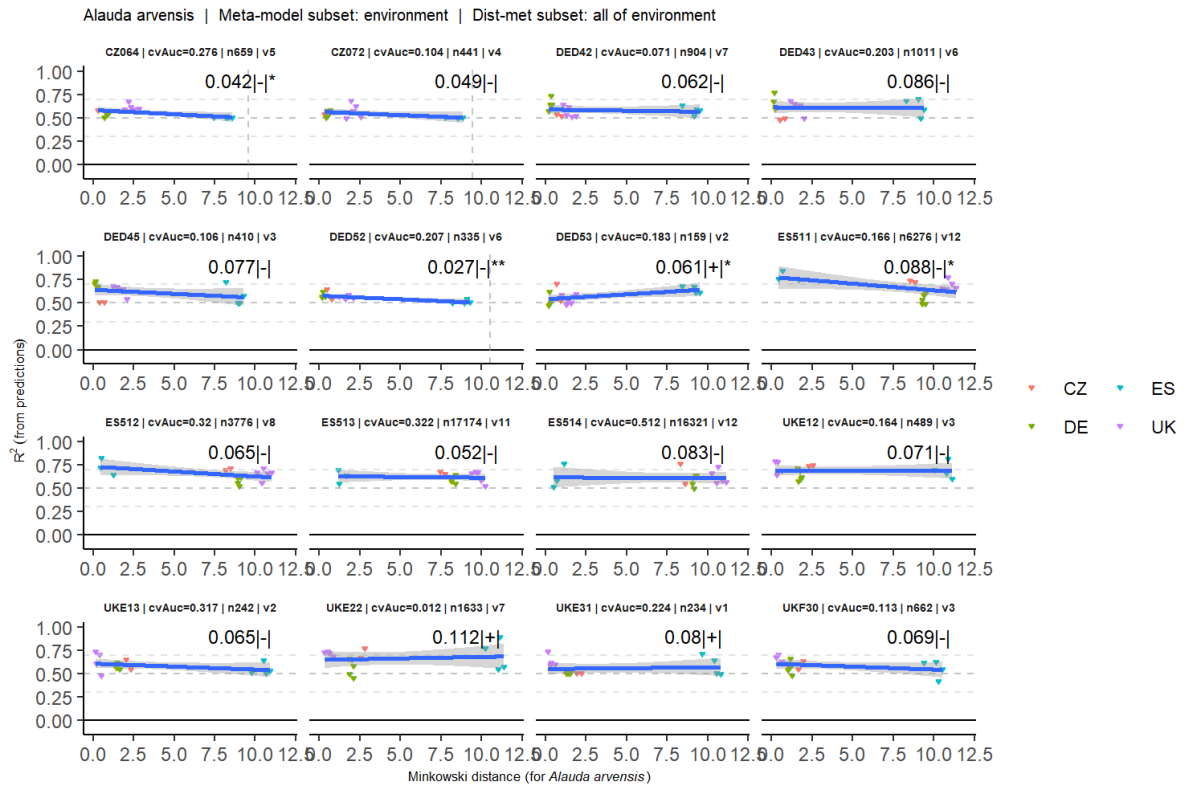

Figure 8: *Transferability diagrams for the* ***biodiversity (Alauda arvensis)*** *ecosystem service based on* ***all environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

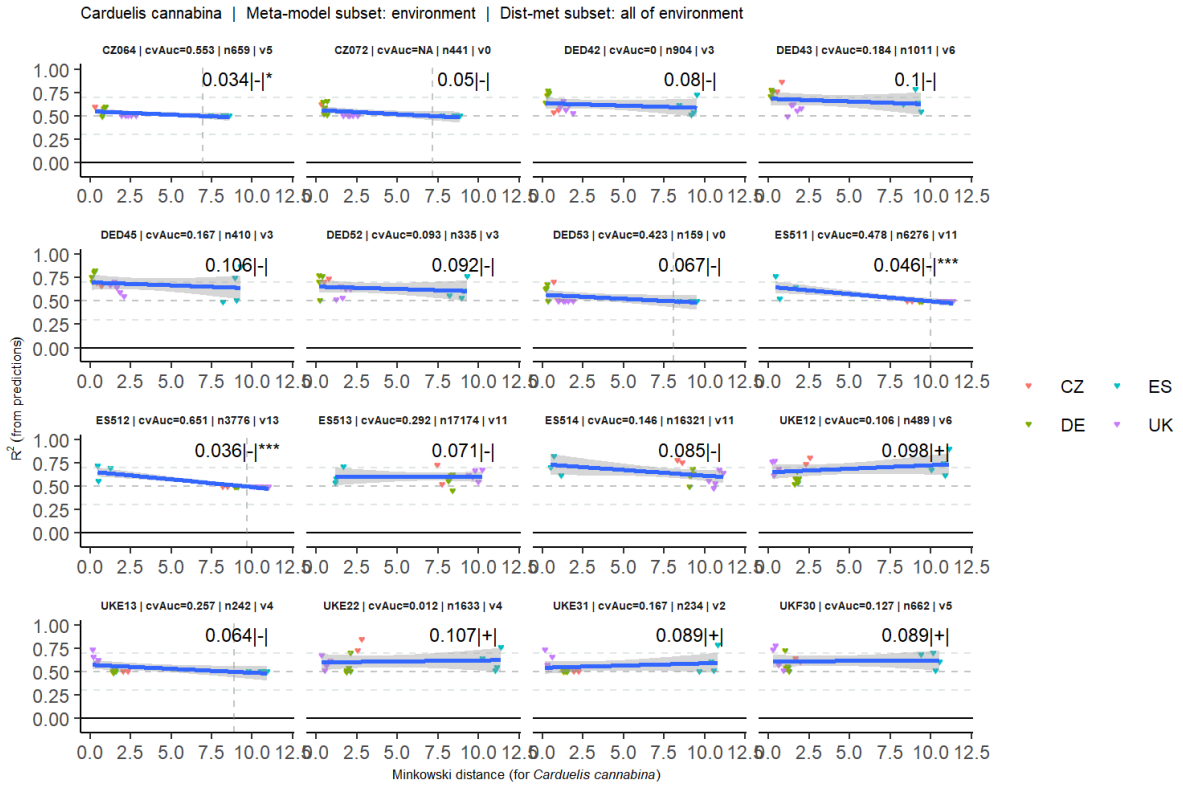

Figure 9: *Transferability diagrams for the* ***biodiversity (Carduelis cannabina)*** *ecosystem service based on* ***all environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

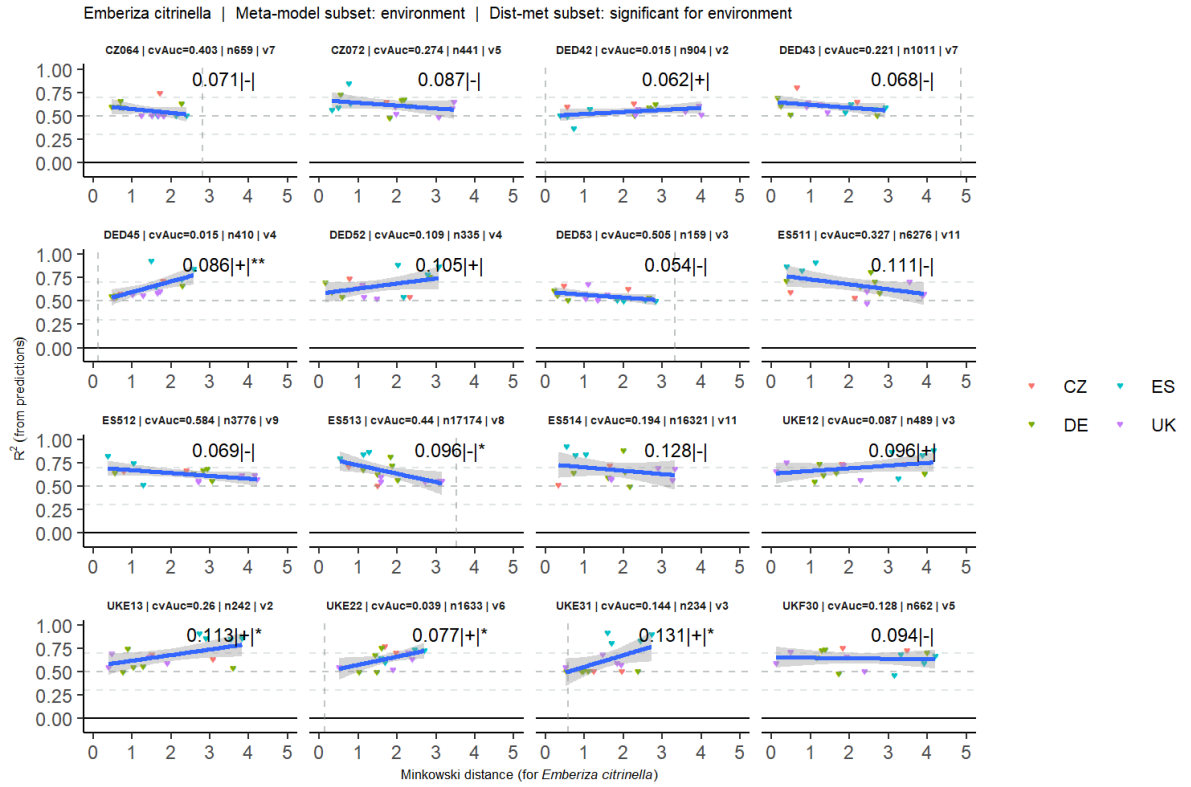

Figure 10: *Transferability diagrams for the* ***biodiversity (Emberiza citrinella)*** *ecosystem service based on* ***all environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

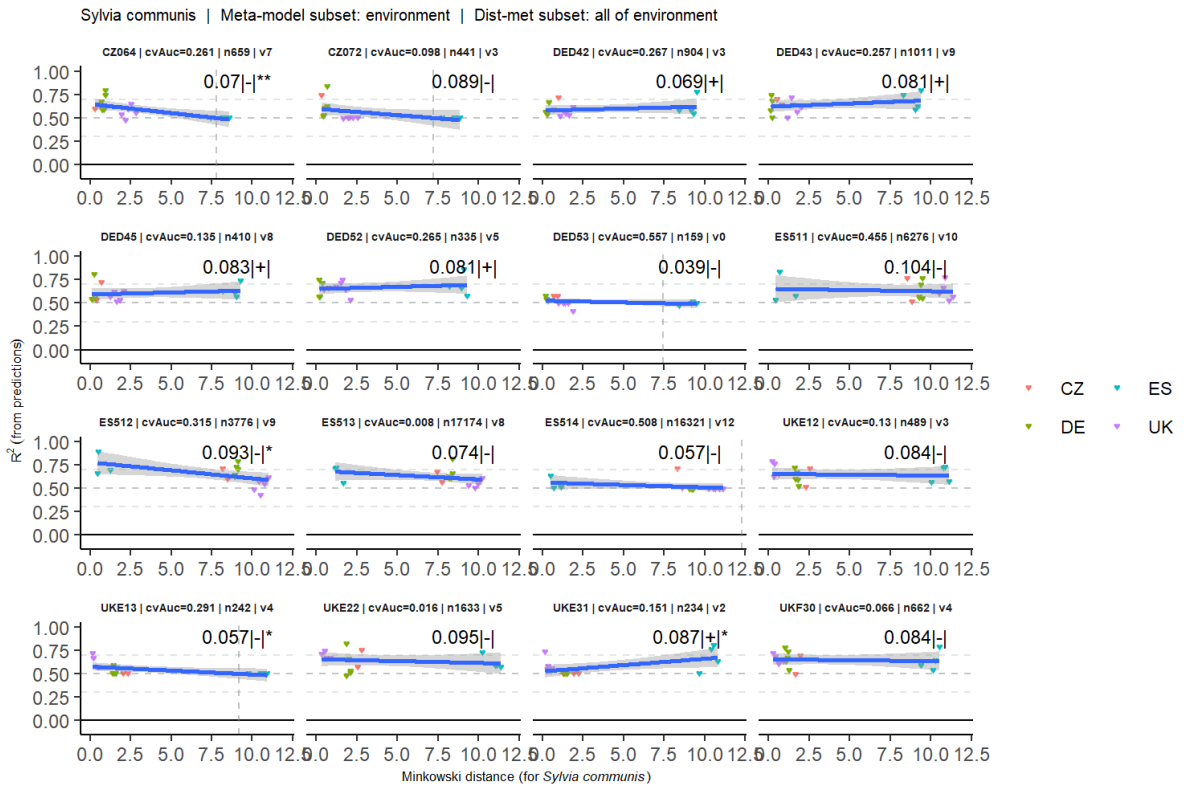

Figure 11: *Transferability diagrams for the* ***biodiversity (Sylvia communis)*** *ecosystem service based on* ***all environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

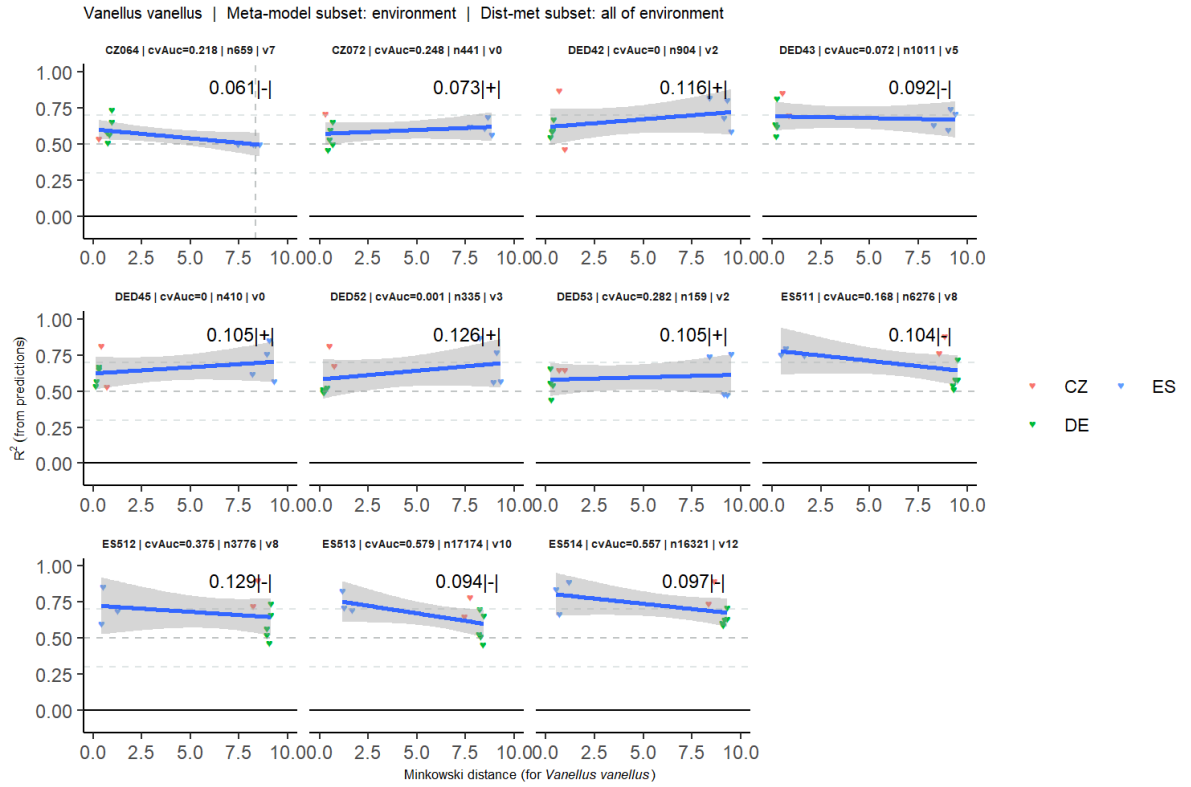

Figure 12: *Transferability diagrams for the* ***biodiversity (Vanellus vanellus)*** *ecosystem service based on* ***all environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

3.3 Transferability diagrams based on significant environmental variables

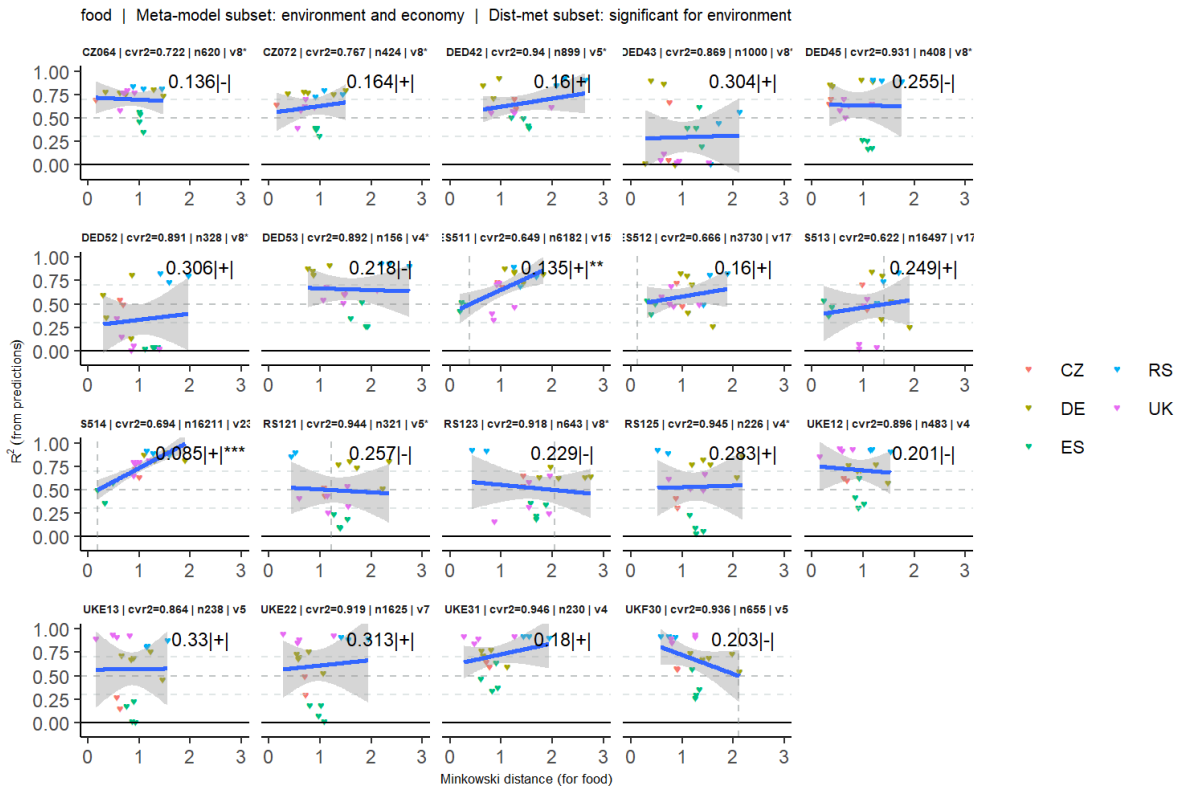

Figure 13: *Transferability diagrams for the* ***food*** *ecosystem service based on* ***significant environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

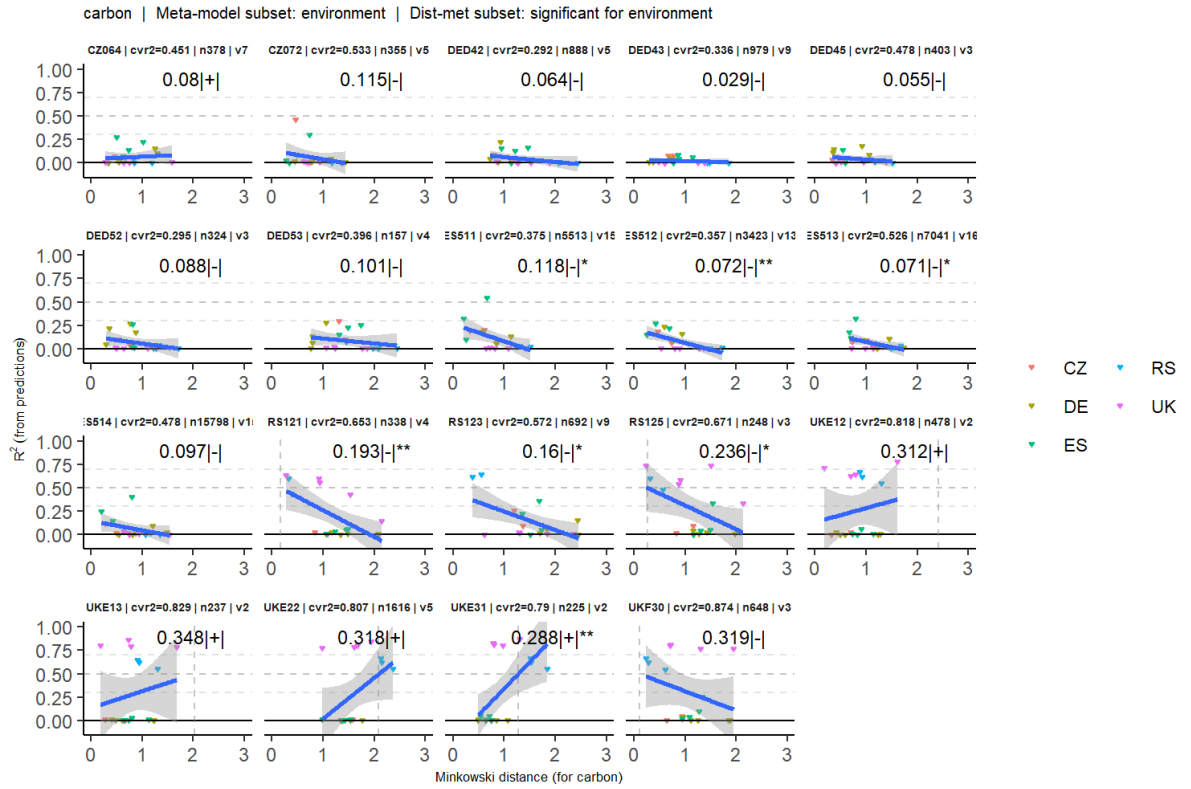

Figure 14: *Transferability diagrams for the* ***carbon*** *ecosystem service based on* ***significant environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

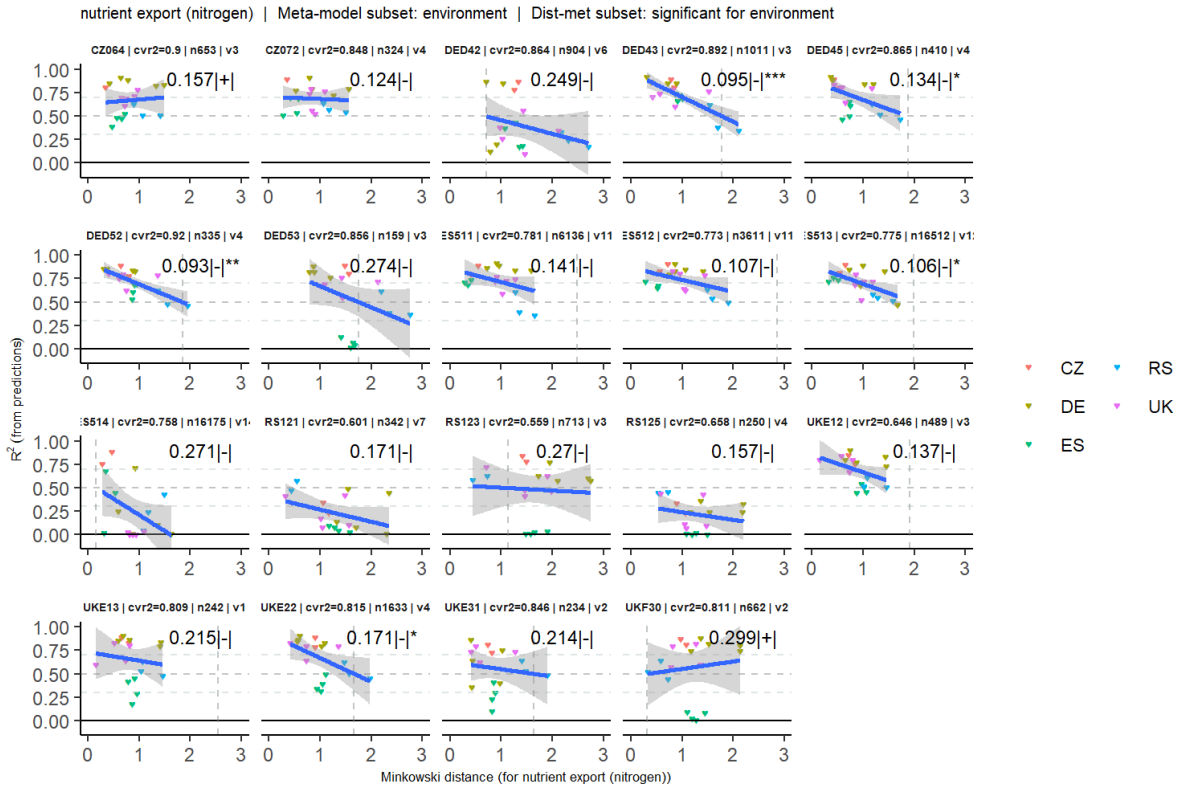

Figure 15: *Transferability diagrams for the* ***nutrient (nitrogen)*** *ecosystem service based on* ***significant environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

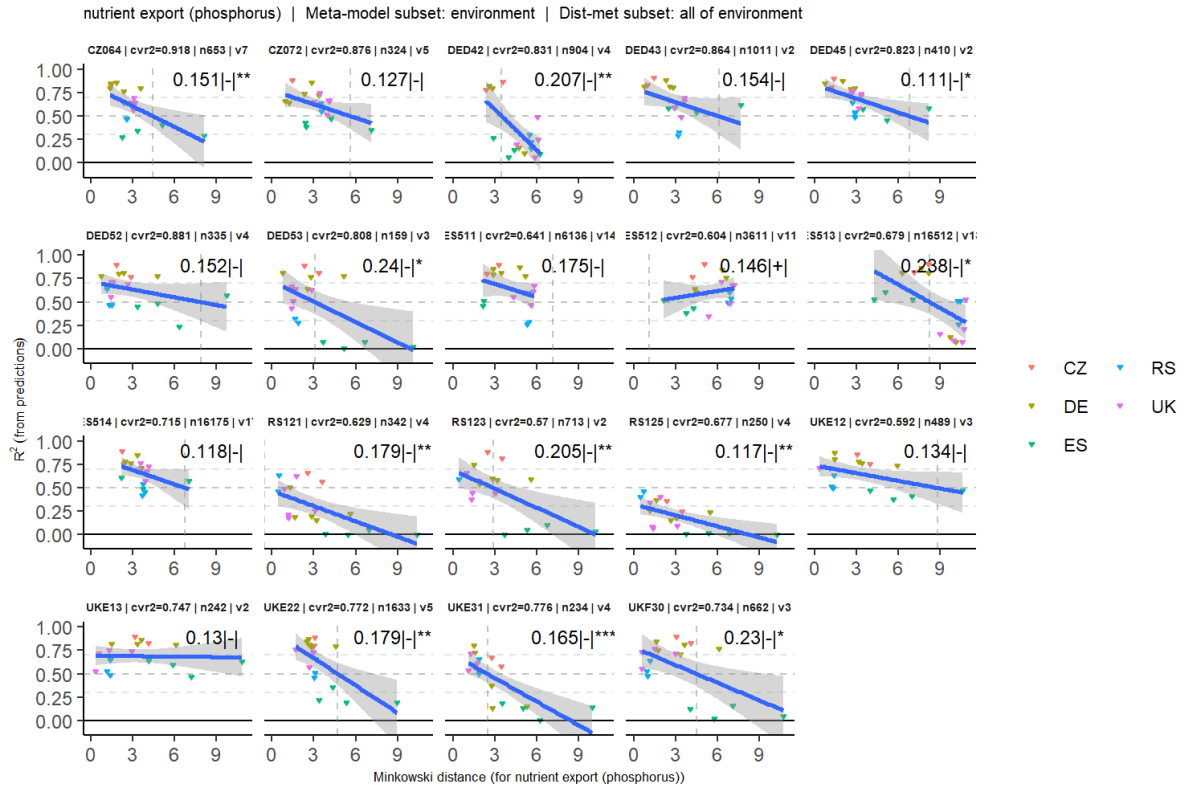

Figure 16: *Transferability diagrams for the* ***nutrient (phosphorus)*** *ecosystem service based on* ***significant environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

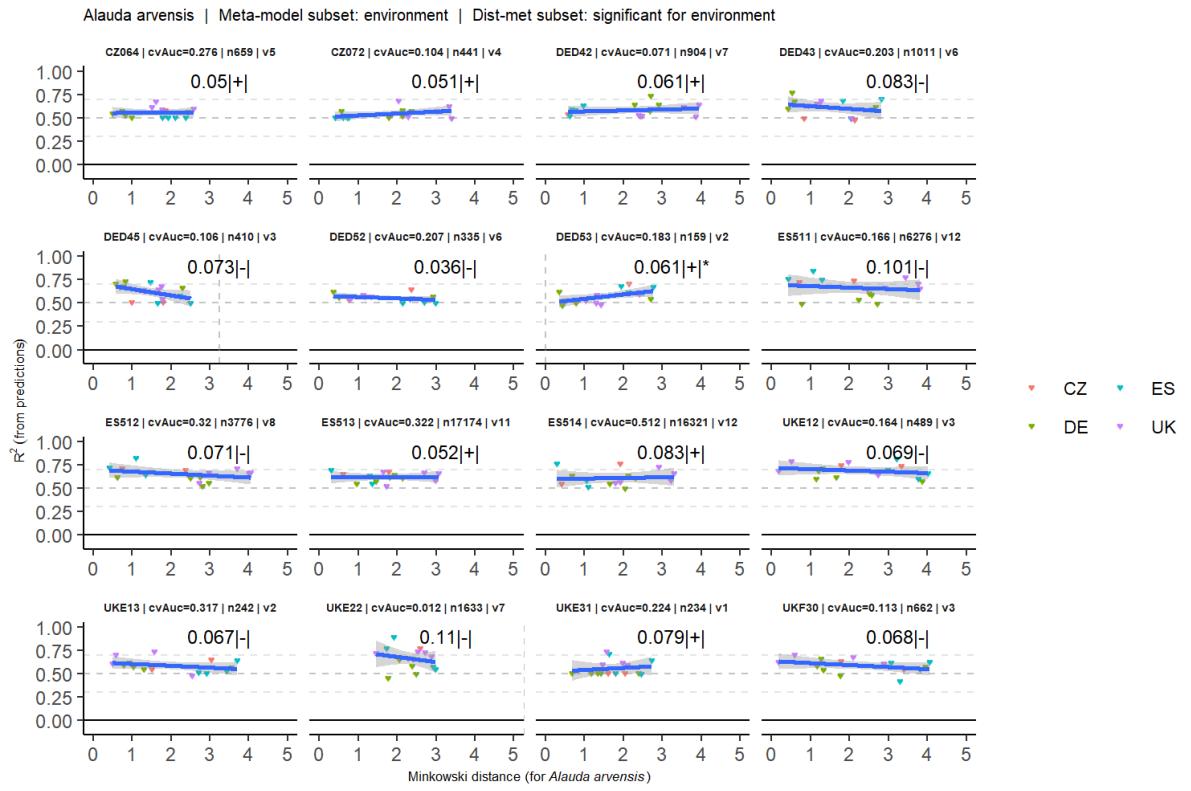

Figure 17: *Transferability diagrams for the* ***biodiversity (Alauda arvensis)*** *ecosystem service based on* ***significant environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

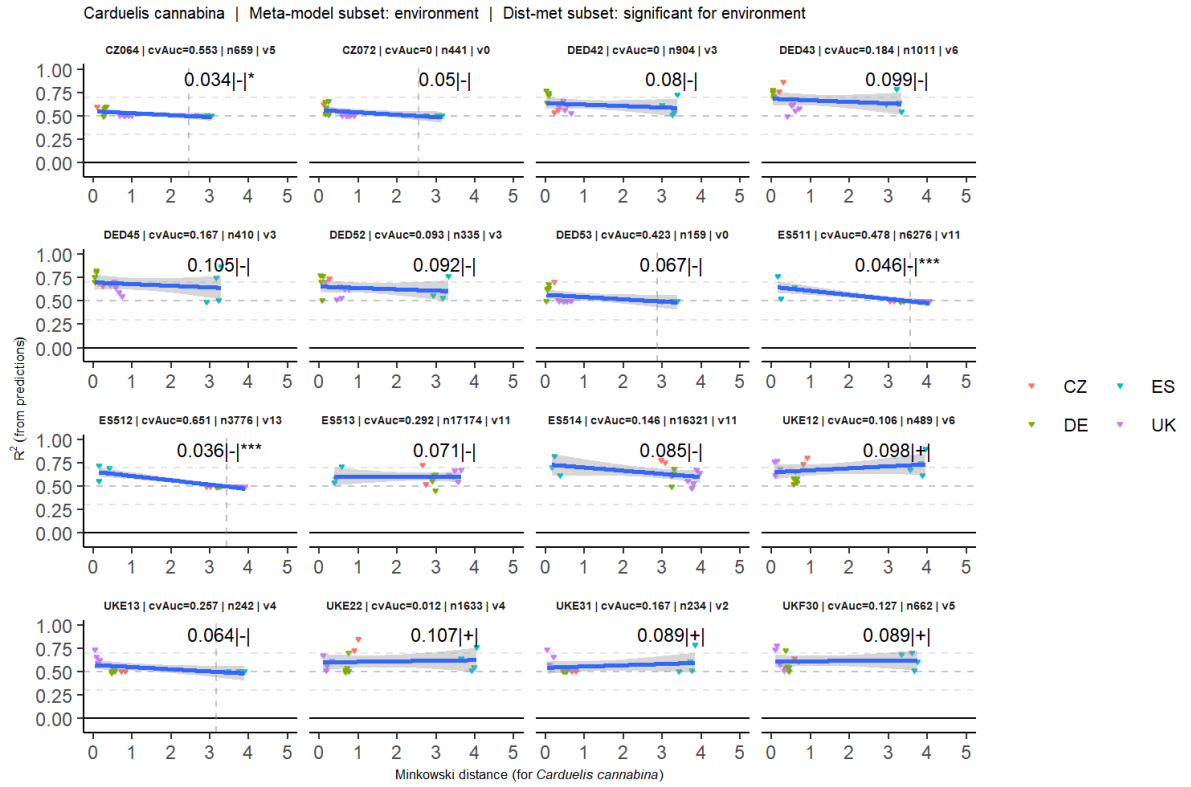

Figure 18: *Transferability diagrams for the* ***biodiversity (Carduelis cannabina)*** *ecosystem service based on* ***significant environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

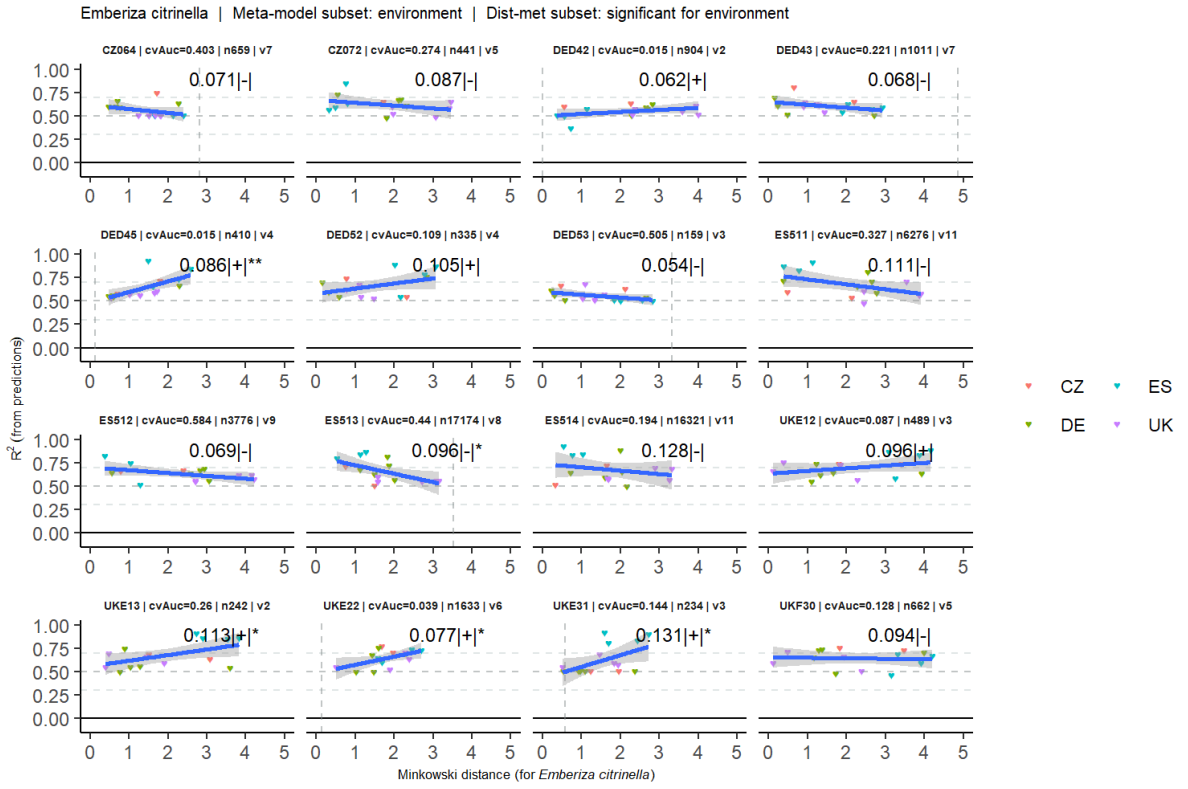

Figure 19: *Transferability diagrams for the* ***biodiversity (Emberiza citrinella)*** *ecosystem service based on* ***significant environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

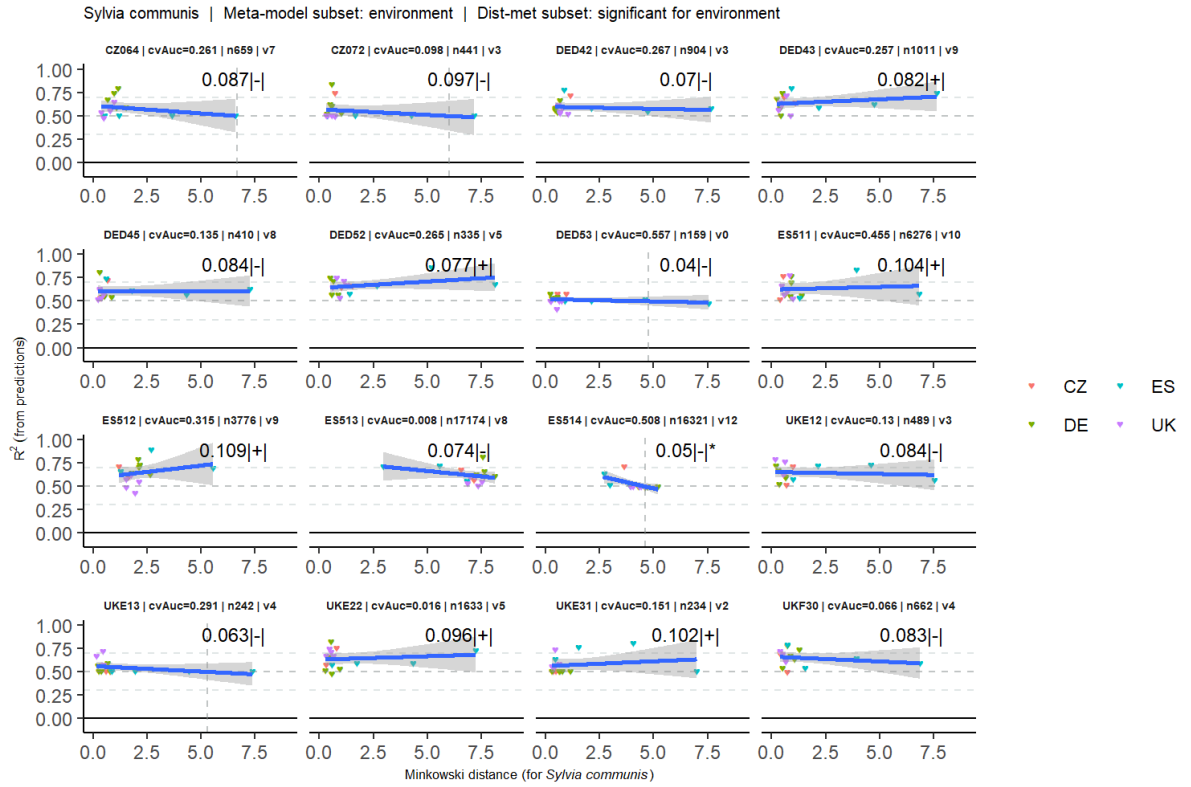

Figure 20: *Transferability diagrams for the* ***biodiversity (Sylvia communis)*** *ecosystem service based on* ***significant environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

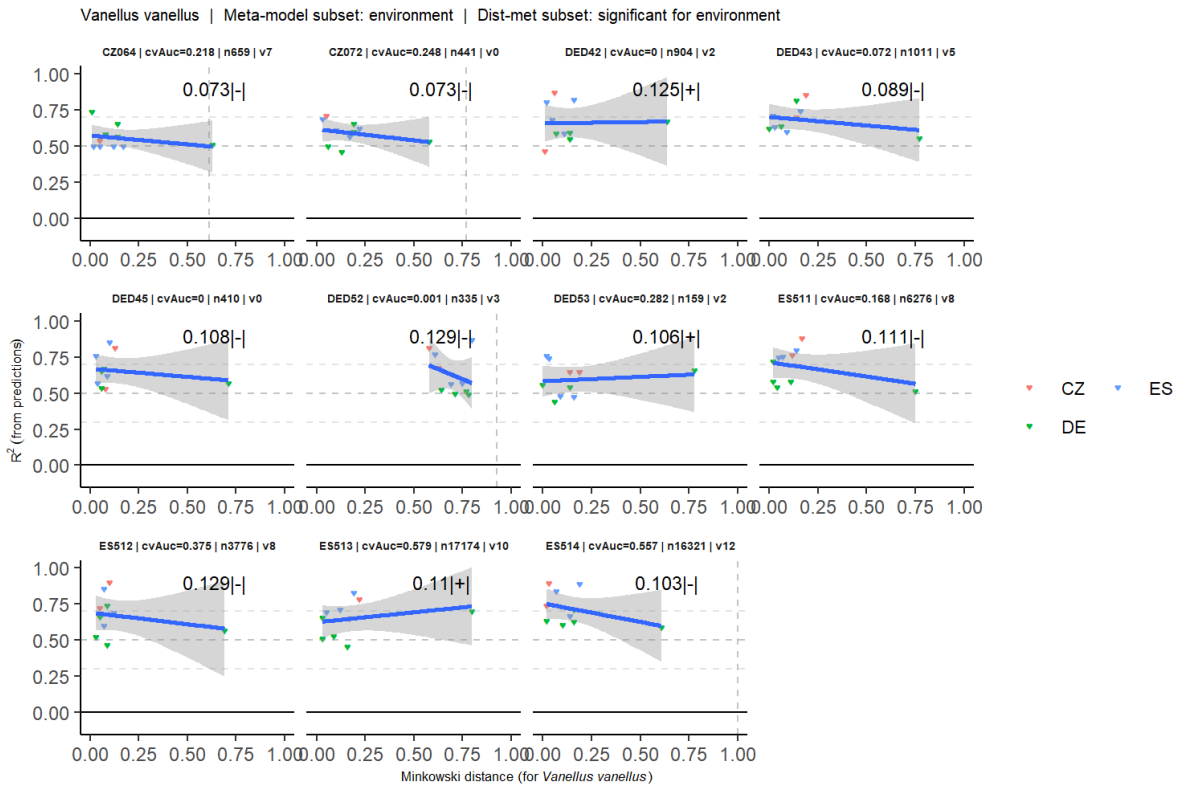

Figure 21: *Transferability diagrams for the* ***biodiversity (Vanellus vanellus)*** *ecosystem service based on* ***significant environmental*** *variables. See Figure 4 for a full explanation of the diagrams.*

3.4 Transferability diagrams based on all environmental and economic variables

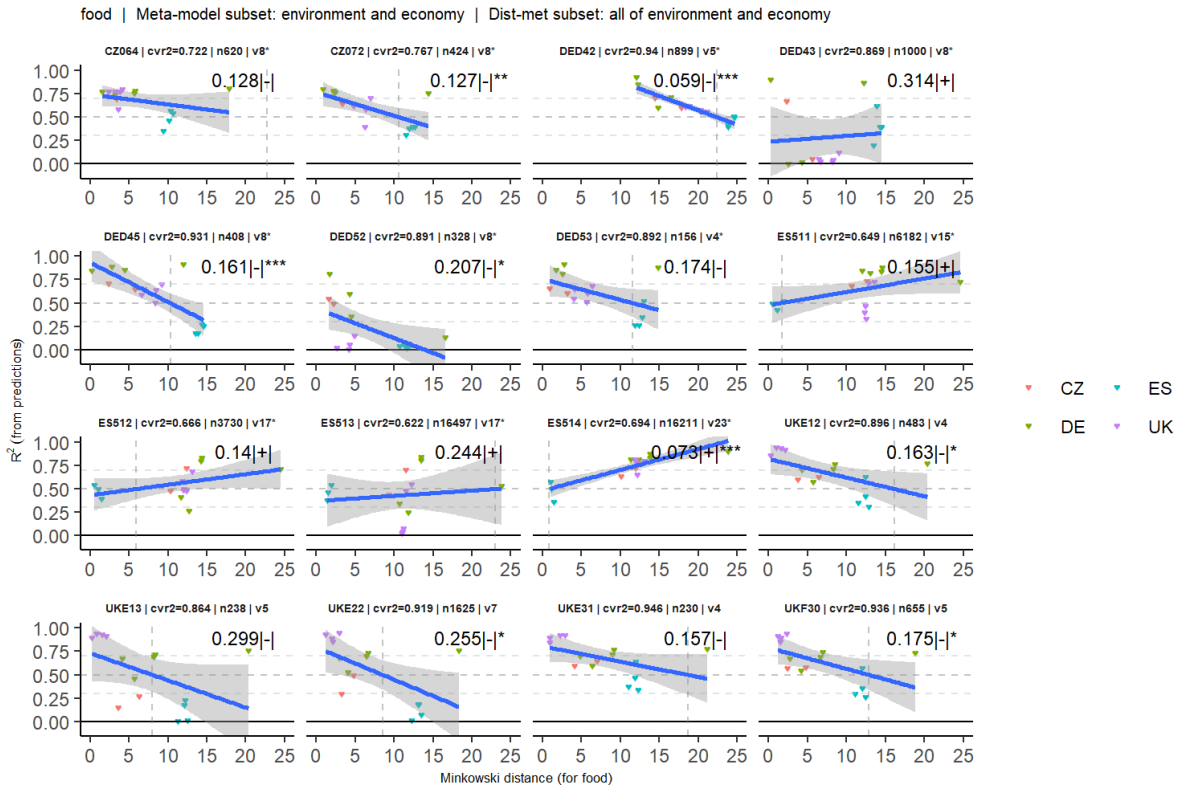

Figure 22: *Transferability diagrams for the* ***food*** *ecosystem service based on* ***all environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

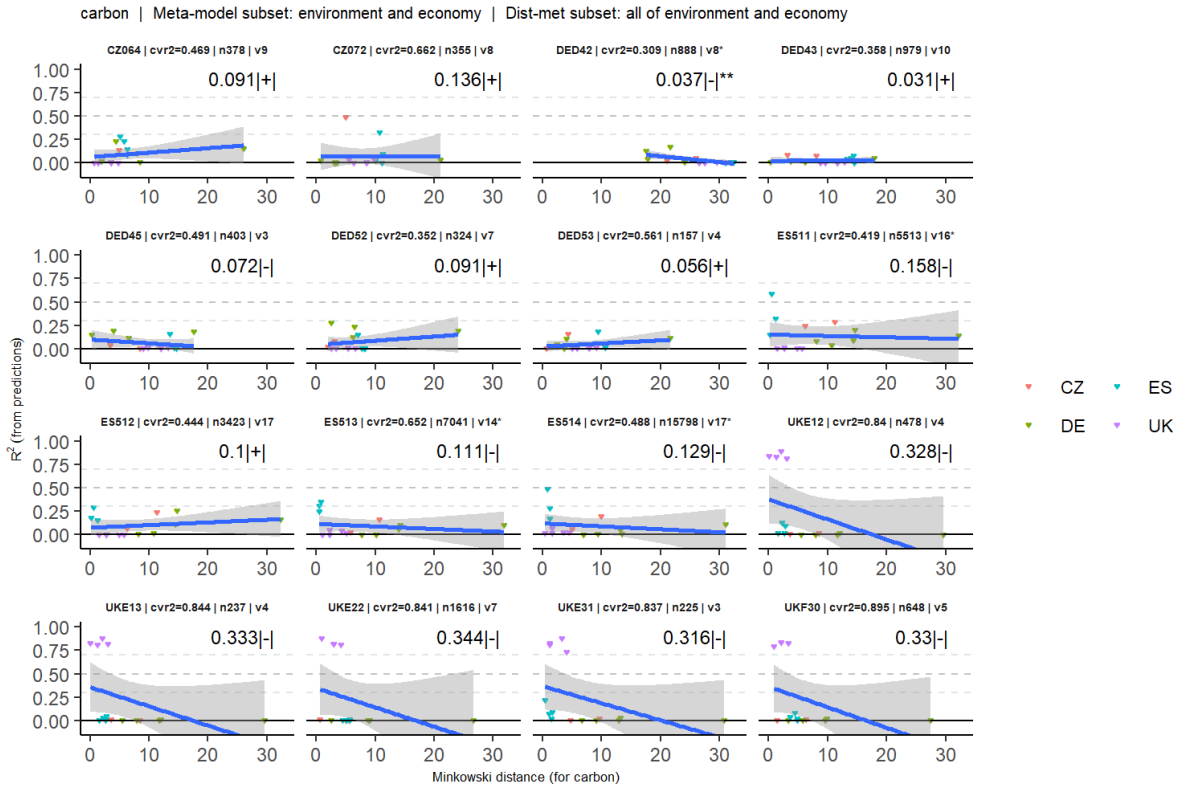

Figure 23: *Transferability diagrams for the* ***carbon*** *ecosystem service based on all* ***environmental*** *and* ***economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

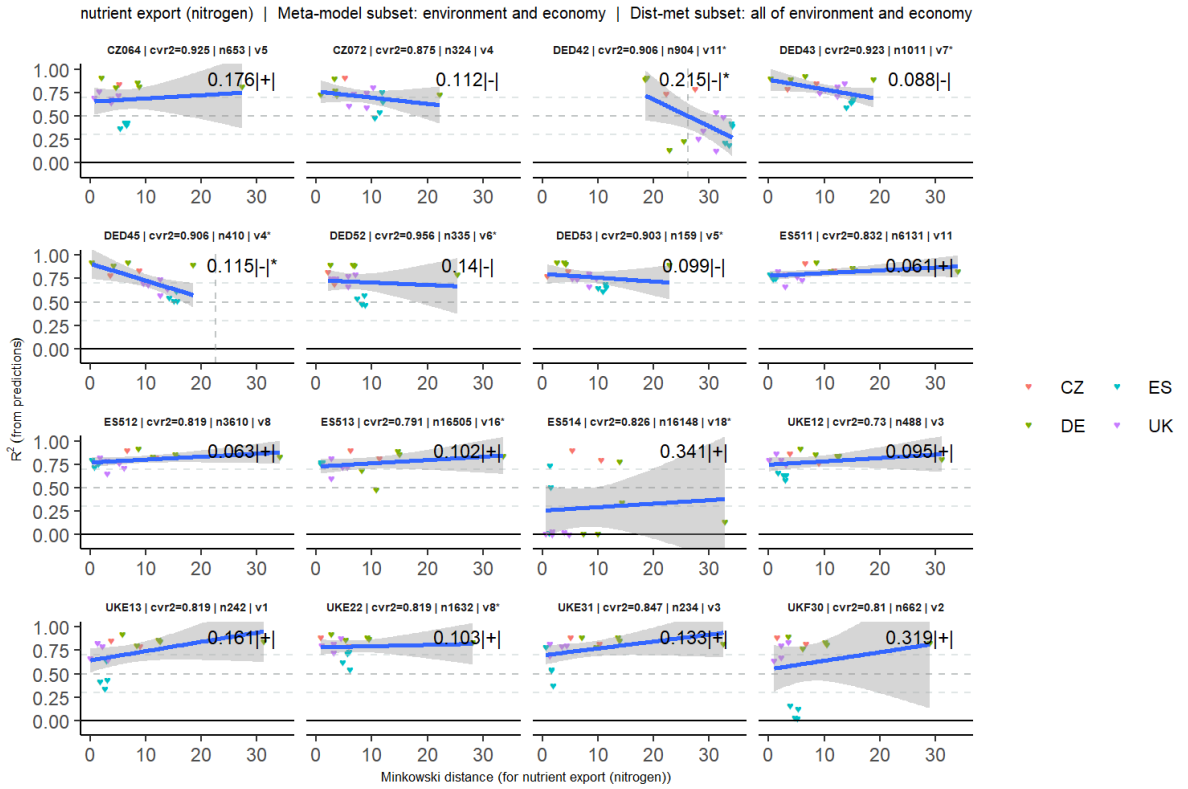

Figure 24: *Transferability diagrams for the* ***nitrogen (nutrient)*** *ecosystem service based on* ***all environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

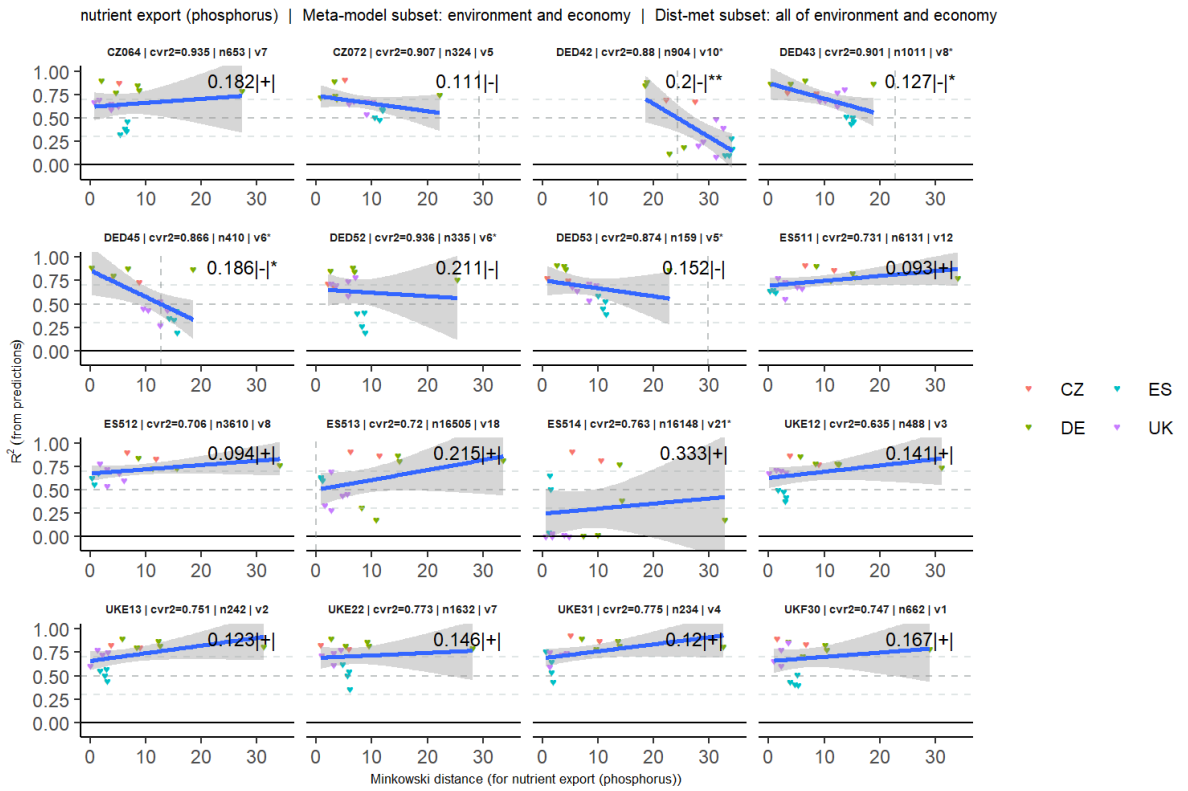

Figure 25: *Transferability diagrams for the* ***phosphorus (nutrient)*** *ecosystem service based on* ***all environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

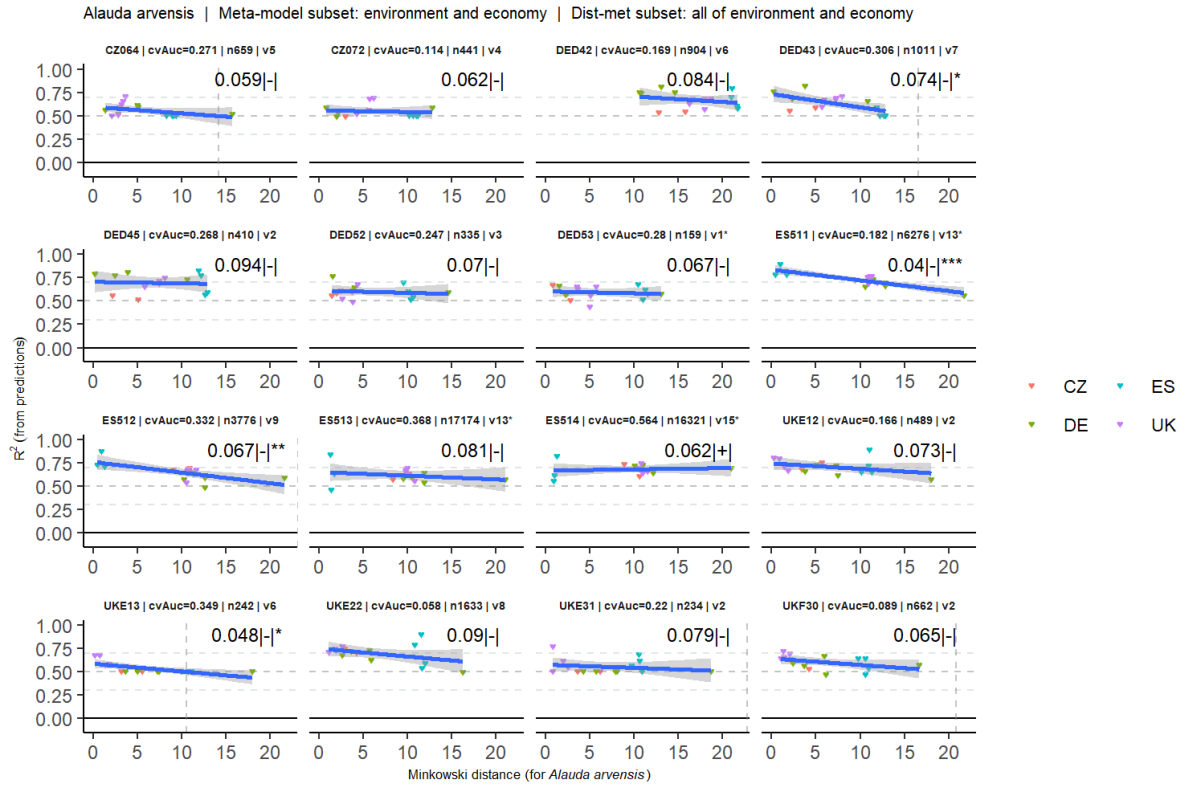

Figure 26: *Transferability diagrams for the* ***biodiversity (Alauda arvensis)*** *ecosystem service based on* ***all environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

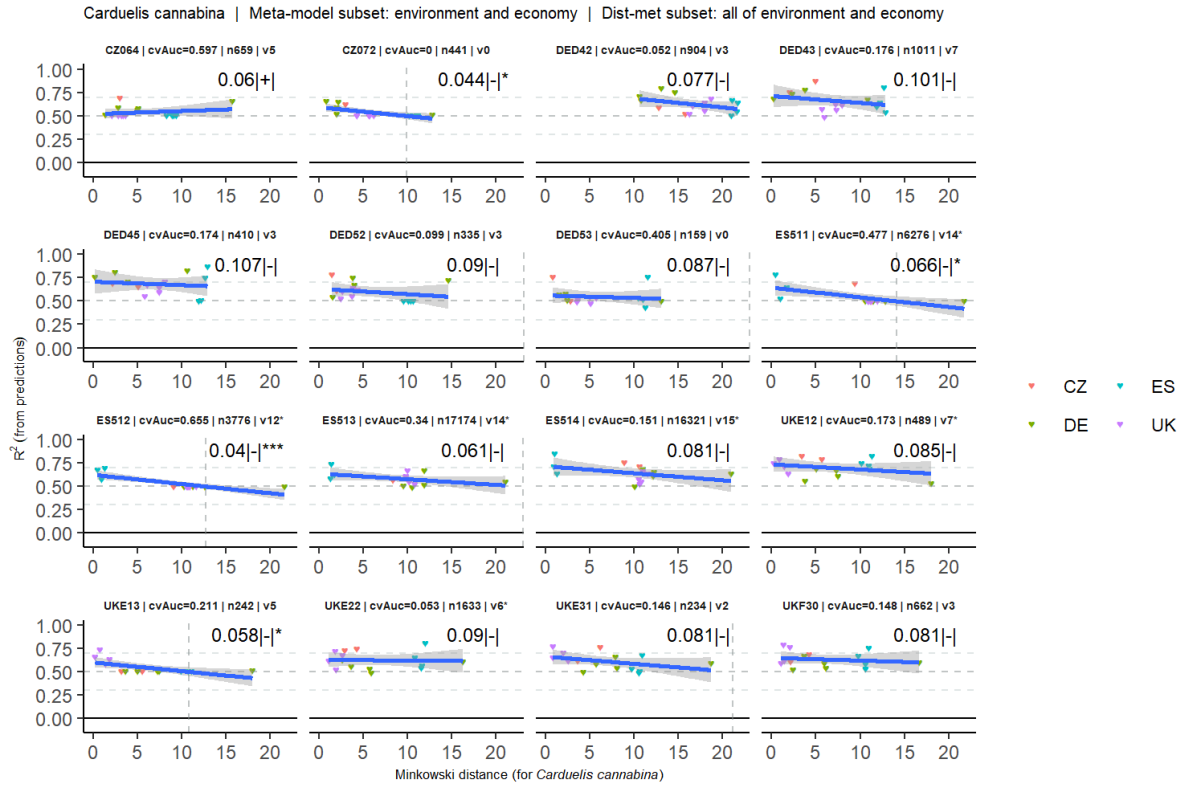

Figure 27: *Transferability diagrams for the* ***biodiversity (Carduelis cannabina)*** *ecosystem service based on* ***all environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

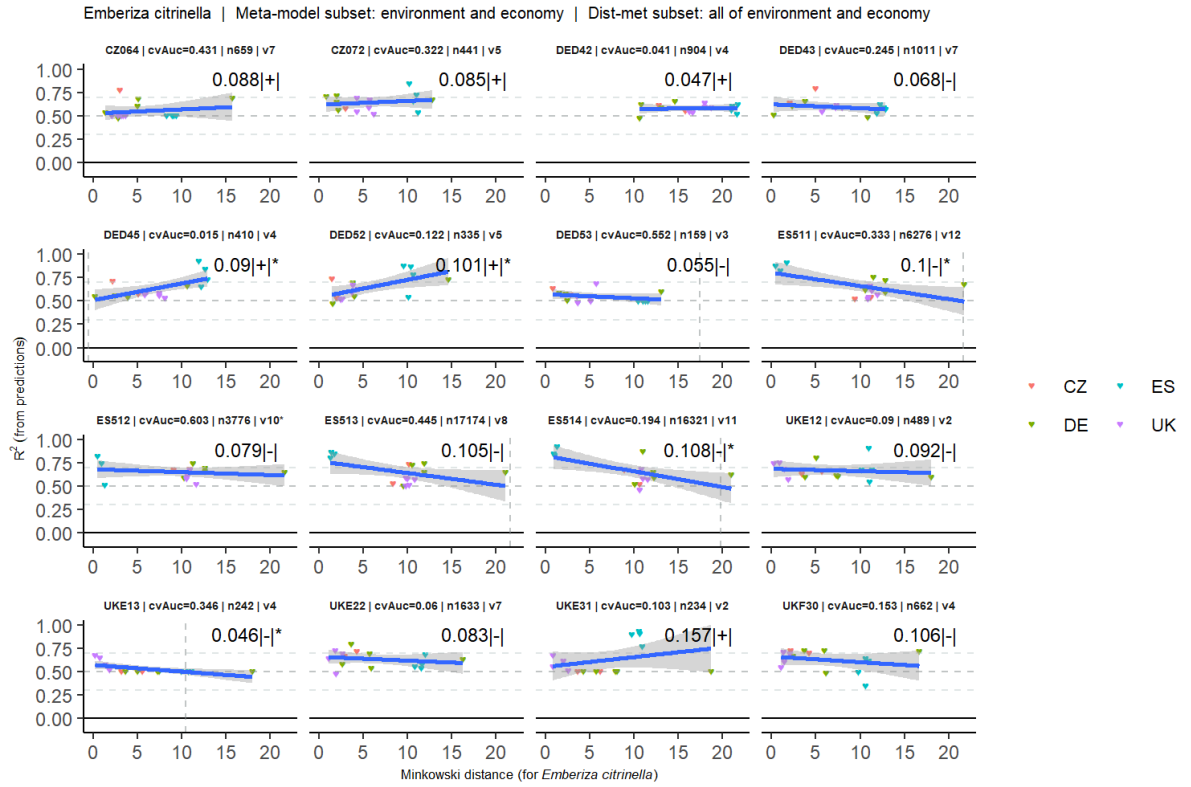

Figure 28: *Transferability diagrams for the* ***biodiversity (Emberiza citrinella)*** *ecosystem service based on* ***all environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

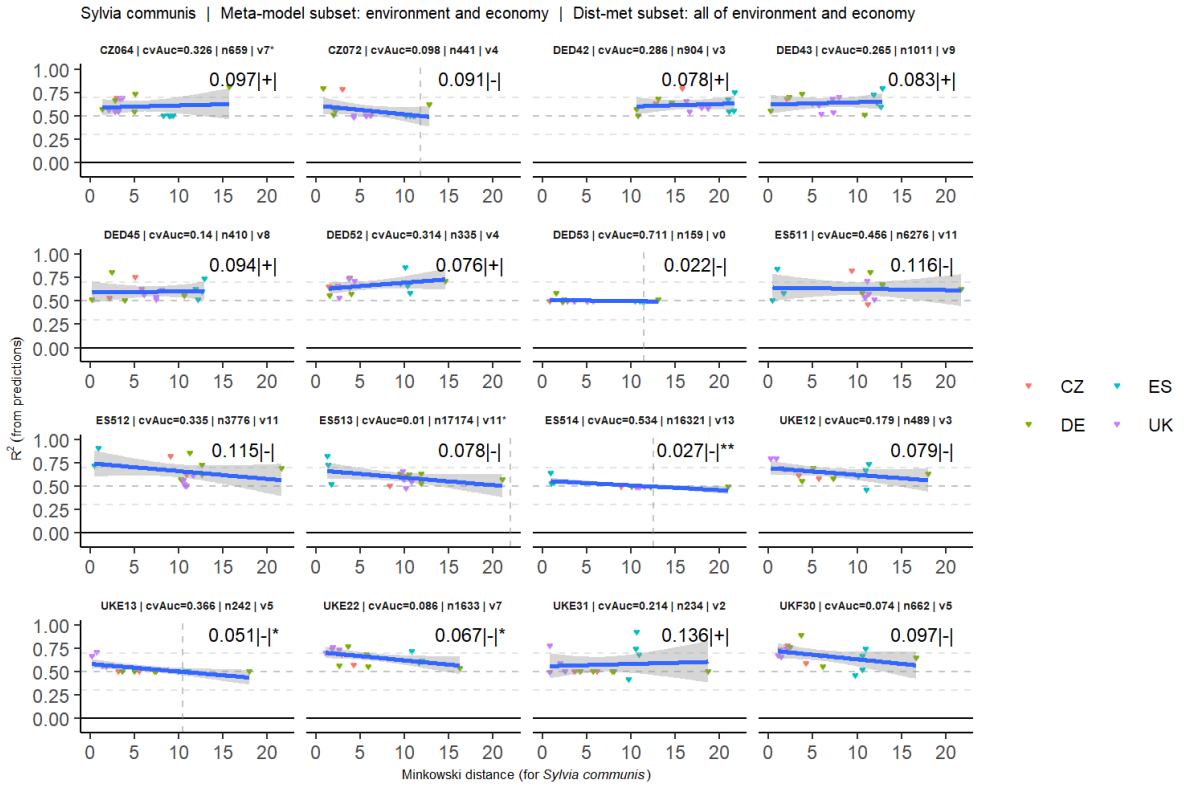

Figure 29: *Transferability diagrams for the* ***biodiversity (Sylvia communis)*** *ecosystem service based on* ***all environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

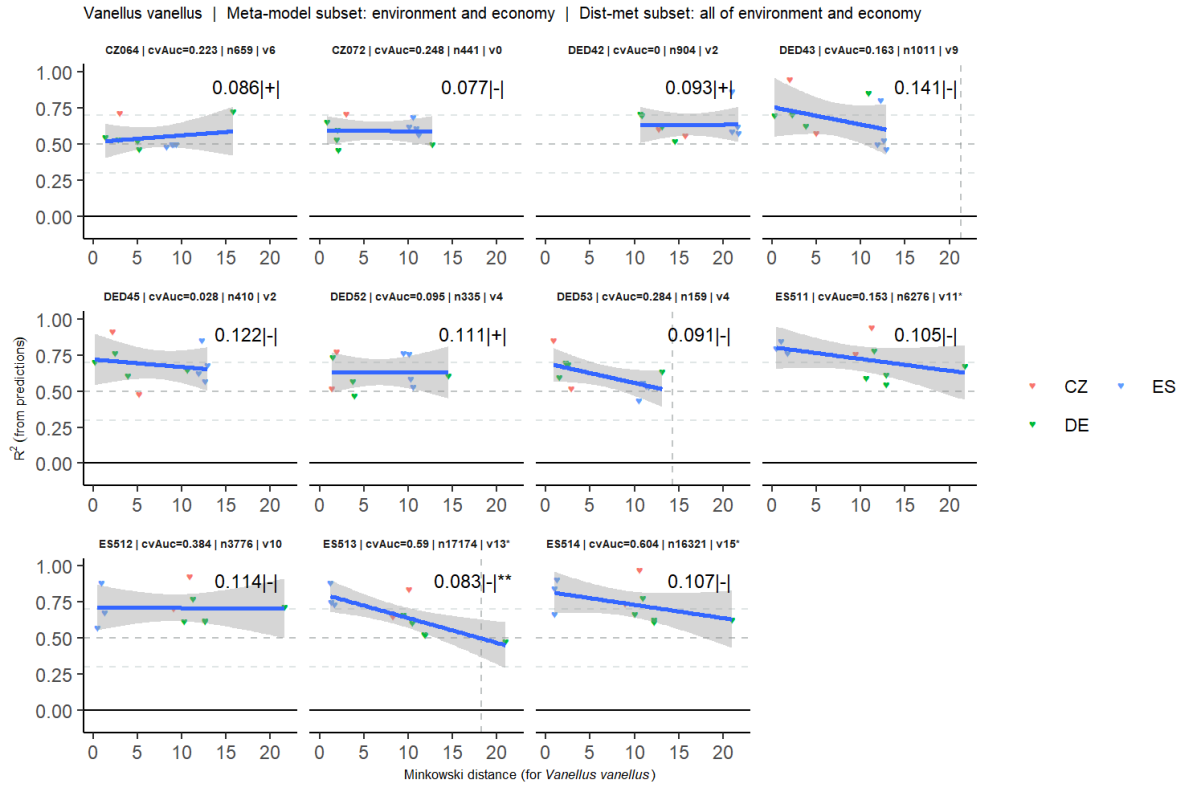

Figure 30: *Transferability diagrams for the* ***biodiversity (Vanellus vanellus)*** *ecosystem service based on* ***all environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

3.5 Transferability diagrams based on significant env. and economic variables

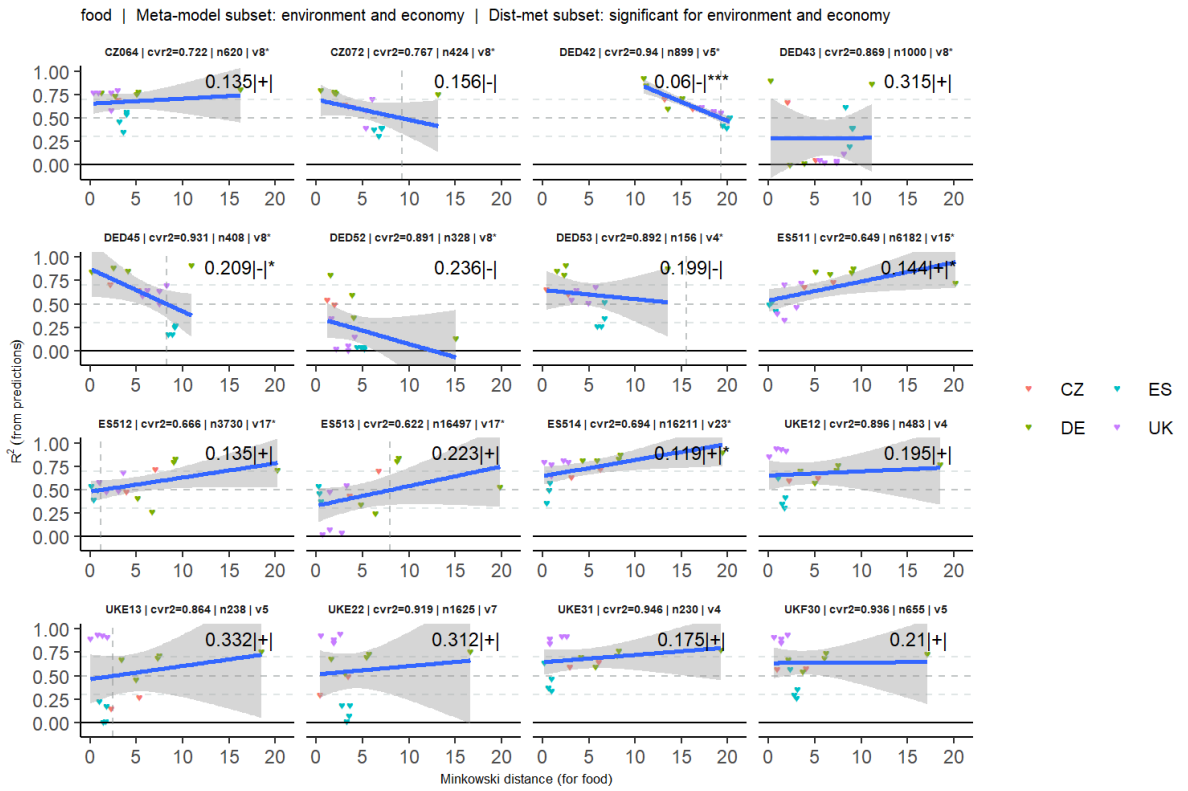

Figure 31: *Transferability diagrams for the* ***food*** *ecosystem service based on* ***significant environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

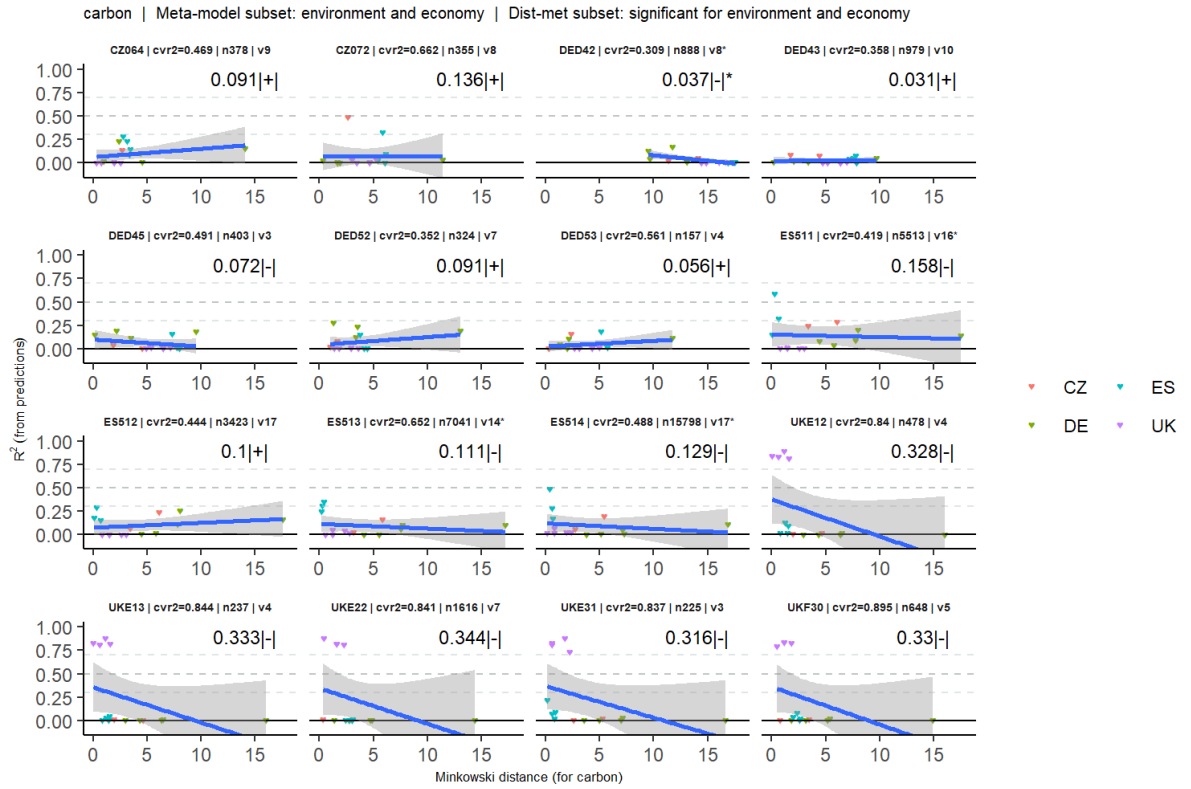

Figure 32: *Transferability diagrams for the* ***carbon*** *ecosystem service based on* ***significant environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

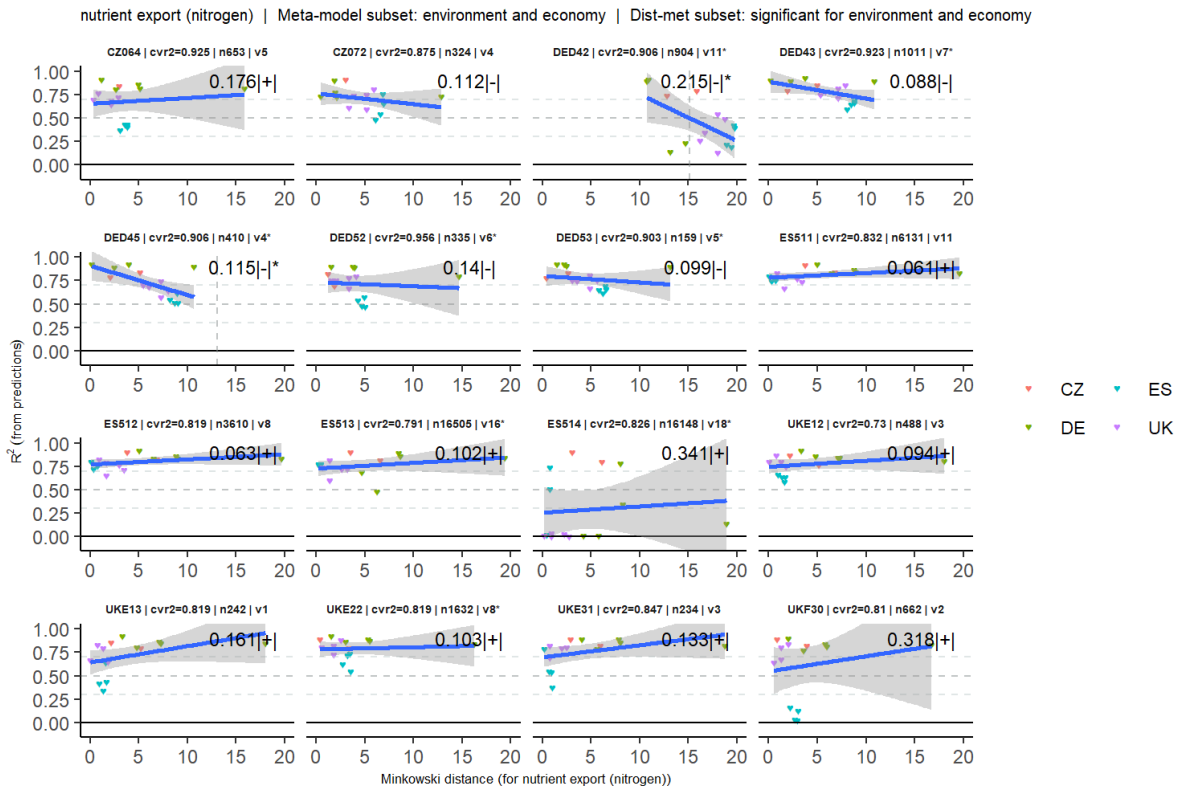

Figure 33: *Transferability diagrams for the* ***nitrogen (nutrient)*** *ecosystem service based on* ***significant environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

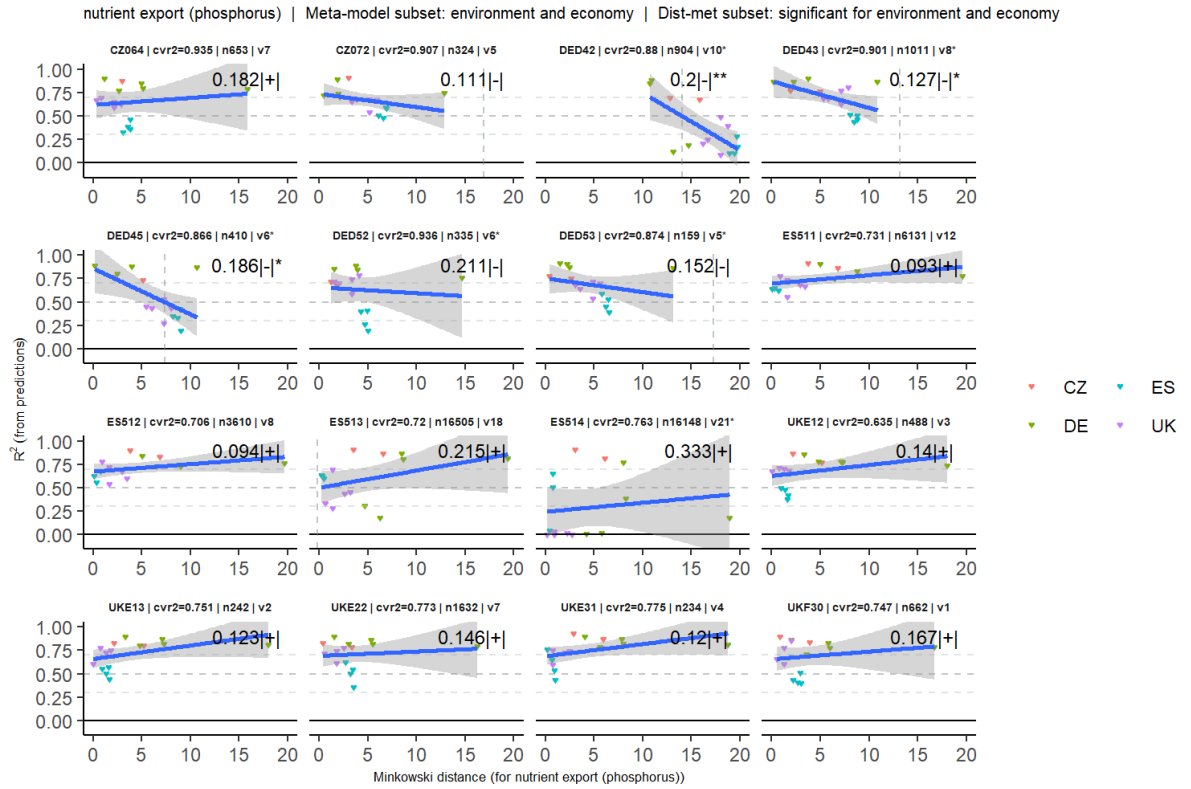

Figure 34: *Transferability diagrams for the* ***phosphorus (nutrient)*** *ecosystem service based on* ***significant environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

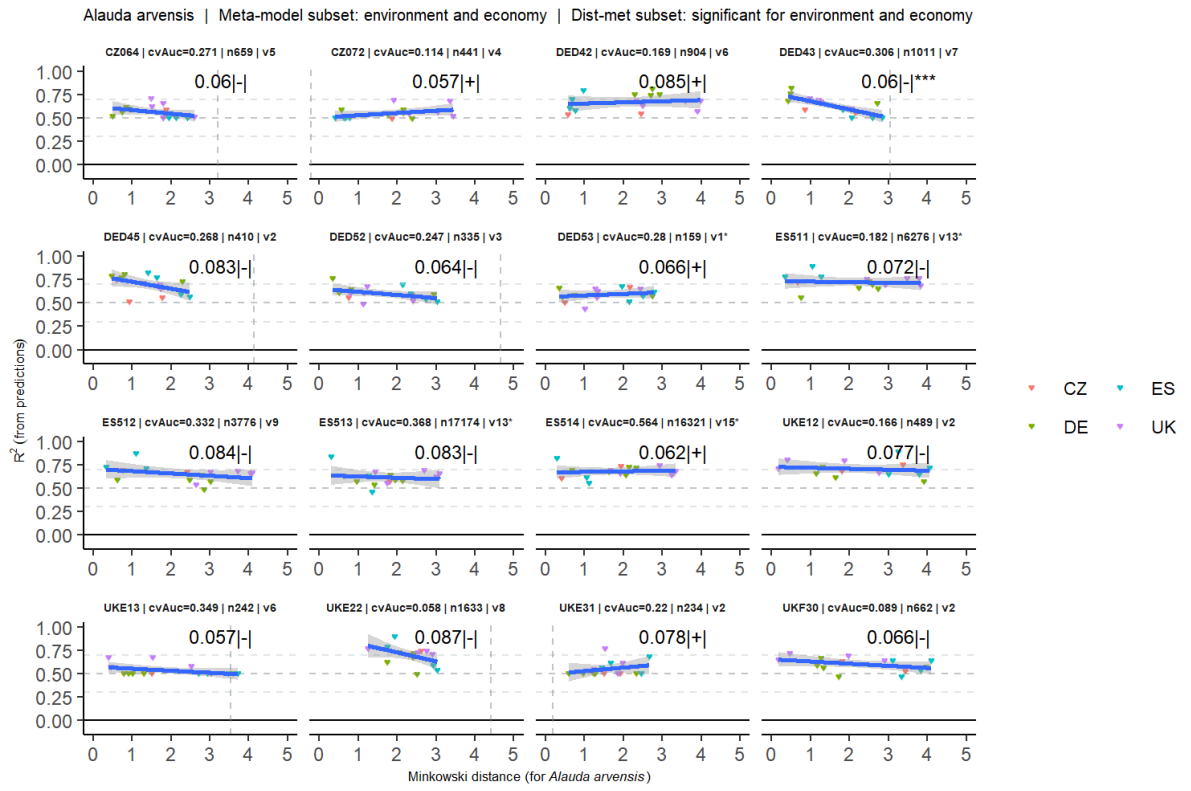

Figure 35: *Transferability diagrams for the* ***biodiversity (Alauda arvensis)*** *ecosystem service based on* ***significant environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

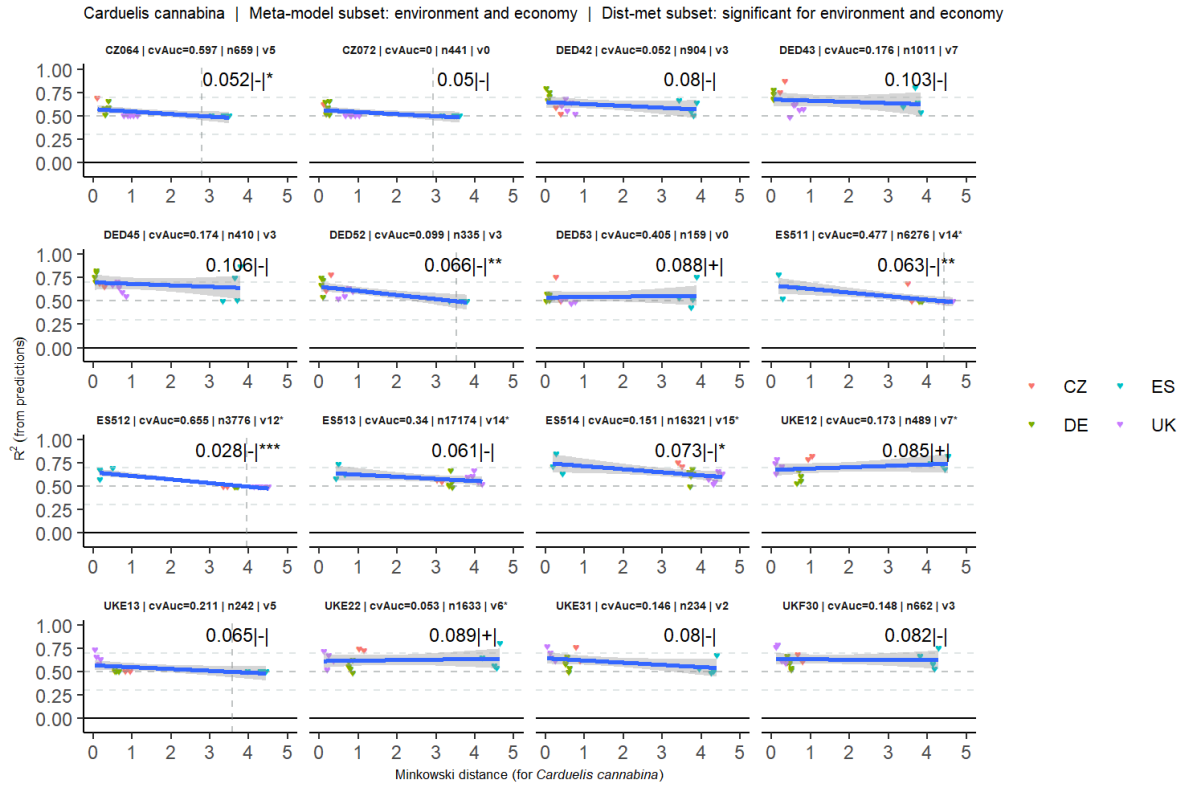

Figure 36: *Transferability diagrams for the* ***biodiversity (Carduelis cannabina)*** *ecosystem service based on* ***significant environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

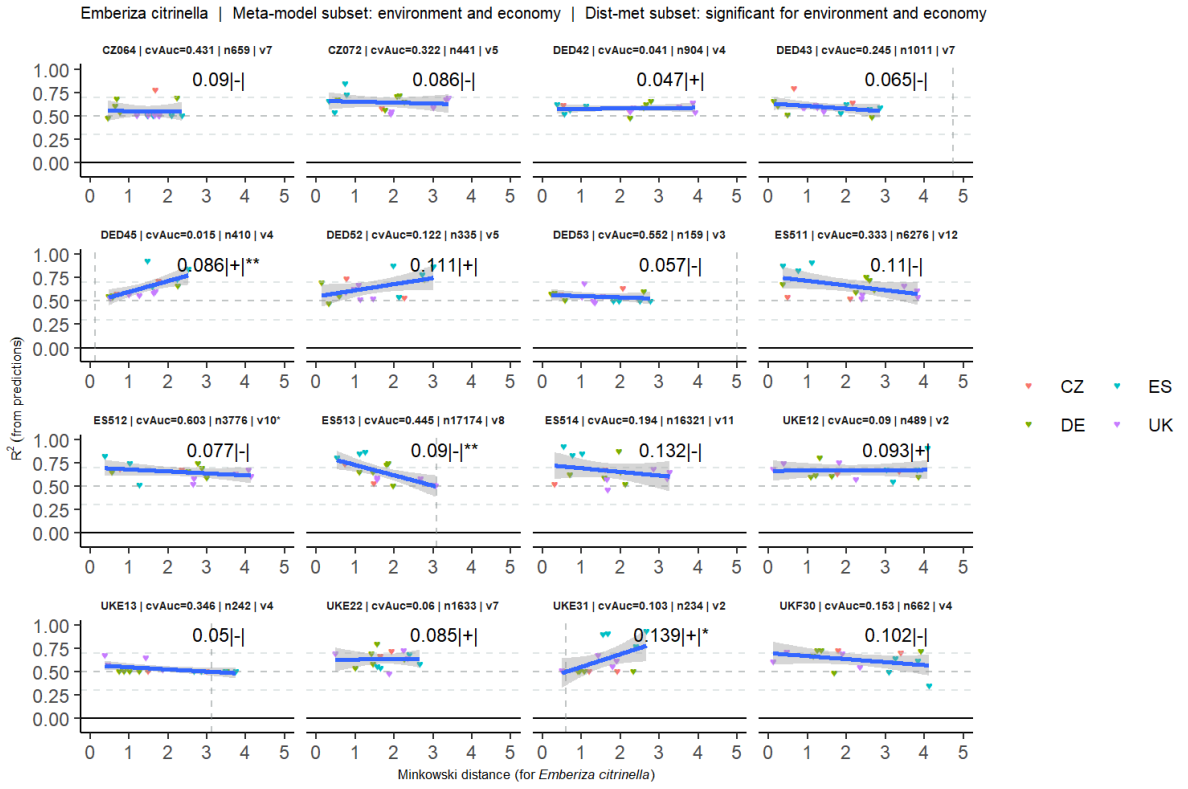

Figure 37: *Transferability diagrams for the* ***biodiversity (Emberiza citrinella)*** *ecosystem service based on* ***significant environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

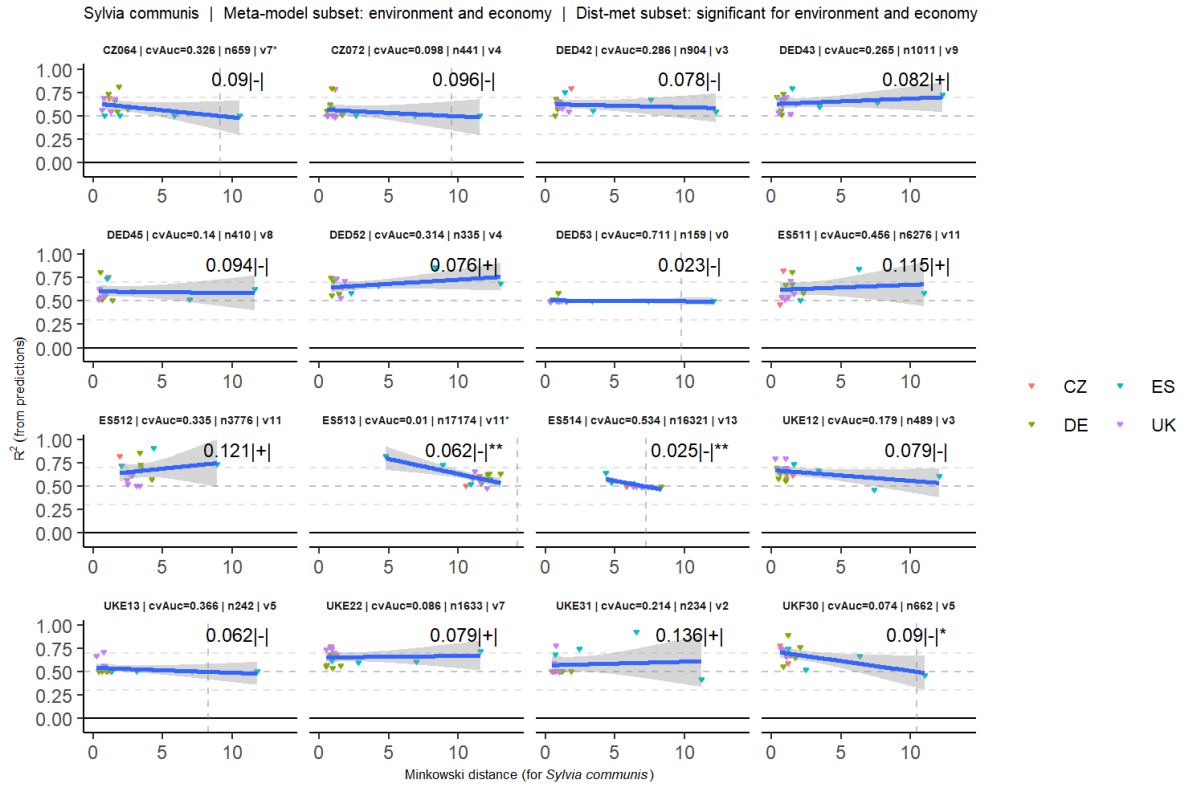

Figure 38: *Transferability diagrams for the* ***biodiversity (Sylvia communis)*** *ecosystem service based on* ***significant environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

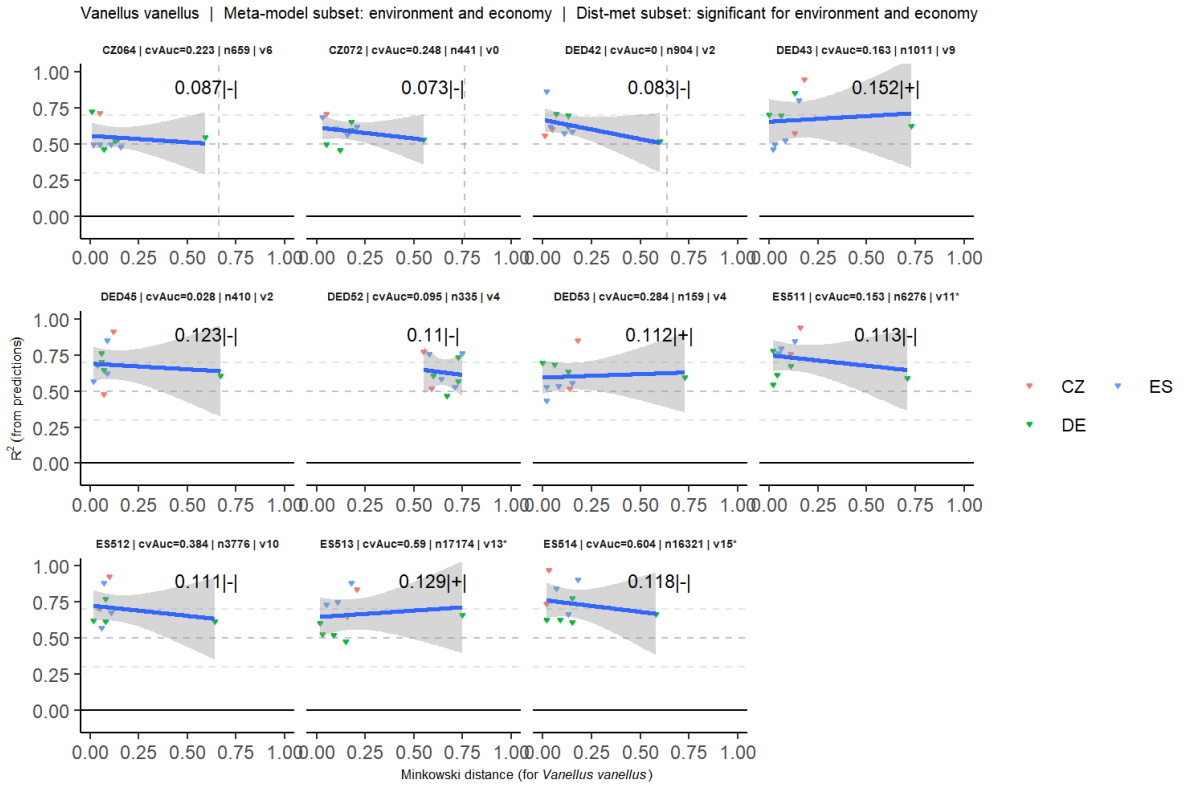

Figure 39: *Transferability diagrams for the* ***biodiversity (Vanellus vanellus)*** *ecosystem service based on* ***significant environmental and economic*** *variables. See Figure 4 for a full explanation of the diagrams.*

4. Maps of transferability

In this section, we present a number of transferability maps based on the results of the previous sections (see Transferability diagrams and Setting transferability thresholds sections for details). Based on the transferability diagrams that were selected (i.e. met the suitability criteria), we used the Minkowski distance threshold corresponding to an R^2 value of 0.5 to identify suitable and unsuitable (above and the below threshold, respectively) NUTS3 regions in terms of transferability. The results were plotted separately for each transferability diagram and then combined using a spatial overlay. The resulting maps (see Figures 24-43) show the NUTS3 regions, showing values from 0 (no transferability), through 1 (confirmed transferability) to a value representing the sum of the overlapping transferability maps. We have produced transferability maps for all ESS when using environmental variables, and separately for those based on environmental and economic variables. If there is no map corresponding to the above transferability diagrams that is because, for that ESS and distance metric, the criteria were not met on any of the graphs, and therefore the model is not transferable (see Figure 40 with extended legend for the full description of how to read the transferability maps - Figures 40-75). In the case of the biodiversity models, the

transferability potential of different species should also be constrained by their known ranges. This is currently not shown on the maps.

4.1 Maps based on all environmental variables

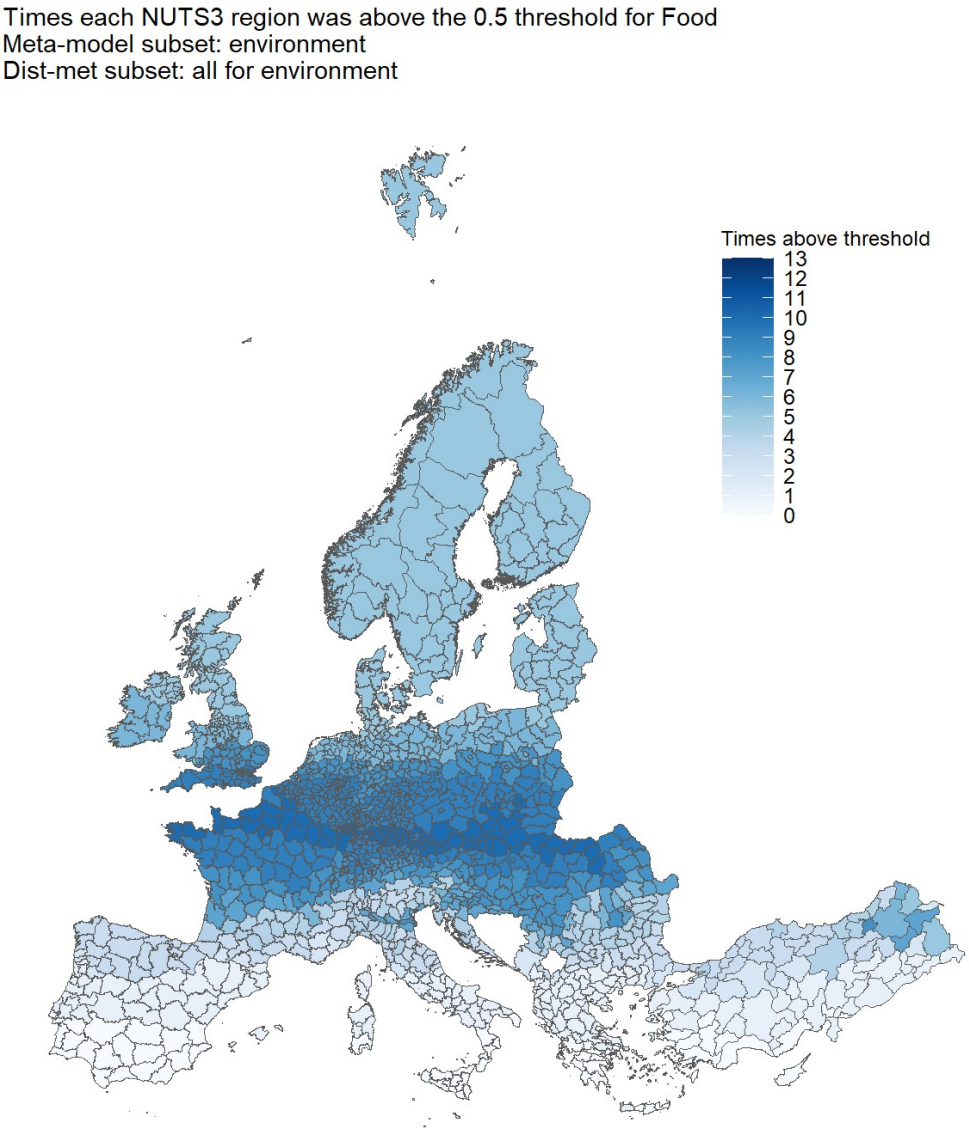

Figure 40: *Transferability map for the* ***food*** *ecosystem service based on* ***all environmental*** *variables. The 'times above threshold' value represents how many of the transferability graphs (of 19 in this case) meet certain criteria, i.e. the threshold, and could therefore be used to help inform transferability. The criteria were that the trend on a graph surpassed the 0.5 R^2 value of the y-axis, and that it had a significant decreasing trend.*

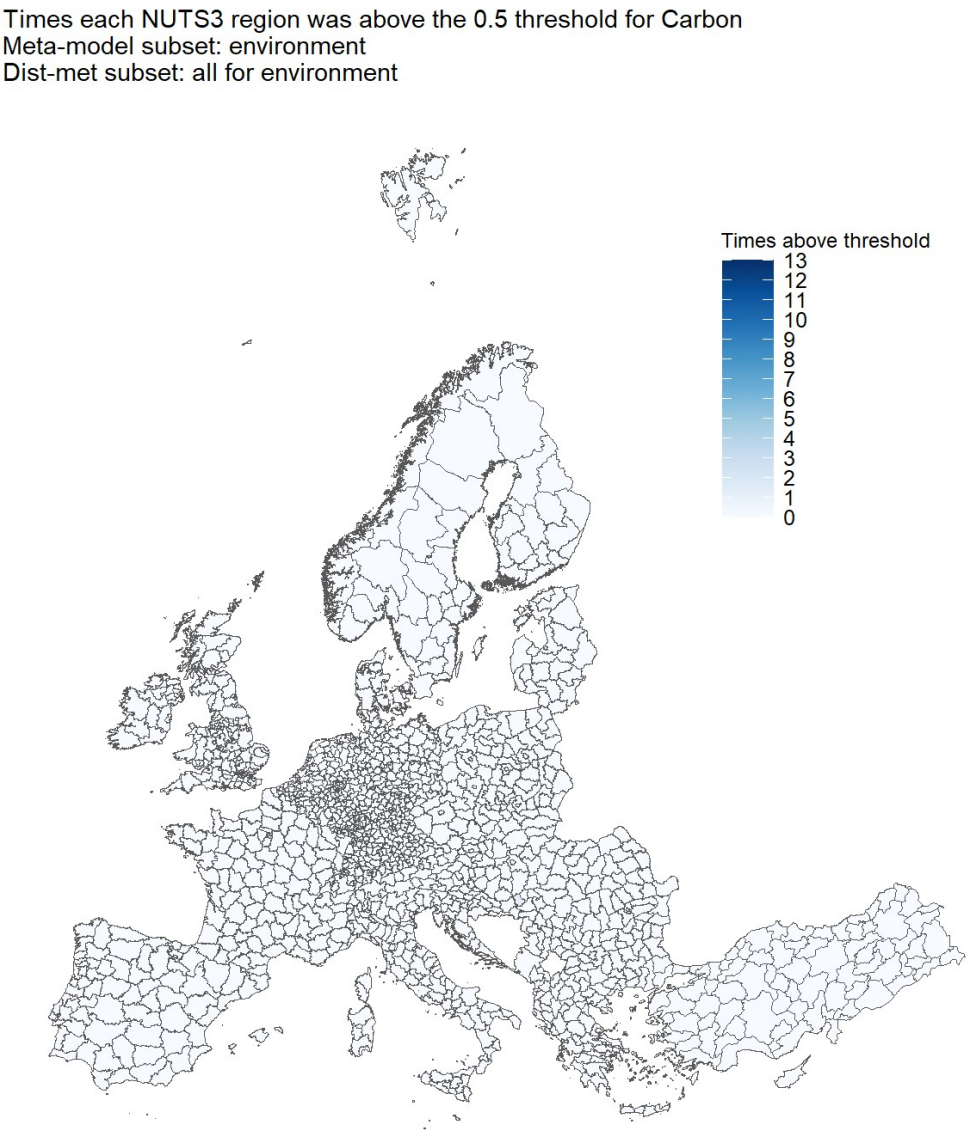

Figure 41: *Transferability map for the* ***carbon*** *ecosystem service based on* ***all environmental*** *variables.*

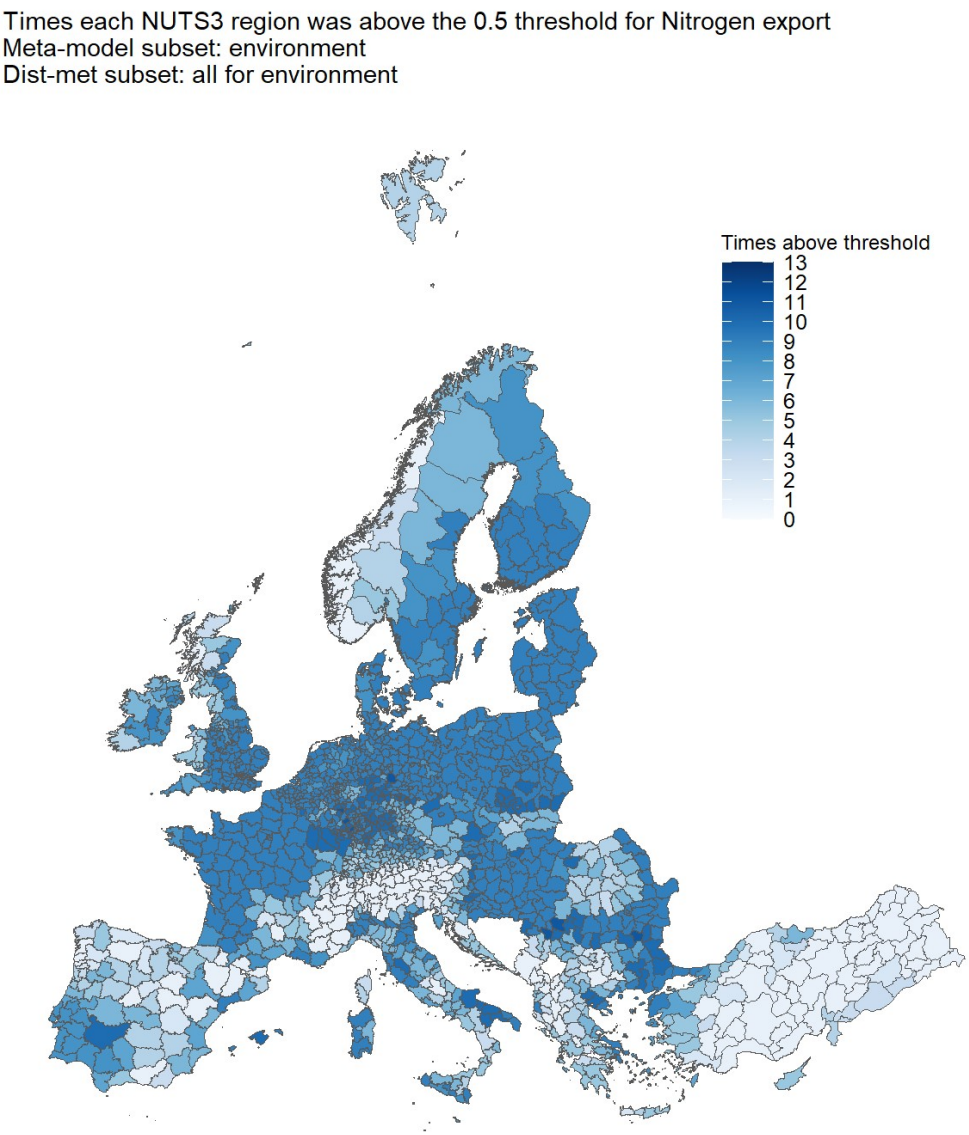

Figure 42: *Transferability map for the* ***nutrient (nitrogen)*** *ecosystem service based on* ***all environmental*** *variables.*

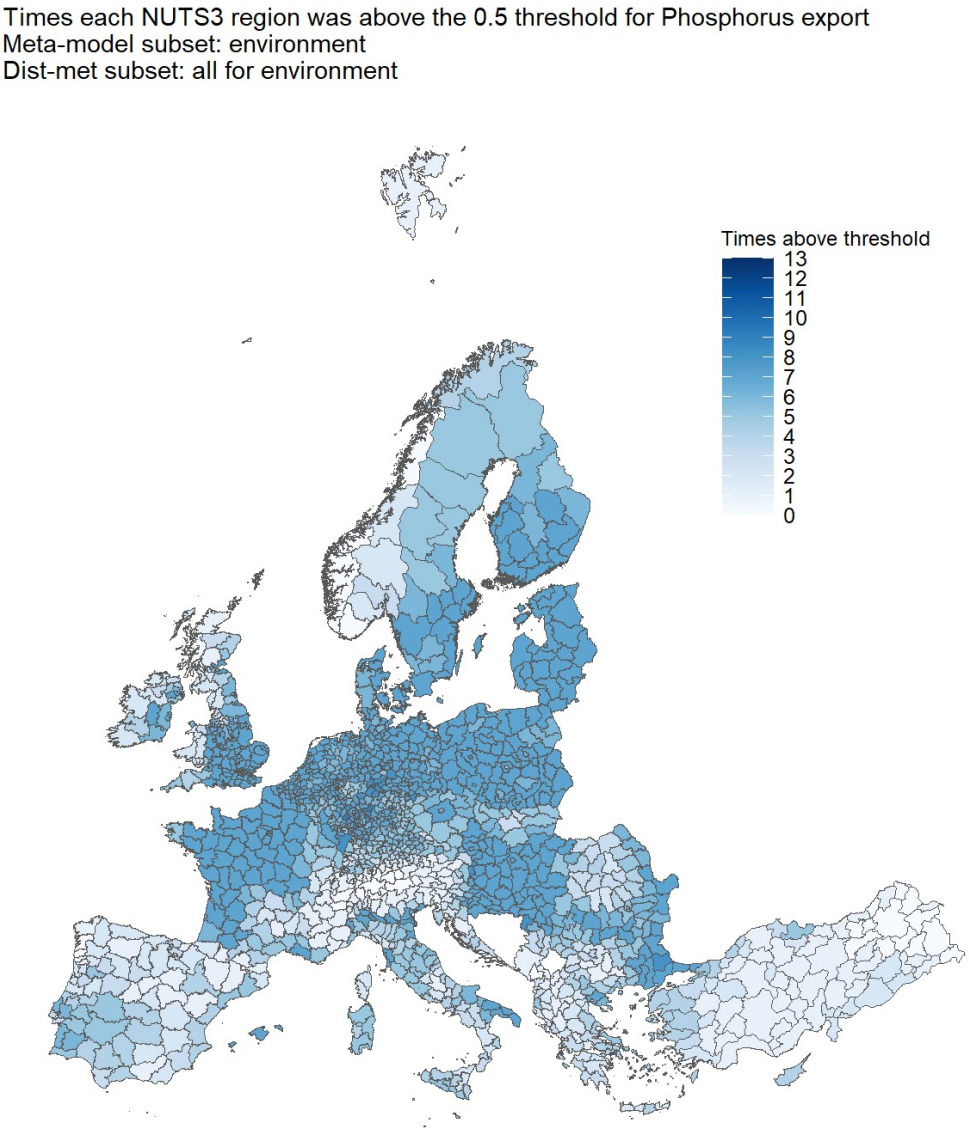

Figure 43: *Transferability map for the* ***nutrient (phosphorus)*** *ecosystem service based on* ***all environmental*** *variables.*

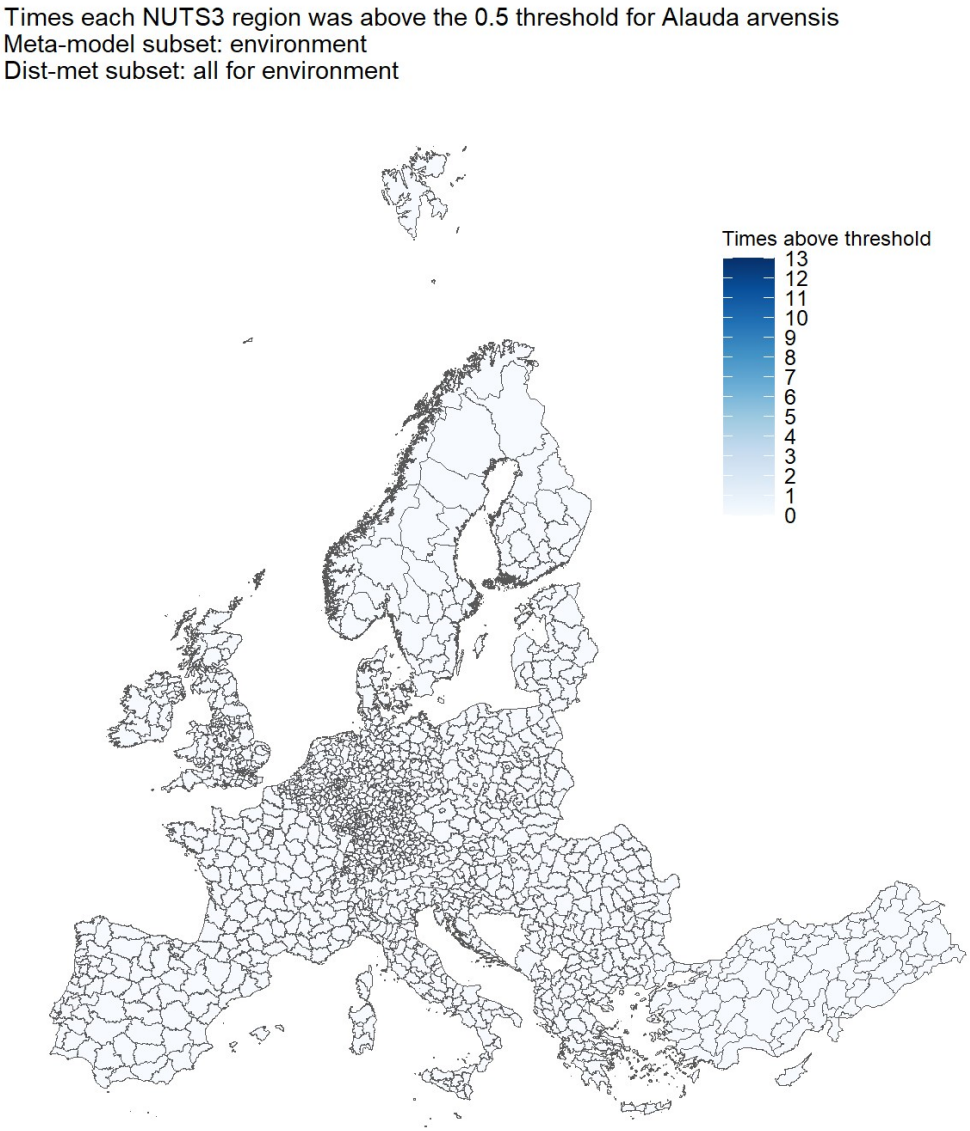

Figure 44: *Transferability map for the* ***biodiversity (Alauda arvensis)*** *ecosystem service based on* ***all environmental*** *variables.*

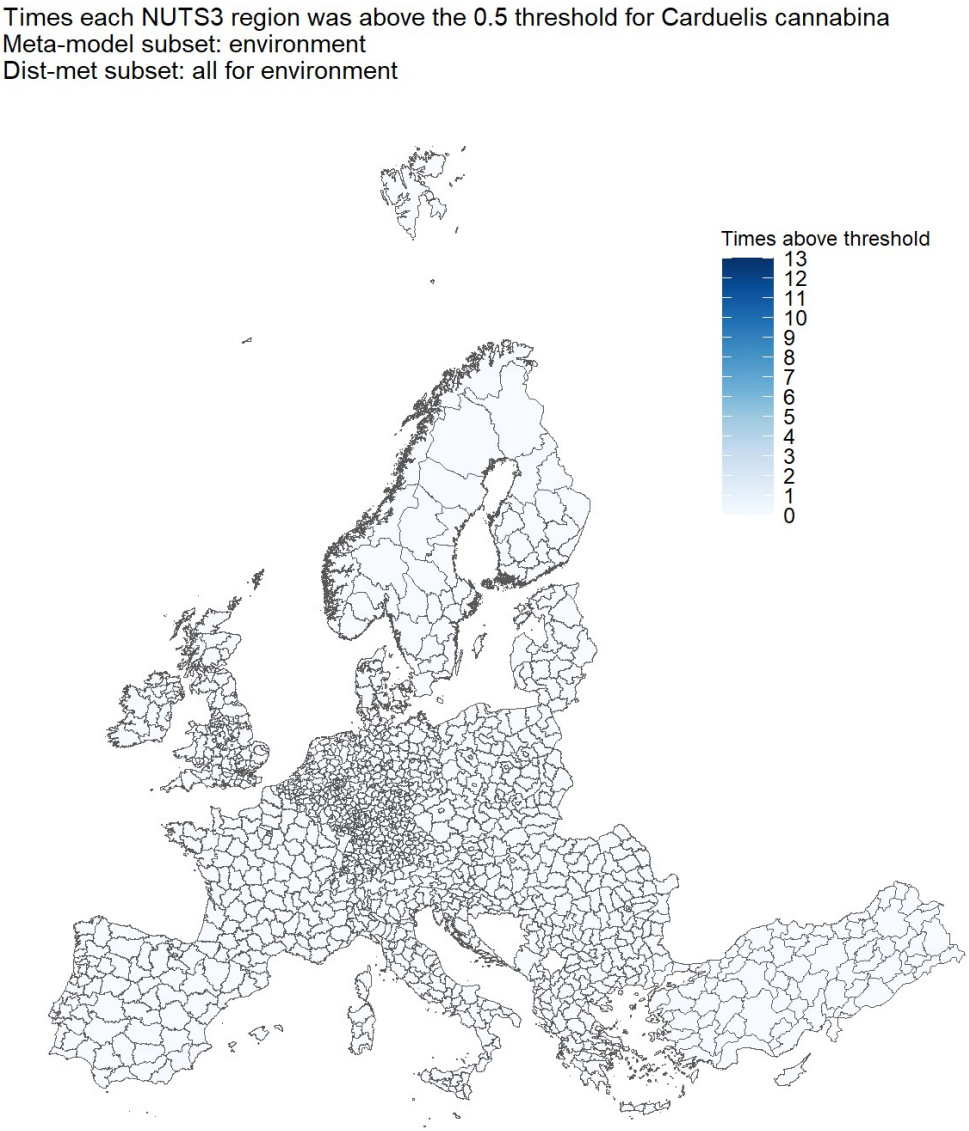

Figure 45: *Transferability map for the* ***biodiversity (Carduelis cannabina)*** *ecosystem service based on* ***all environmental*** *variables.*

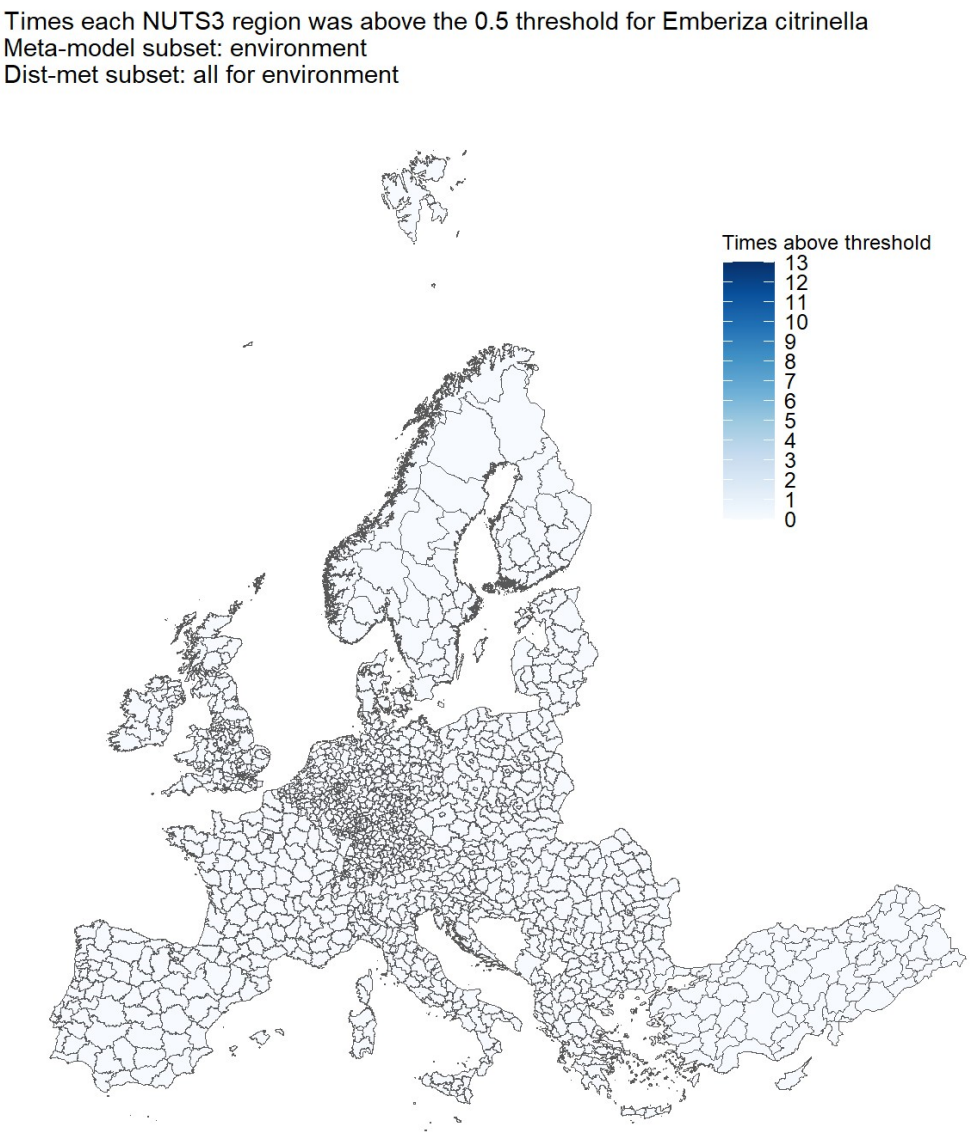

Figure 46: *Transferability map for the* ***biodiversity (Emberiza citrinella)*** *ecosystem service based on* ***all environmental*** *variables.*

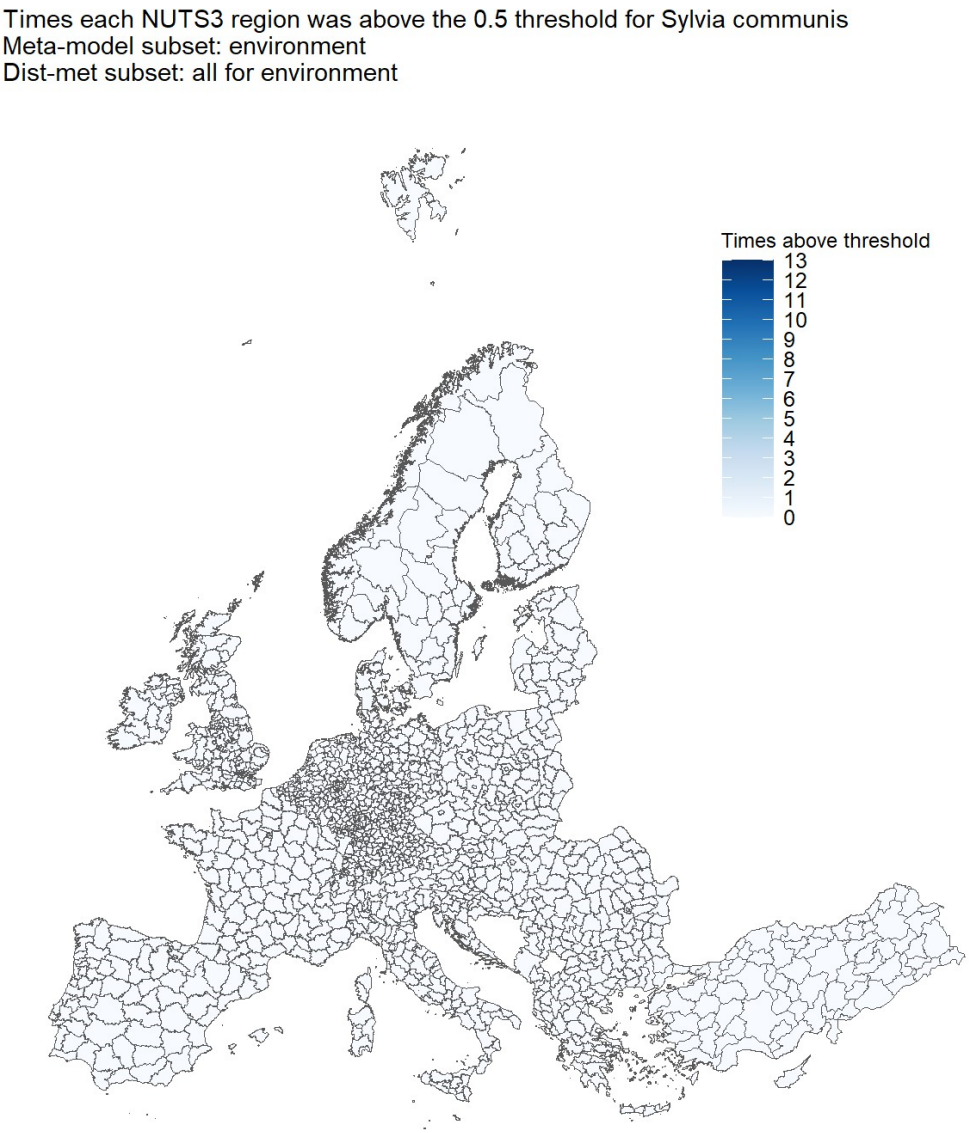

Figure 47: *Transferability map for the* ***biodiversity (Sylvia communis)*** *ecosystem service based on* ***all environmental*** *variables.*

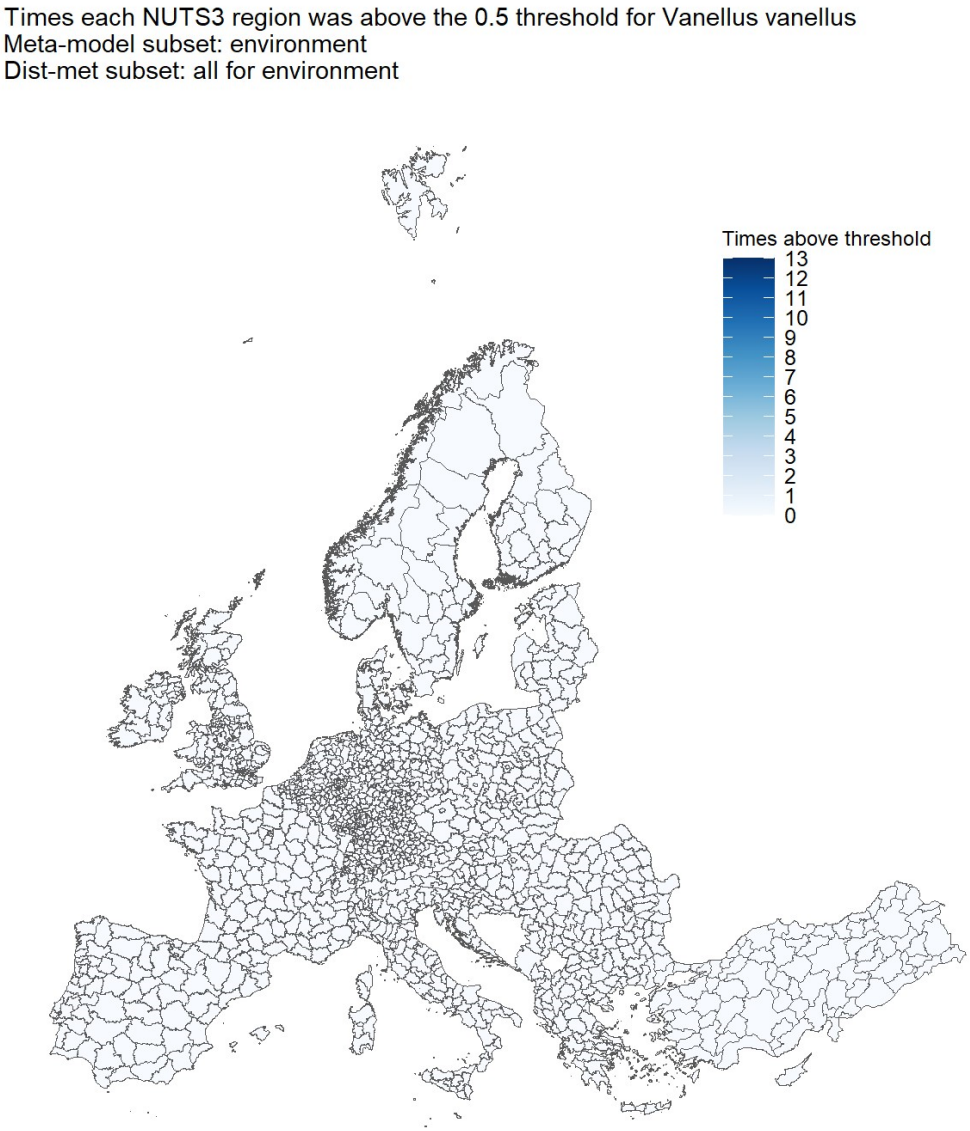

Figure 48: *Transferability map for the* ***biodiversity (Vanellus vanellus)*** *ecosystem service based on* ***all environmental*** *variables.*

4.2 Maps based on significant environmental variables

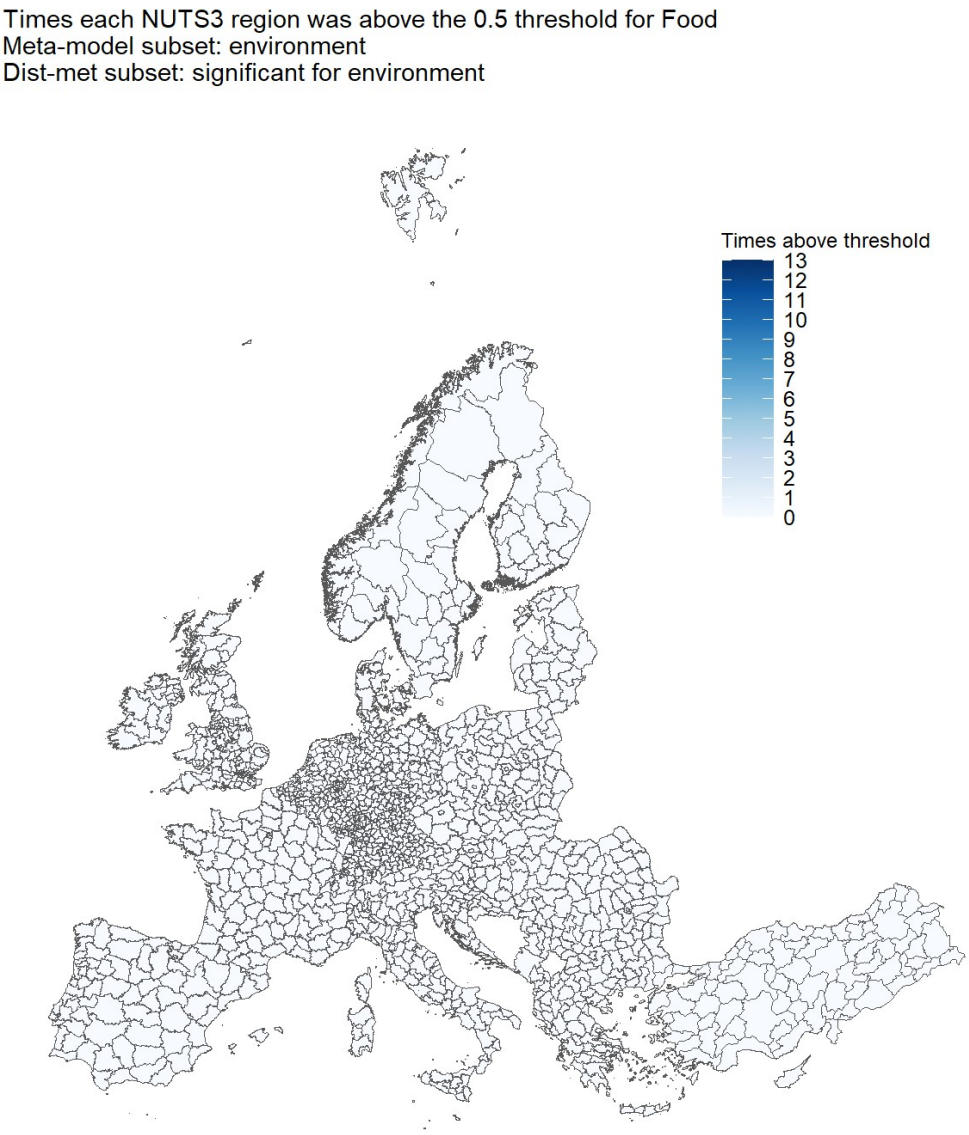

Figure 49: *Transferability map for the* ***food*** *ecosystem service based on* ***significant environmental*** *variables.*

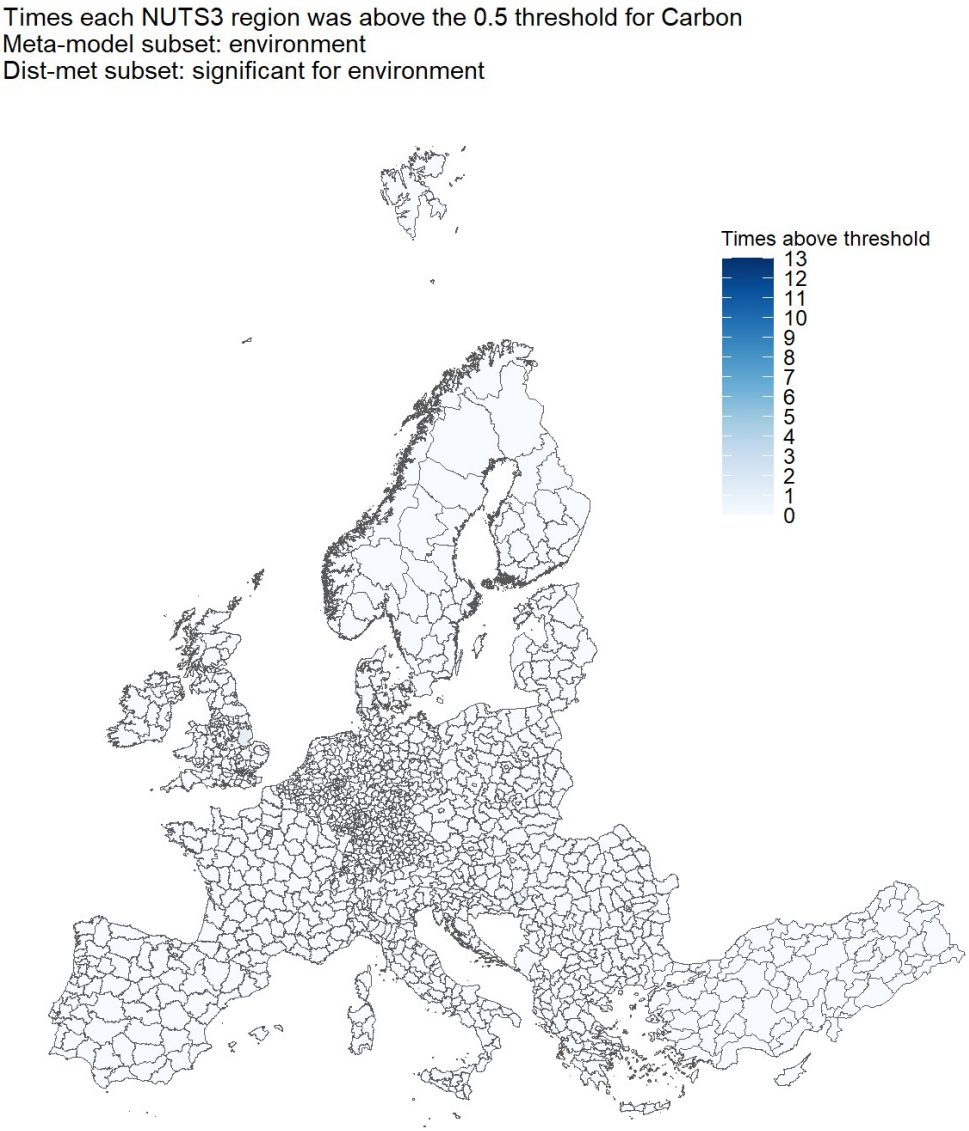

Figure 50: *Transferability map for the* ***carbon*** *ecosystem service based on* ***significant environmental*** *variables.*

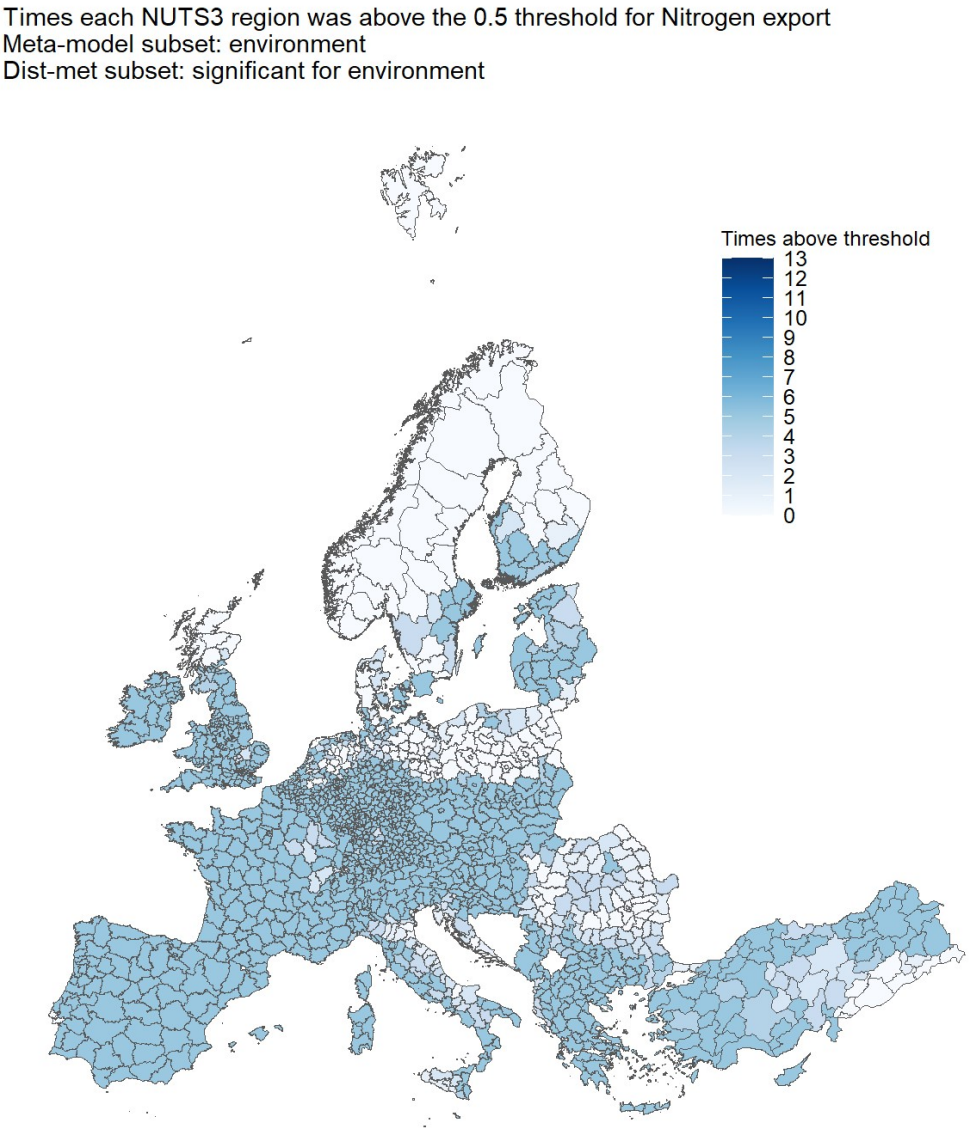

Figure 51: *Transferability map for the* ***nutrient (nitrogen)*** *ecosystem service based on* ***significant environmental*** *variables.*

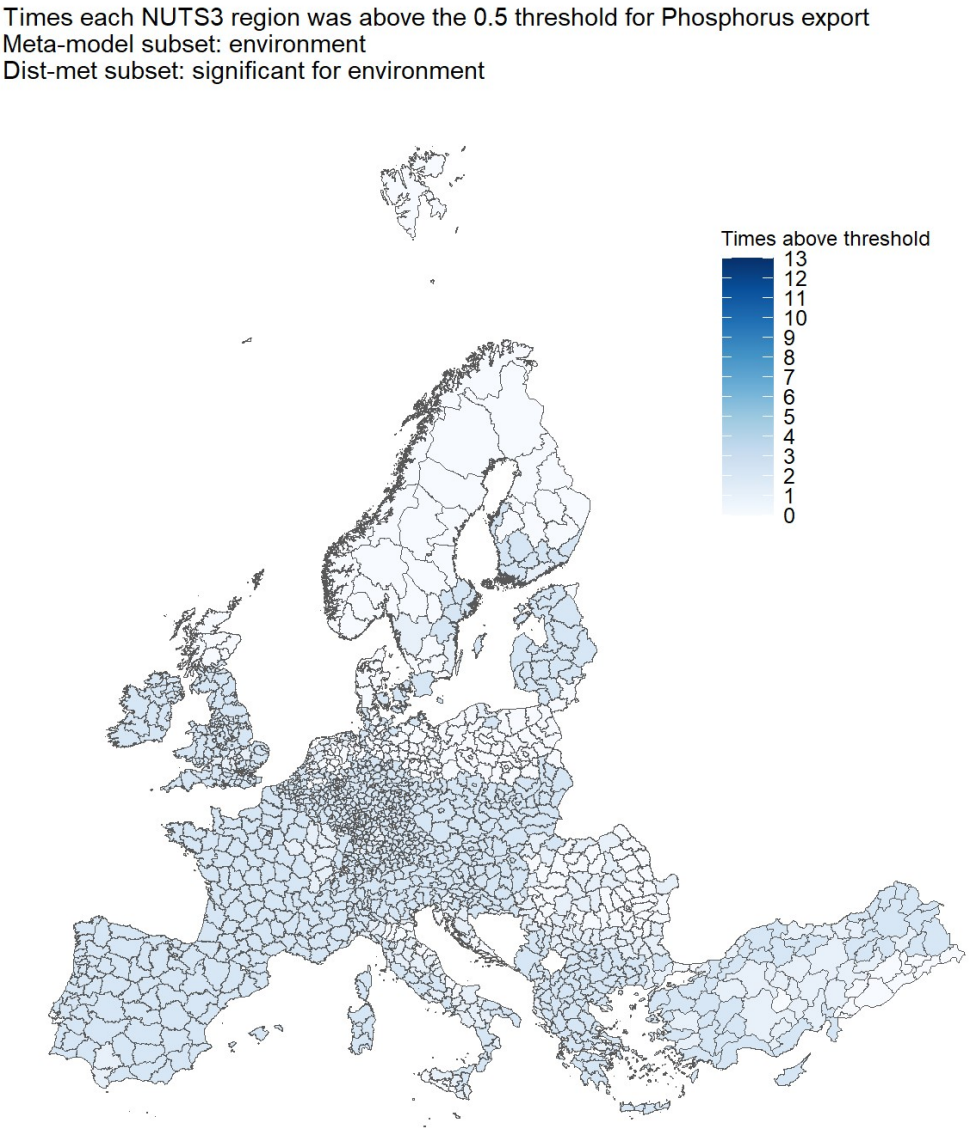

Figure 52: *Transferability map for the* ***nutrient (phosphorus)*** *ecosystem service based on* ***significant environmental*** *variables.*

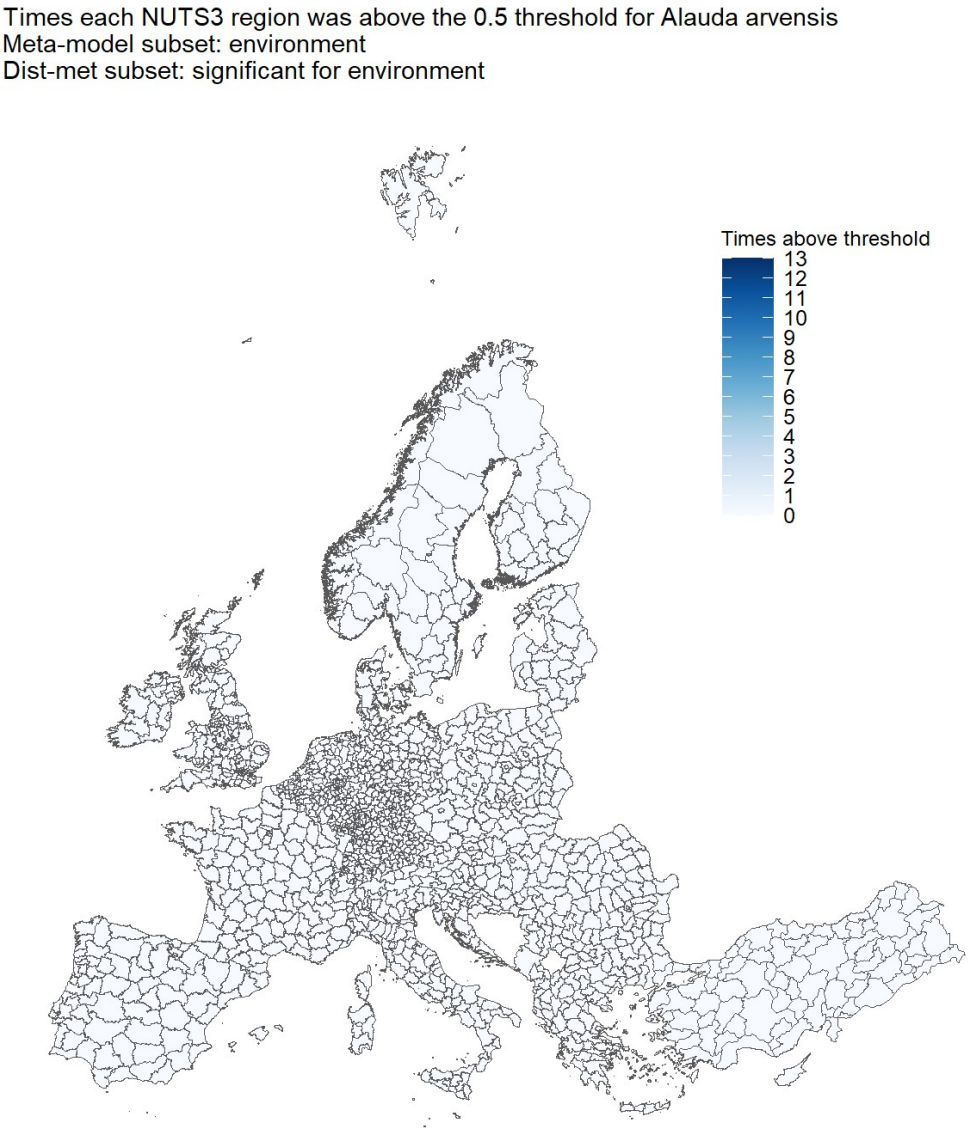

Figure 53: *Transferability map for the* ***biodiversity (Alauda arvensis)*** *ecosystem service based on* ***significant environmental*** *variables.*

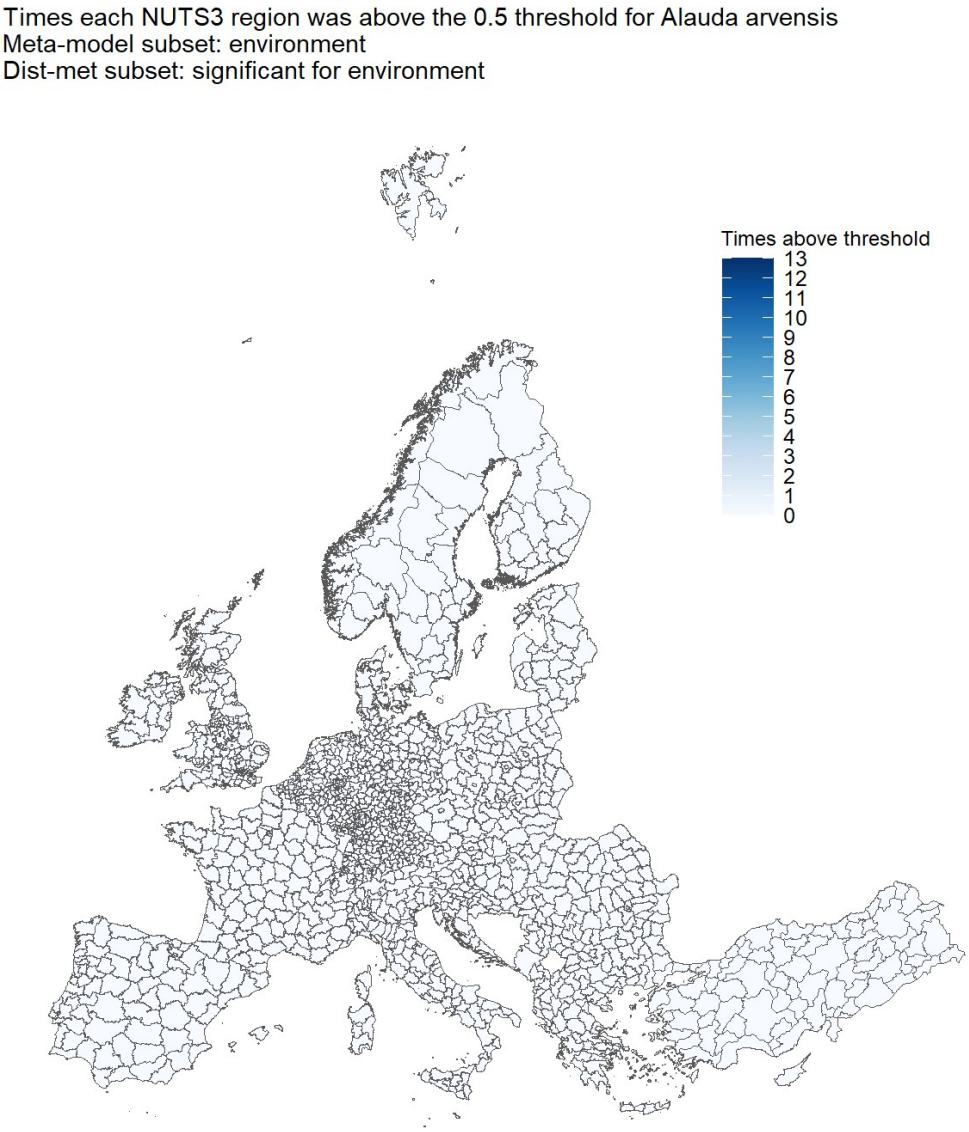

Figure 54: *Transferability map for the* ***biodiversity (Carduelis cannabina)*** *ecosystem service based on* ***significant environmental*** *variables.*

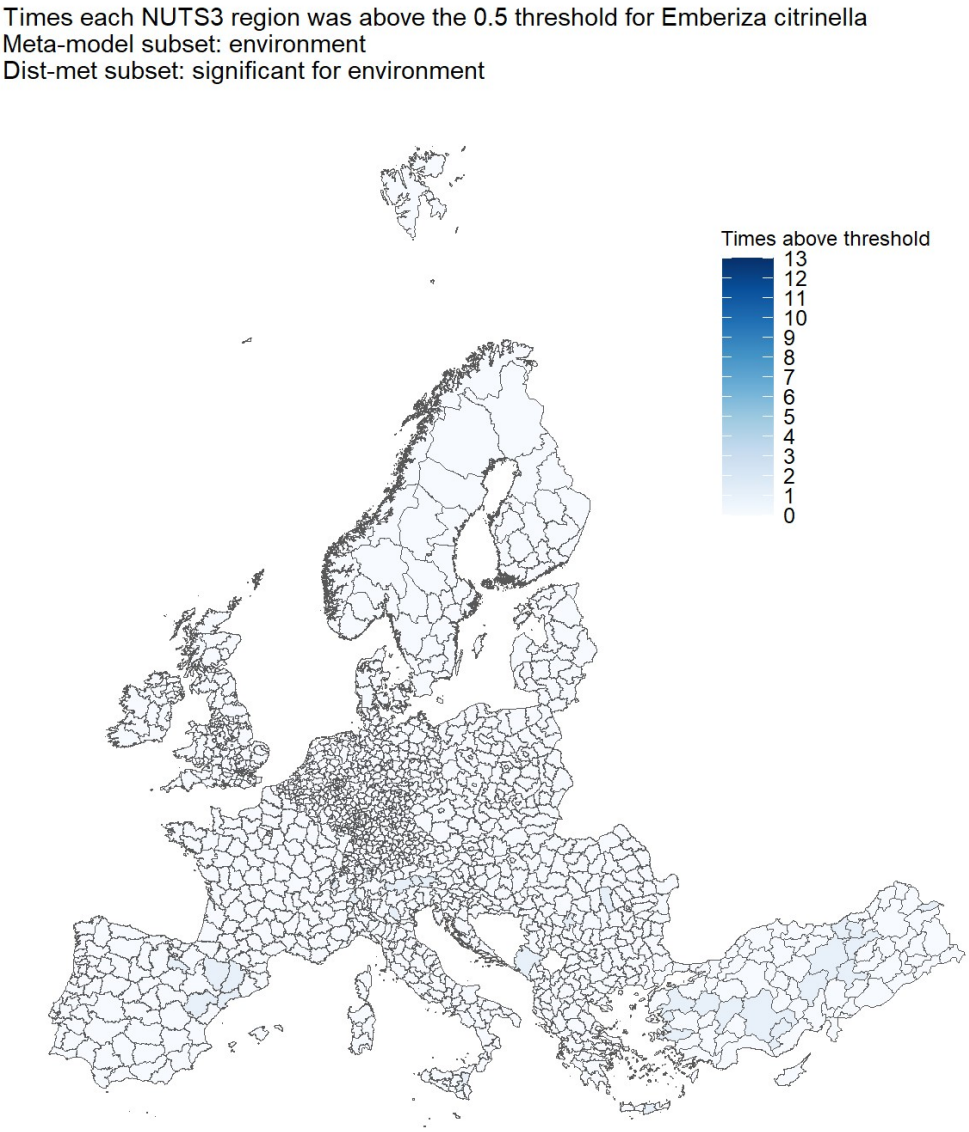

Figure 55: *Transferability map for the* ***biodiversity (Emberiza citrinella)*** *ecosystem service based on* ***significant environmental*** *variables.*

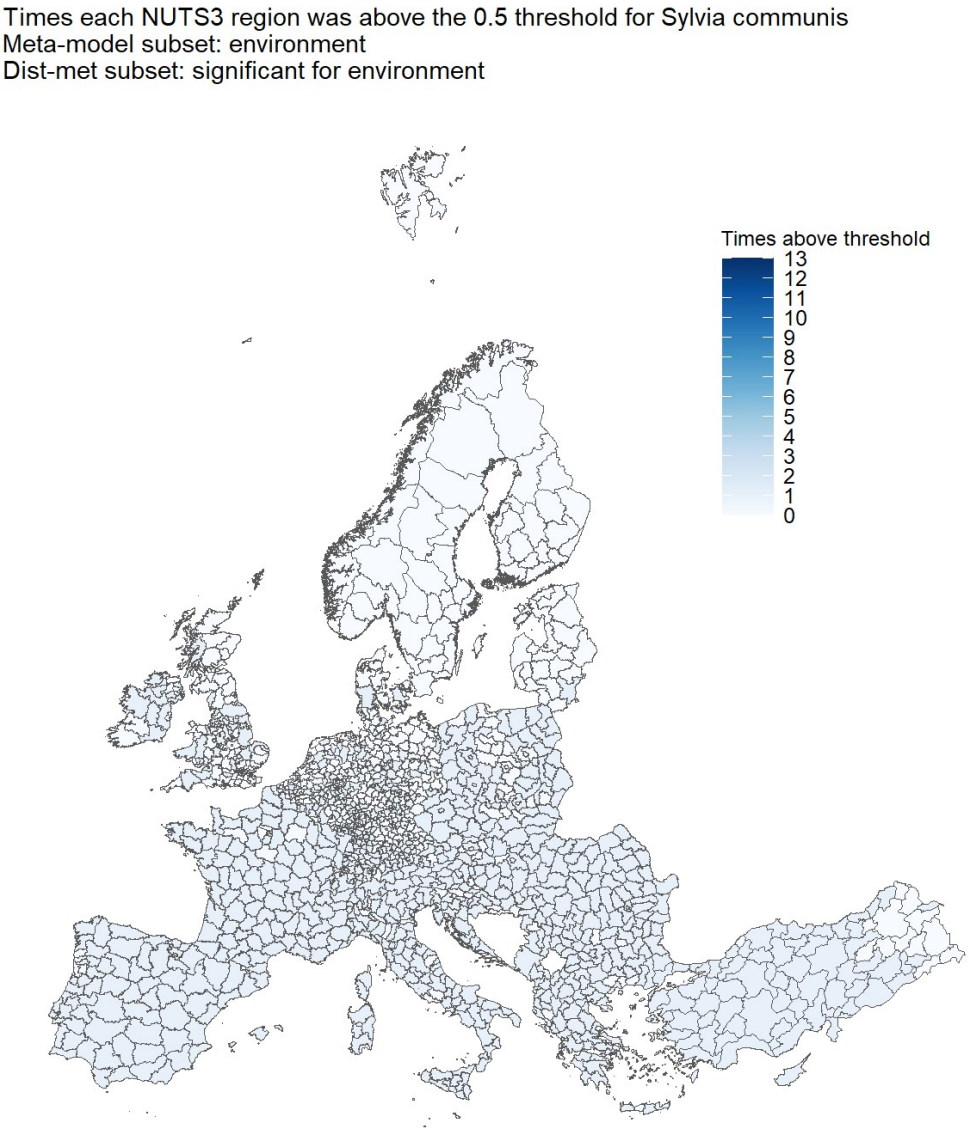

Figure 56: *Transferability map for the* ***biodiversity (Sylvia communis)*** *ecosystem service based on* ***significant environmental*** *variables.*

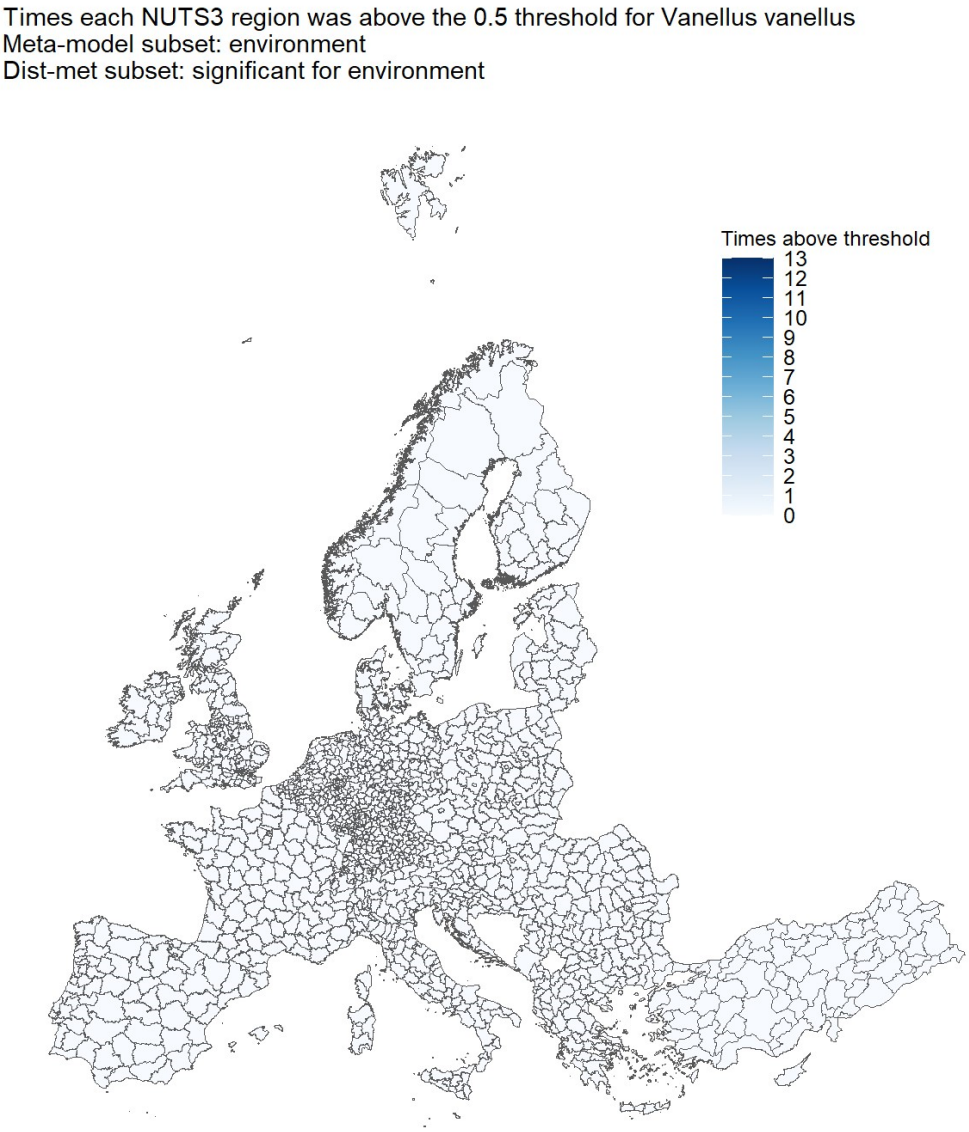

Figure 57: *Transferability map for the* ***biodiversity (Vanellus vanellus)*** *ecosystem service based on* ***significant environmental*** *variables.*

4.3 Maps based on all environmental and economic variables

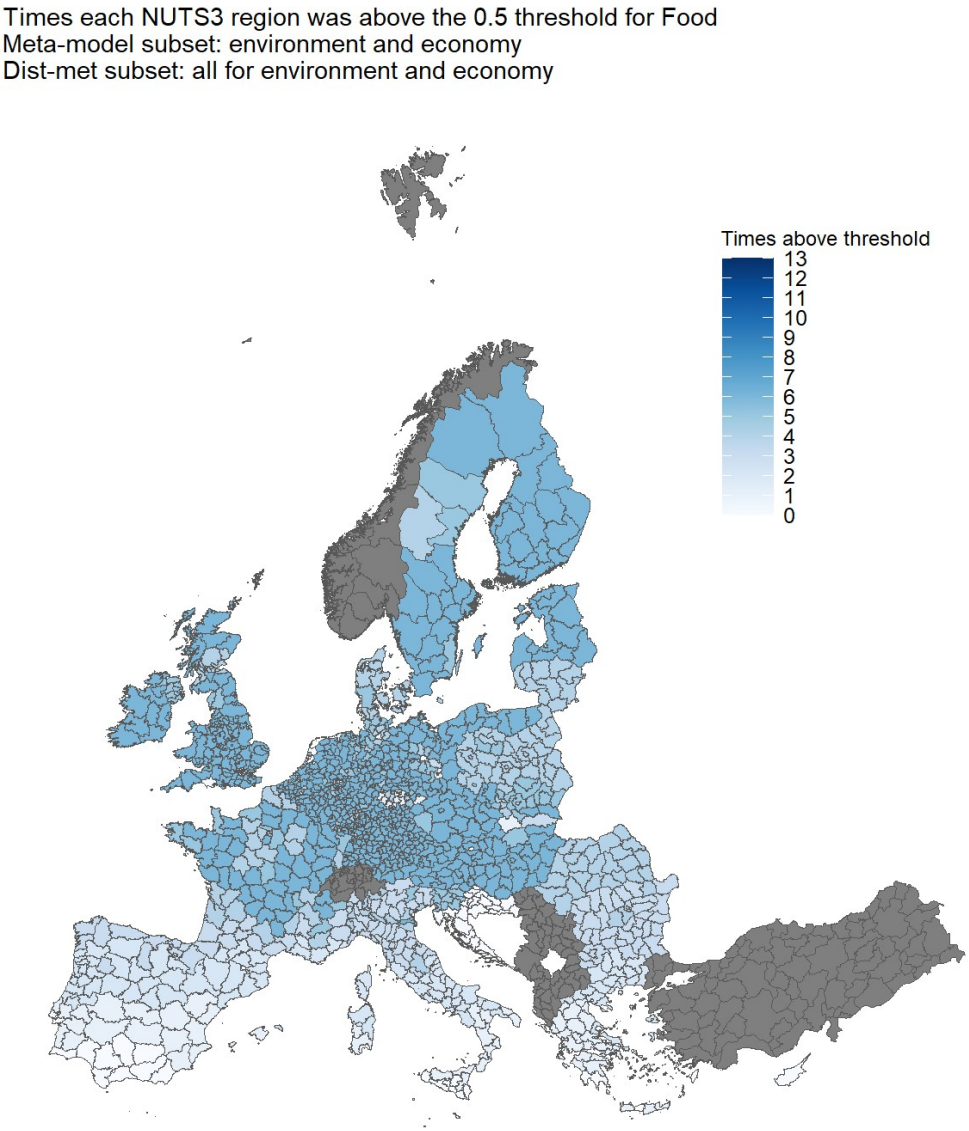

Figure 58: *Transferability map for the* ***food*** *ecosystem service based on* ***all environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

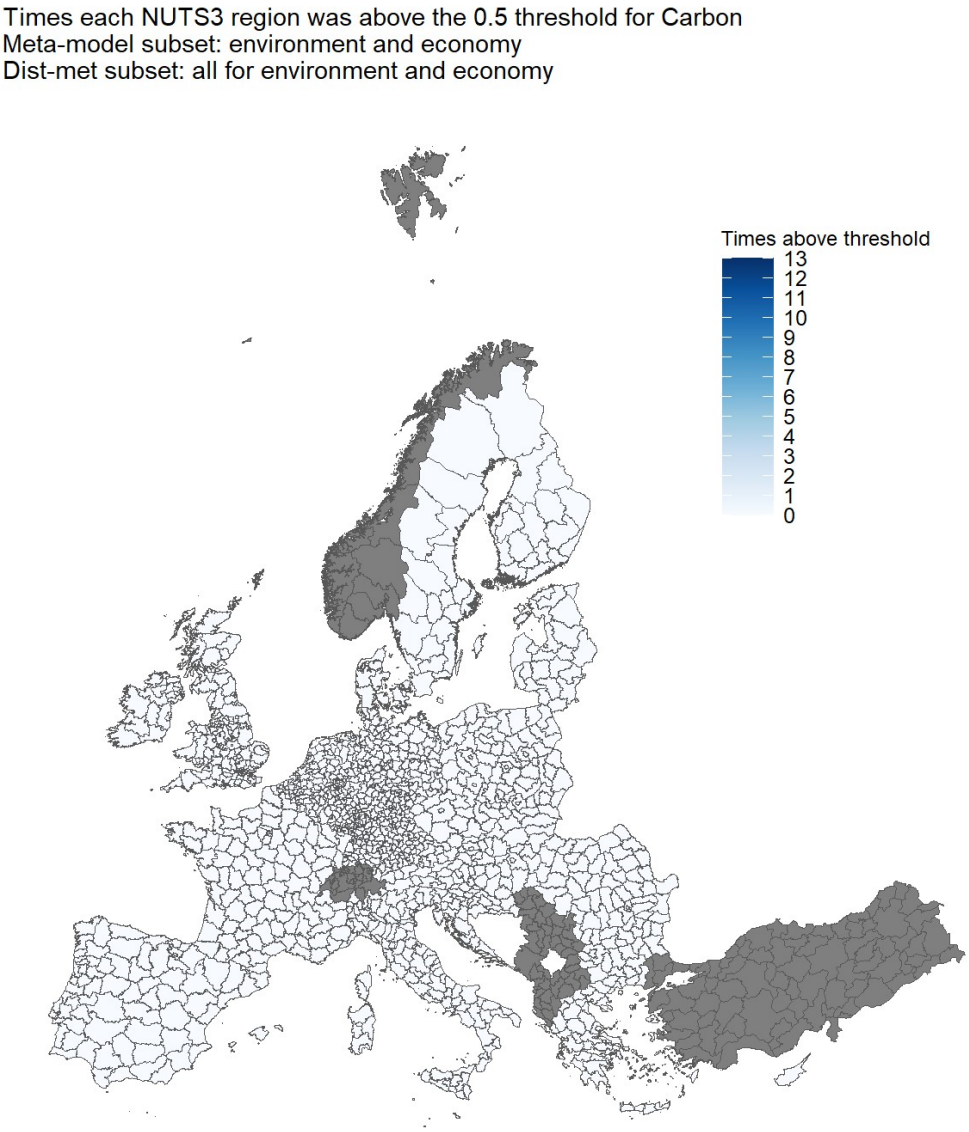

Figure 59: *Transferability map for the* ***carbon*** *ecosystem service based on* ***all environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

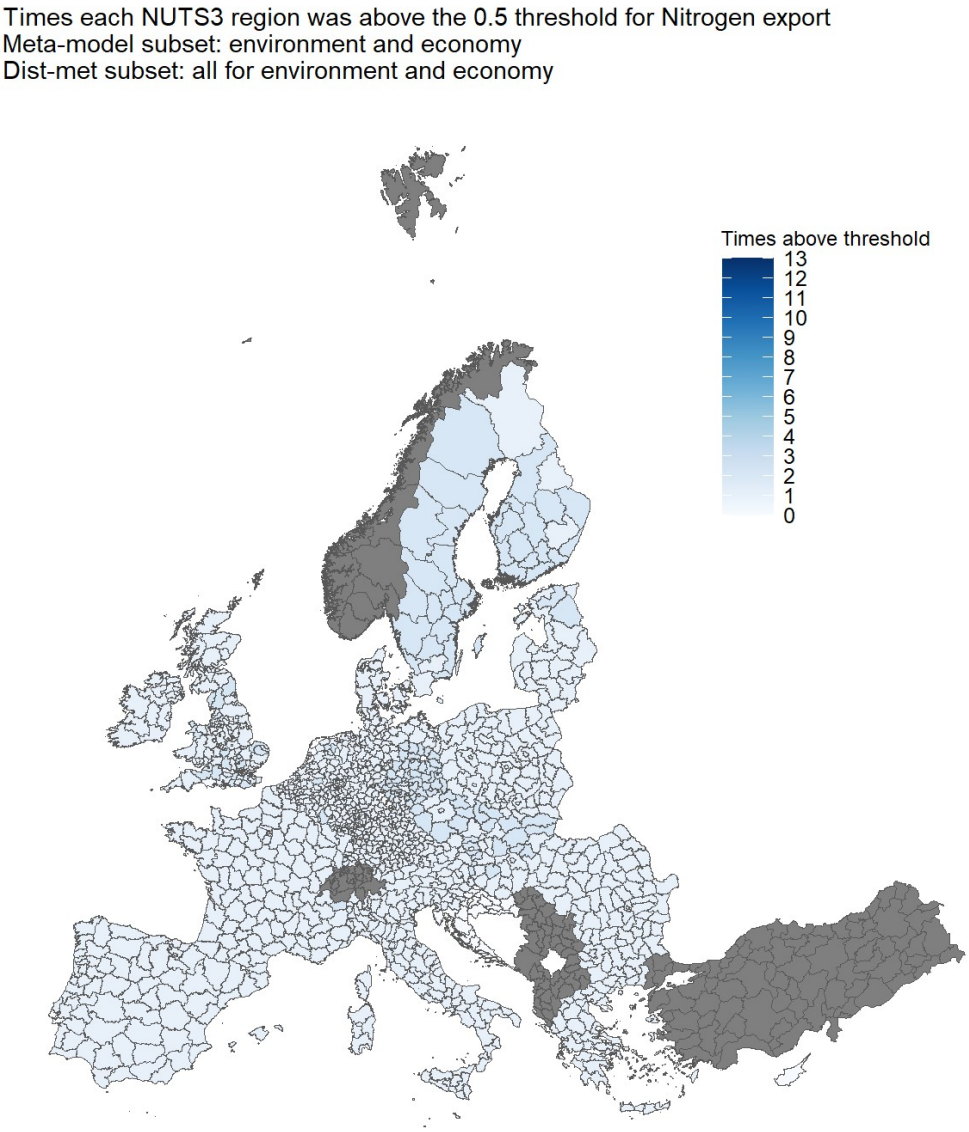

Figure 60: *Transferability map for the* ***nutrient (nitrogen)*** *ecosystem service based on* ***all environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

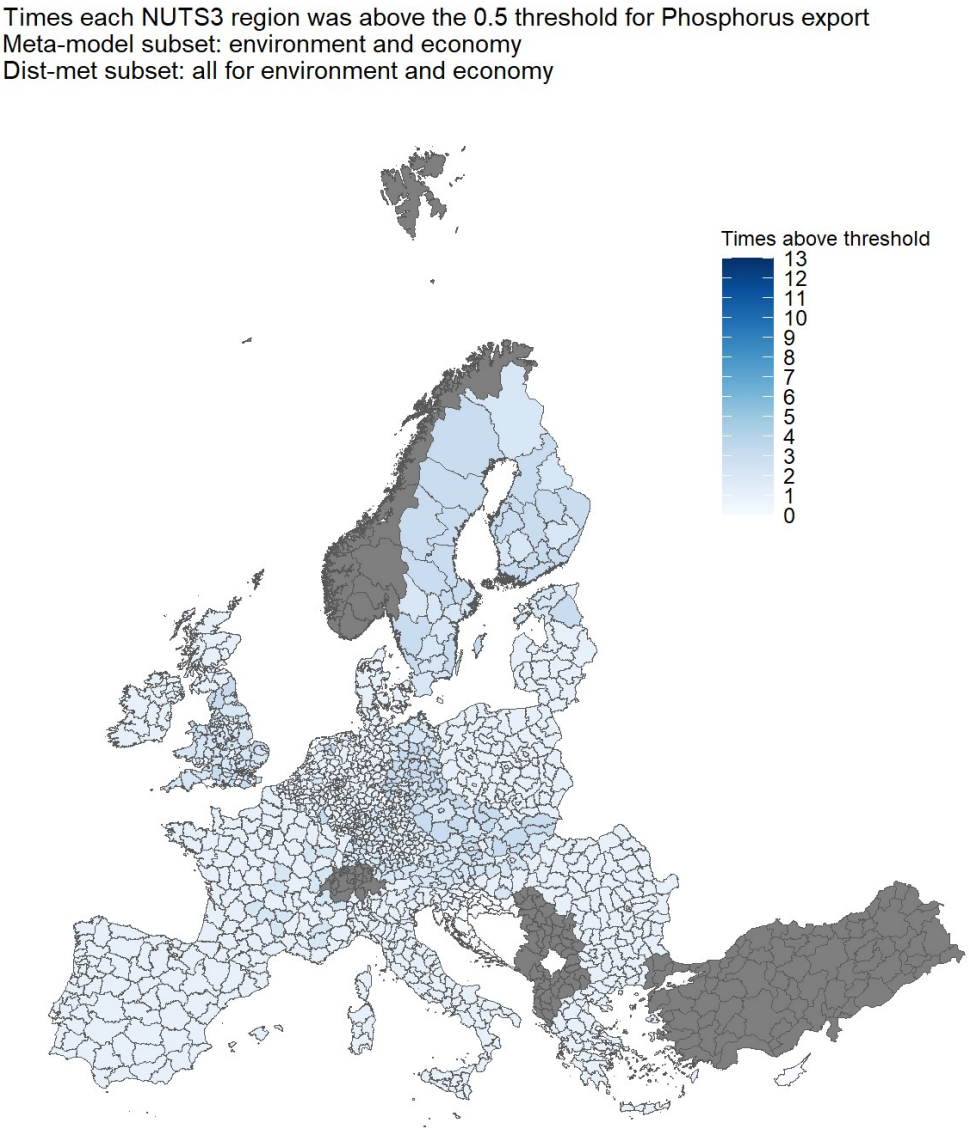

Figure 61: *Transferability map for the* ***nutrient (phosphorus)*** *ecosystem service based on* ***all environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

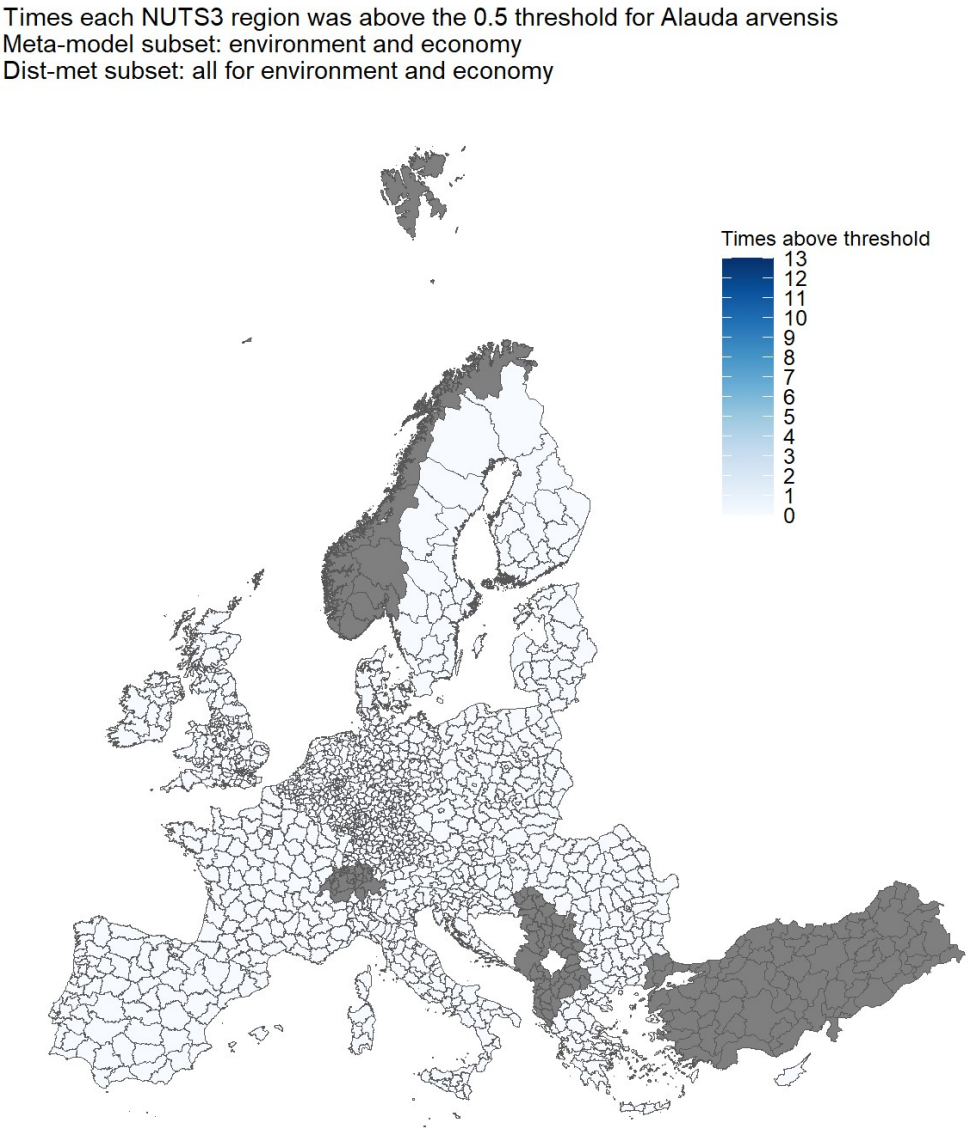

Figure 62: *Transferability map for the* ***biodiversity (Alauda arvensis)*** *ecosystem service based on* ***all environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

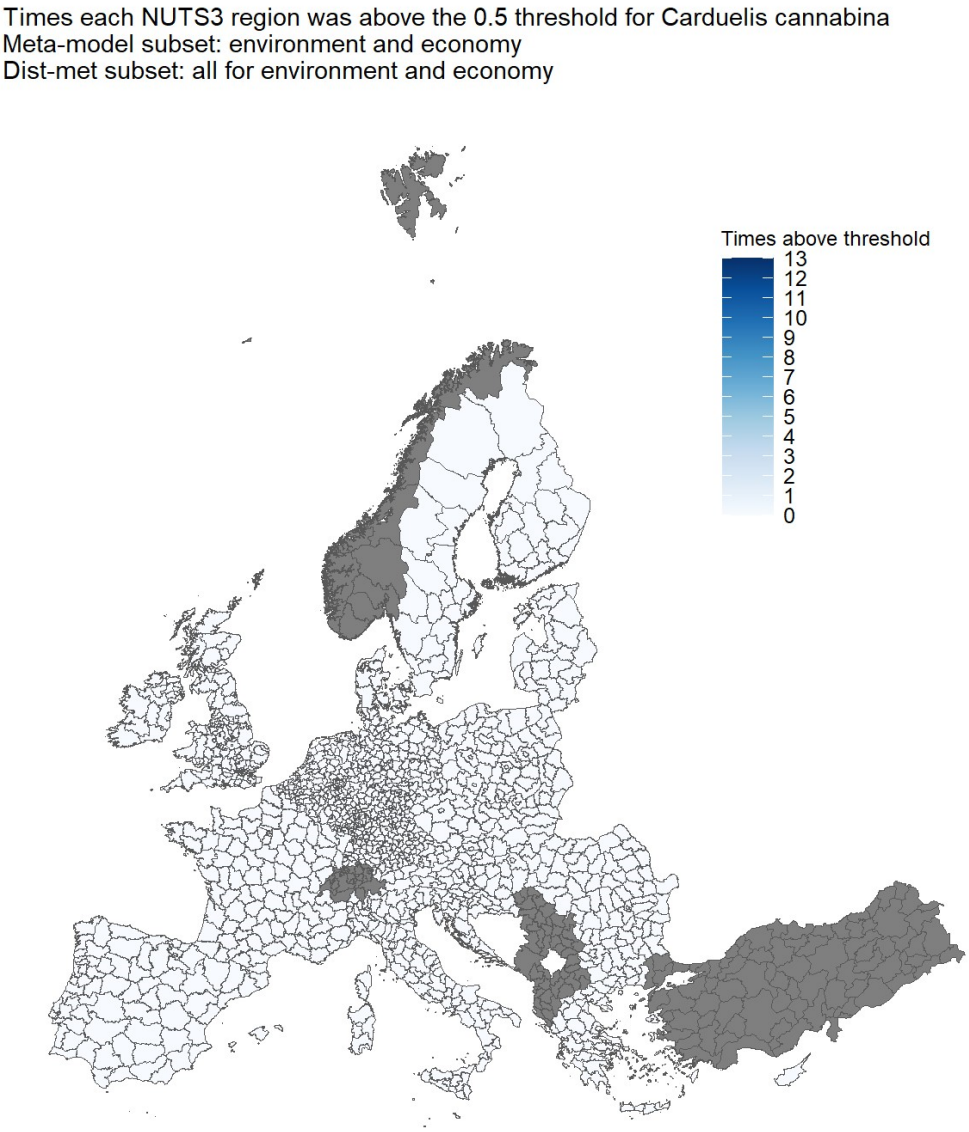

Figure 63: *Transferability map for the* ***biodiversity (Carduelis cannabina)*** *ecosystem service based on* ***all environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

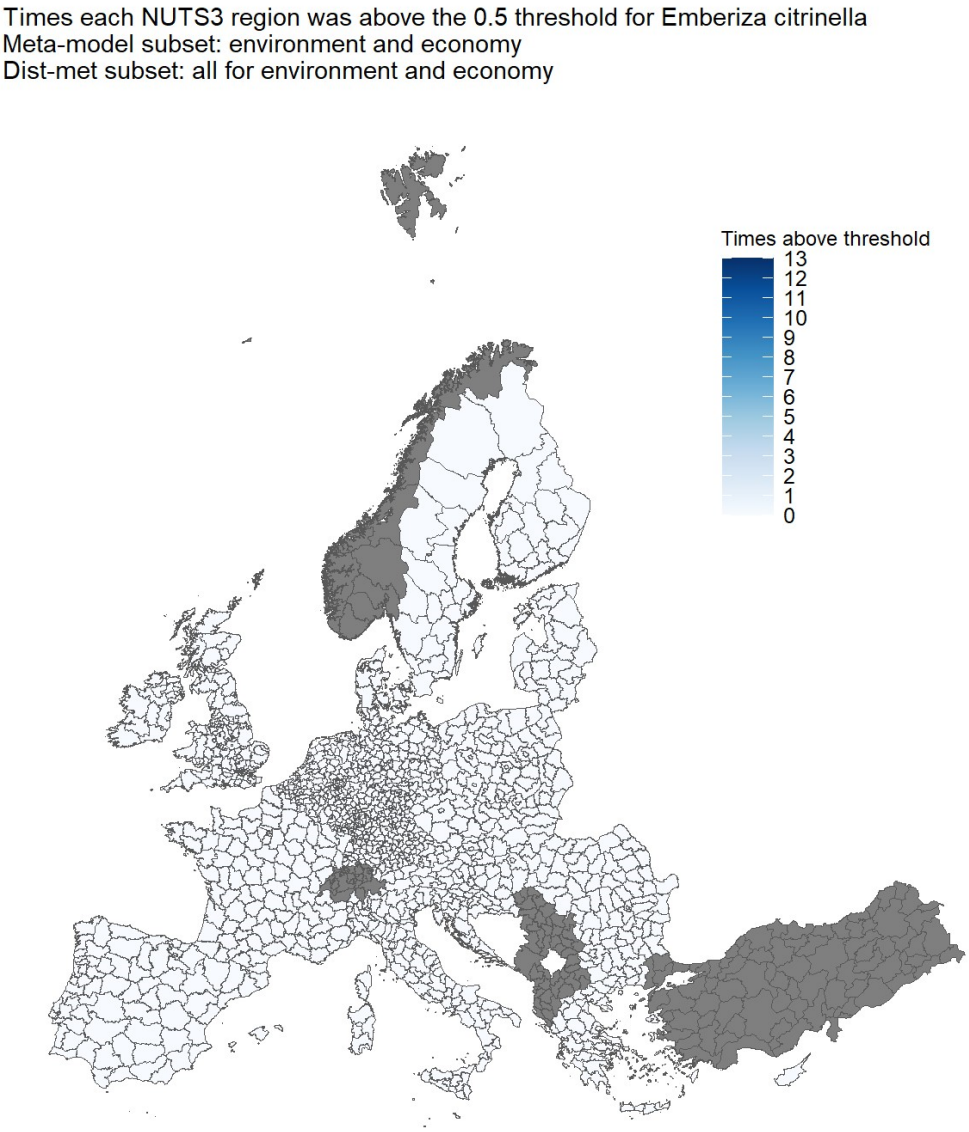

Figure 64: *Transferability map for the* ***biodiversity (Emberiza citrinella)*** *ecosystem service based on* ***all environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

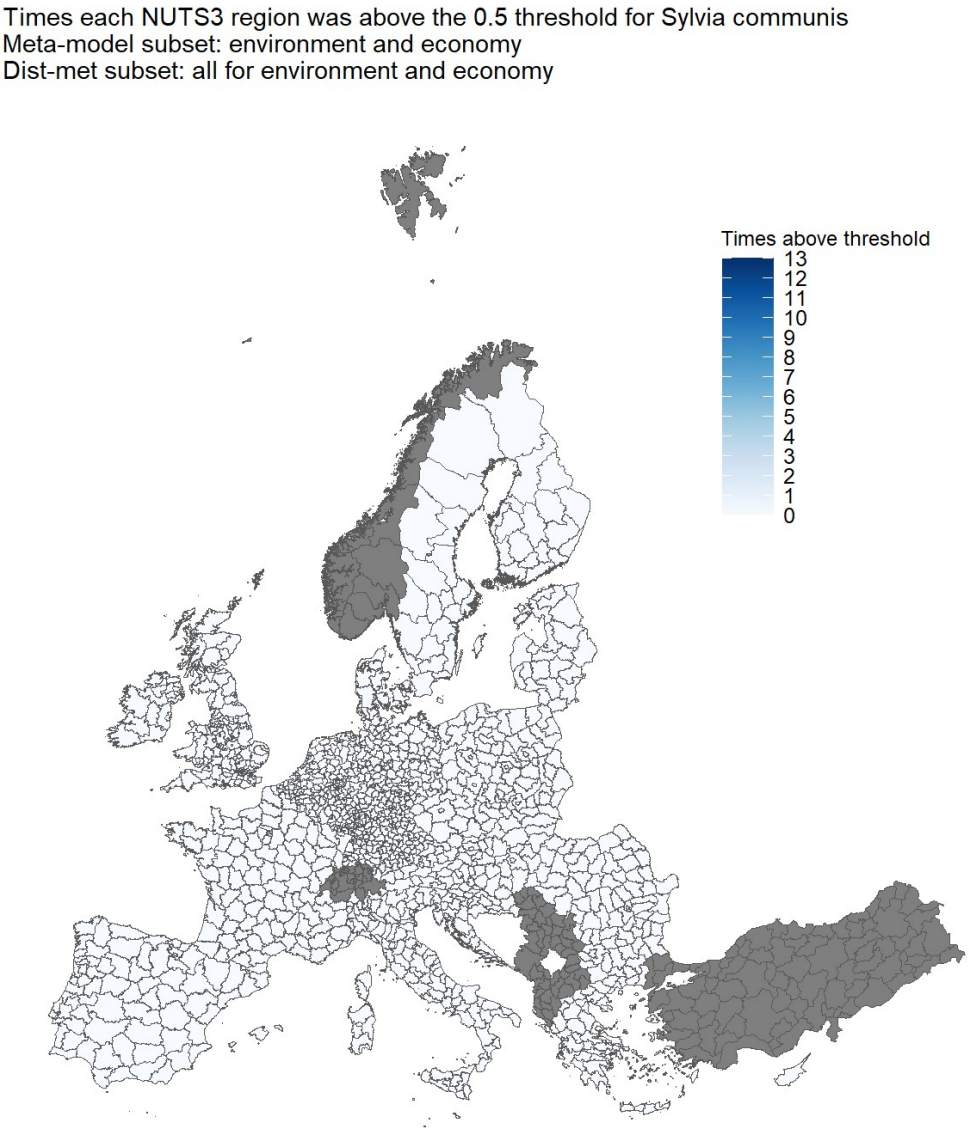

Figure 65: *Transferability map for the* ***biodiversity (Sylvia communis)*** *ecosystem service based on* ***all environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

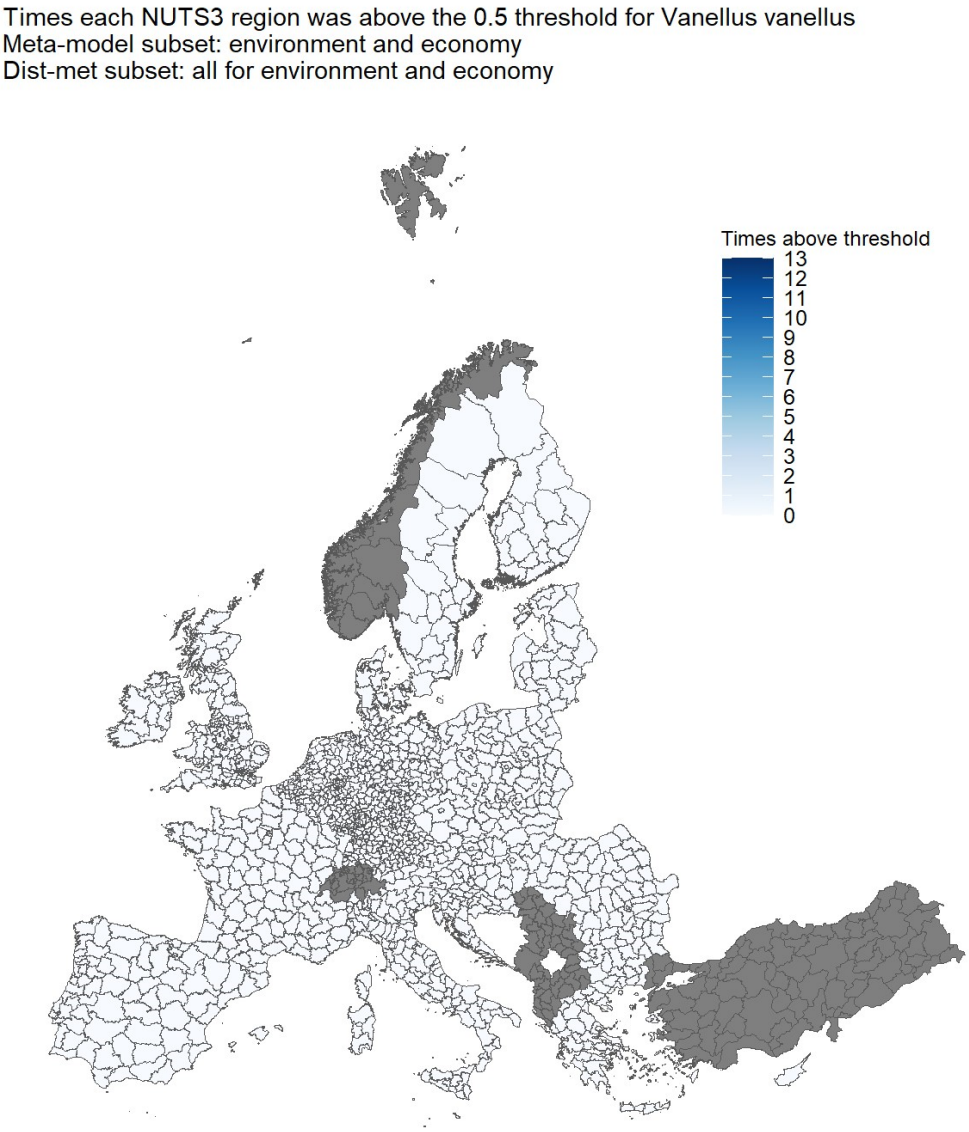

Figure 66: *Transferability map for the* ***biodiversity (Vanellus vanellus)*** *ecosystem service based on* ***all environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

4.4 Maps based on significant environmental and economic variables

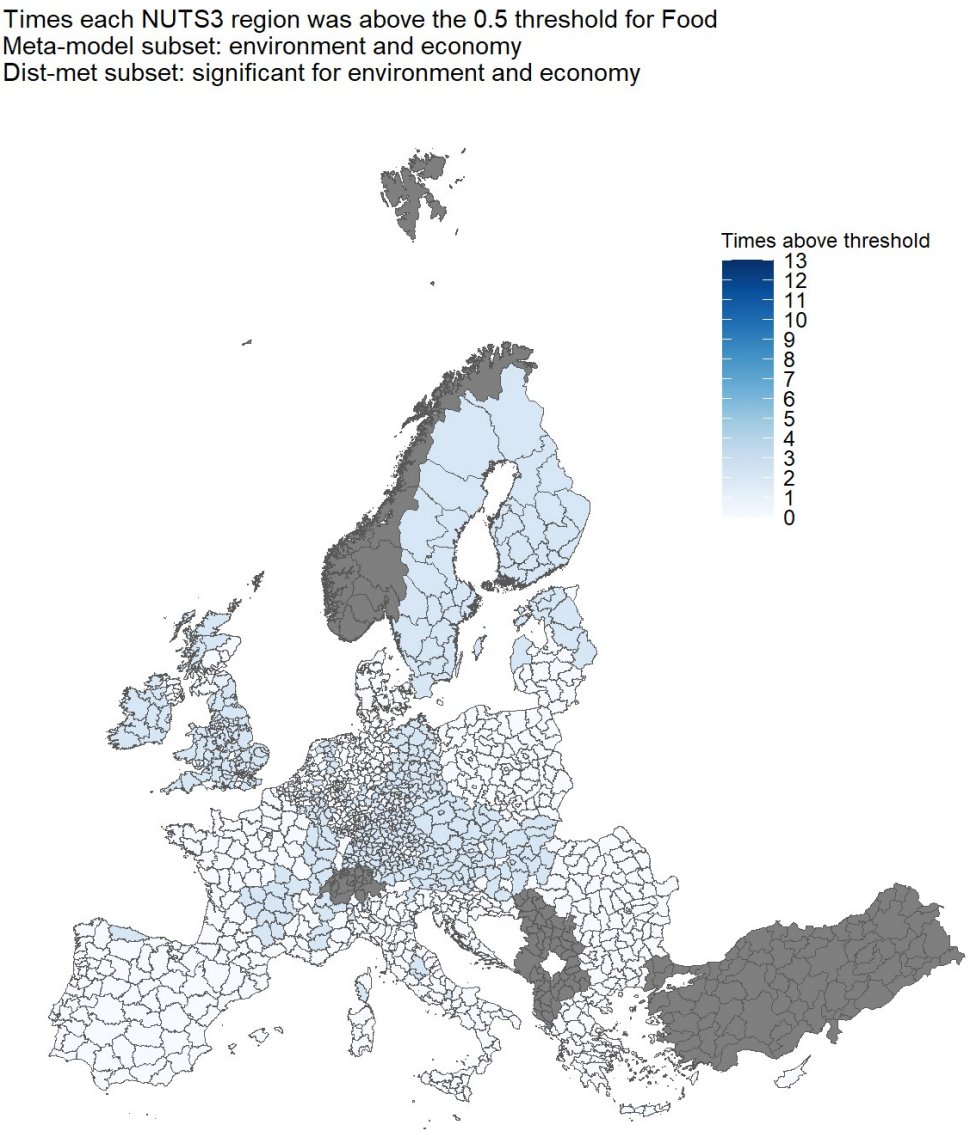

Figure 67: *Transferability map for the* ***food*** *ecosystem service based on* ***significant environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

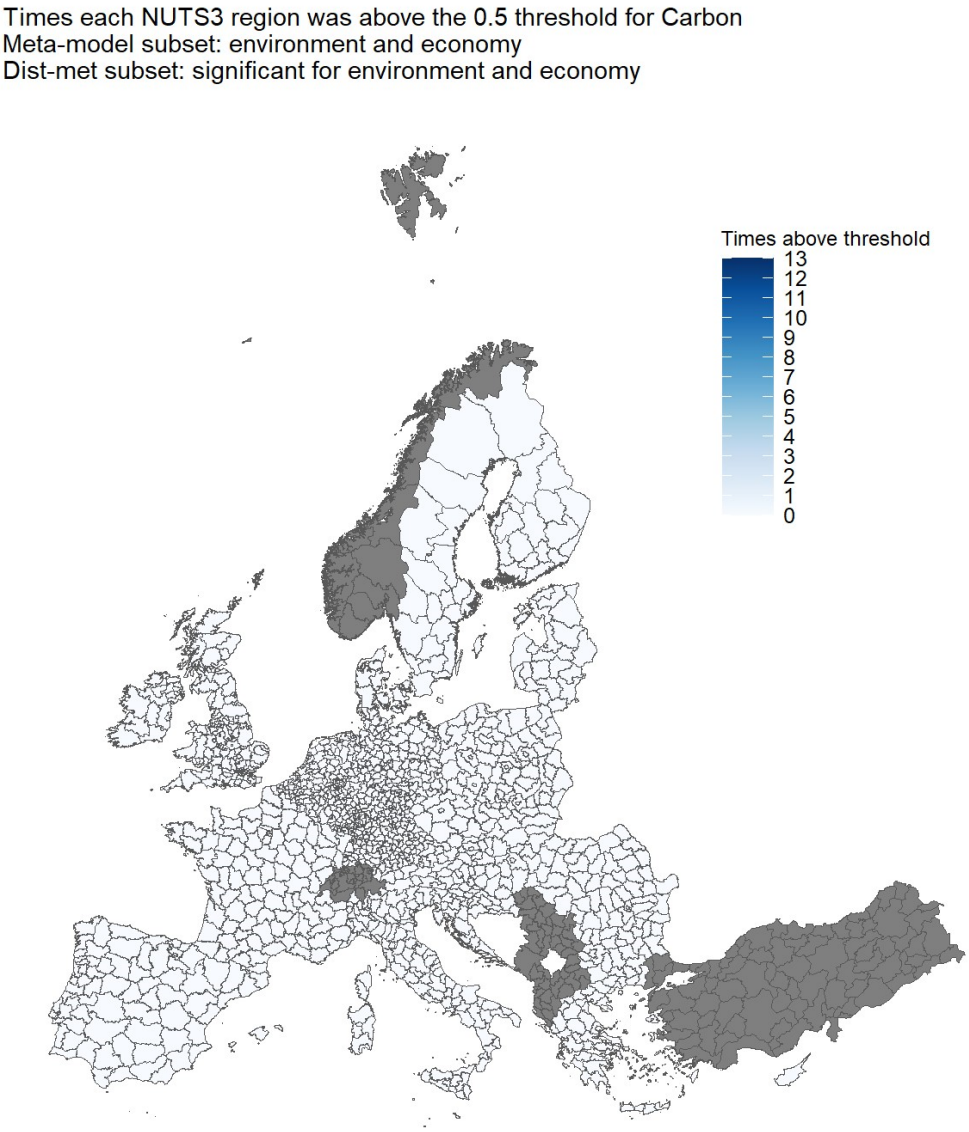

Figure 68: *Transferability map for the* ***carbon*** *ecosystem service based on* ***significant environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

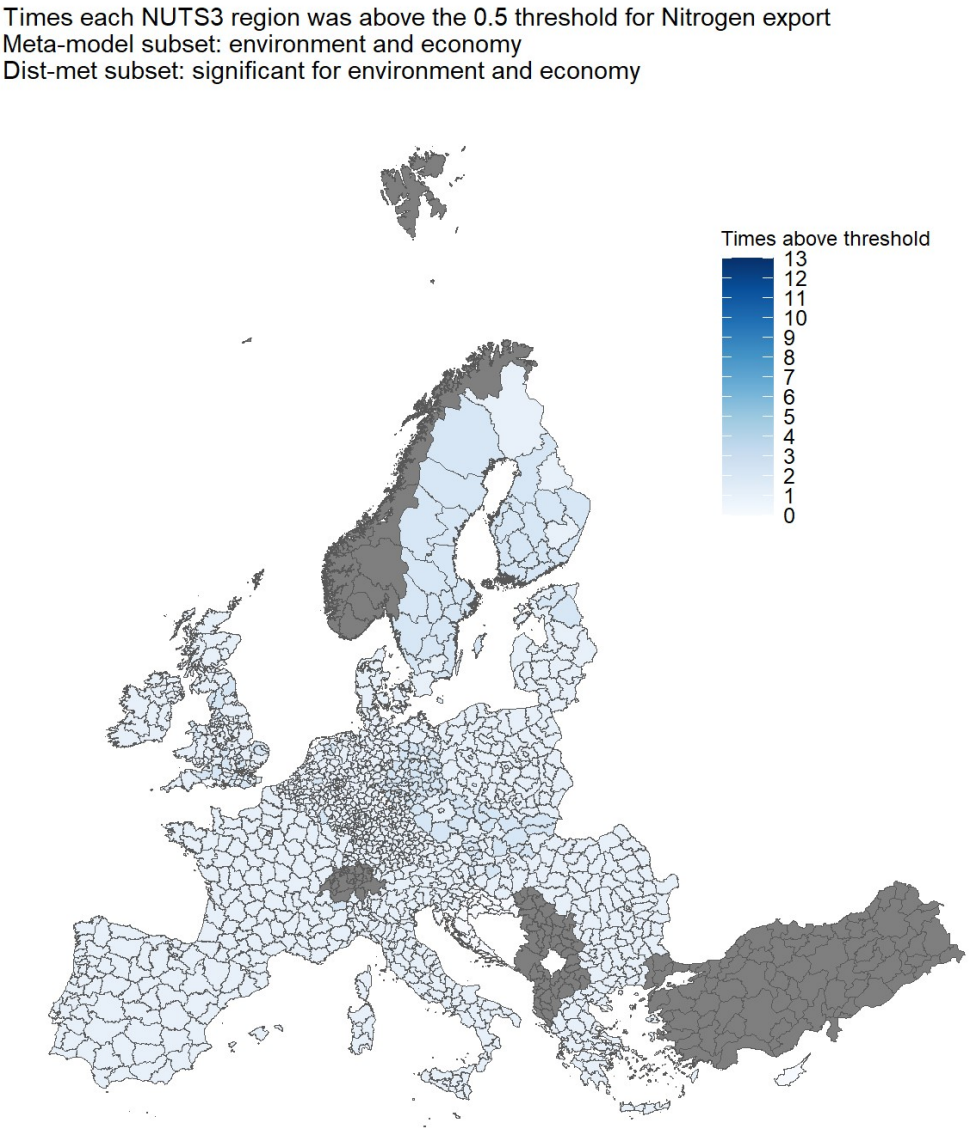

Figure 69: *Transferability map for the* ***nutrient (nitrogen)*** *ecosystem service based on* ***significant environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

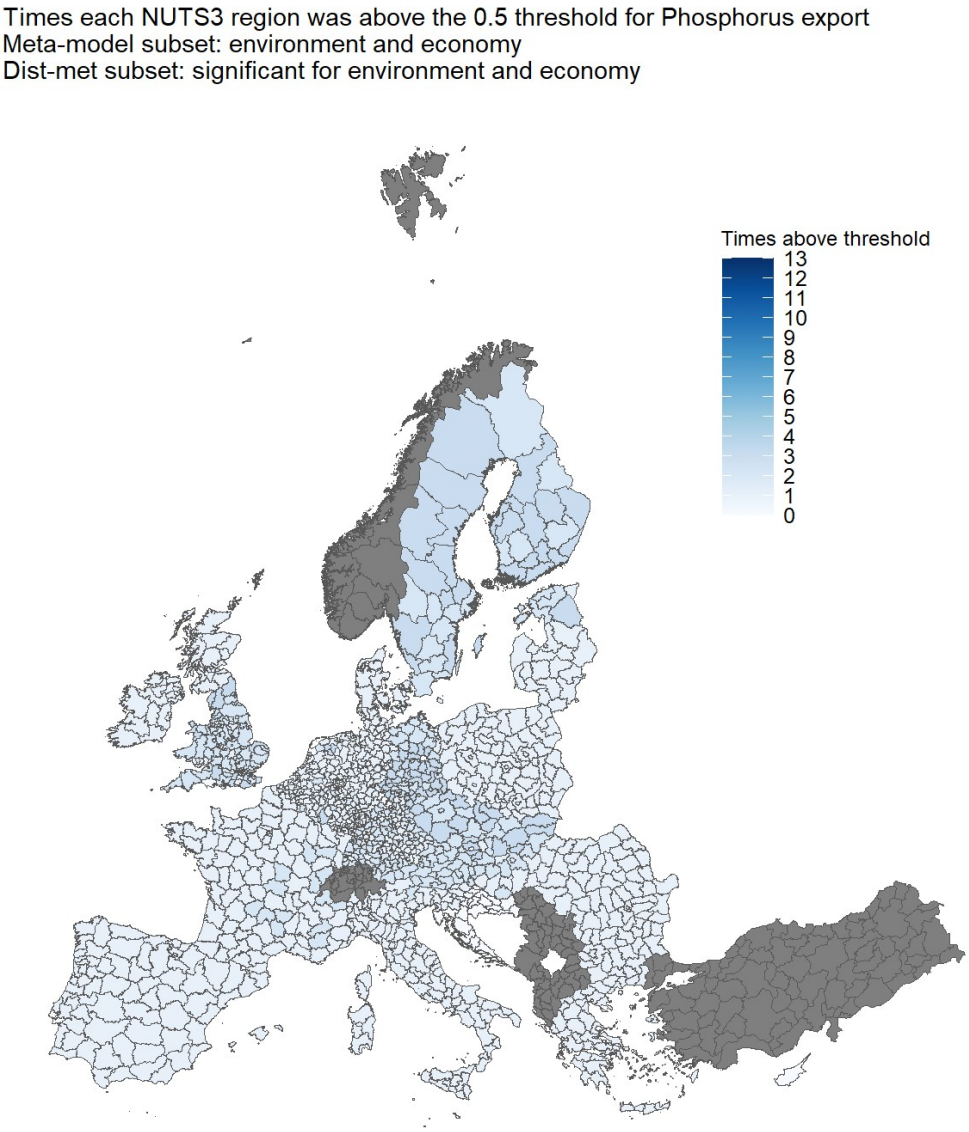

Figure 70: *Transferability map for the* ***nutrient (phosphorus)*** *ecosystem service based on* ***significant environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

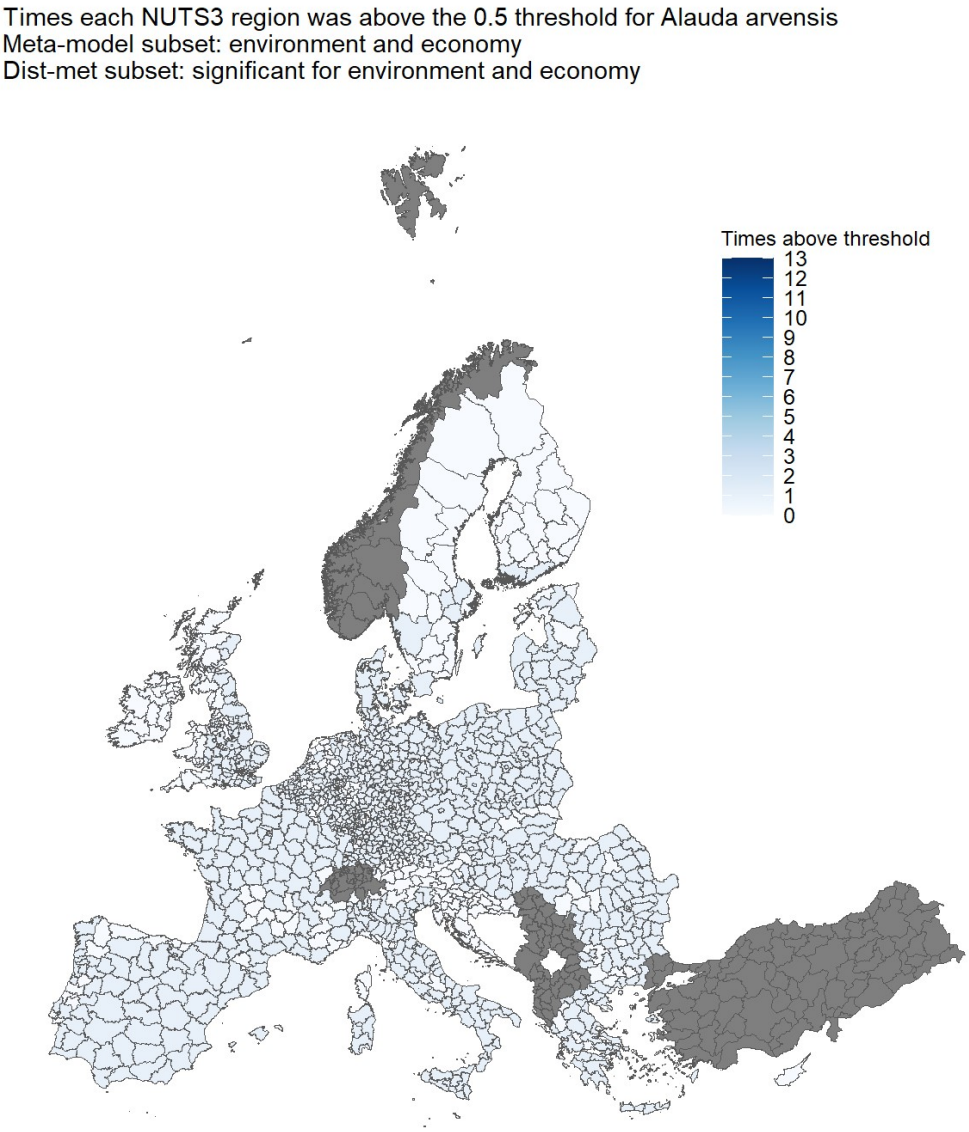

Figure 71: *Transferability map for the* ***biodiversity (Alauda arvensis)*** *ecosystem service based on* ***significant environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

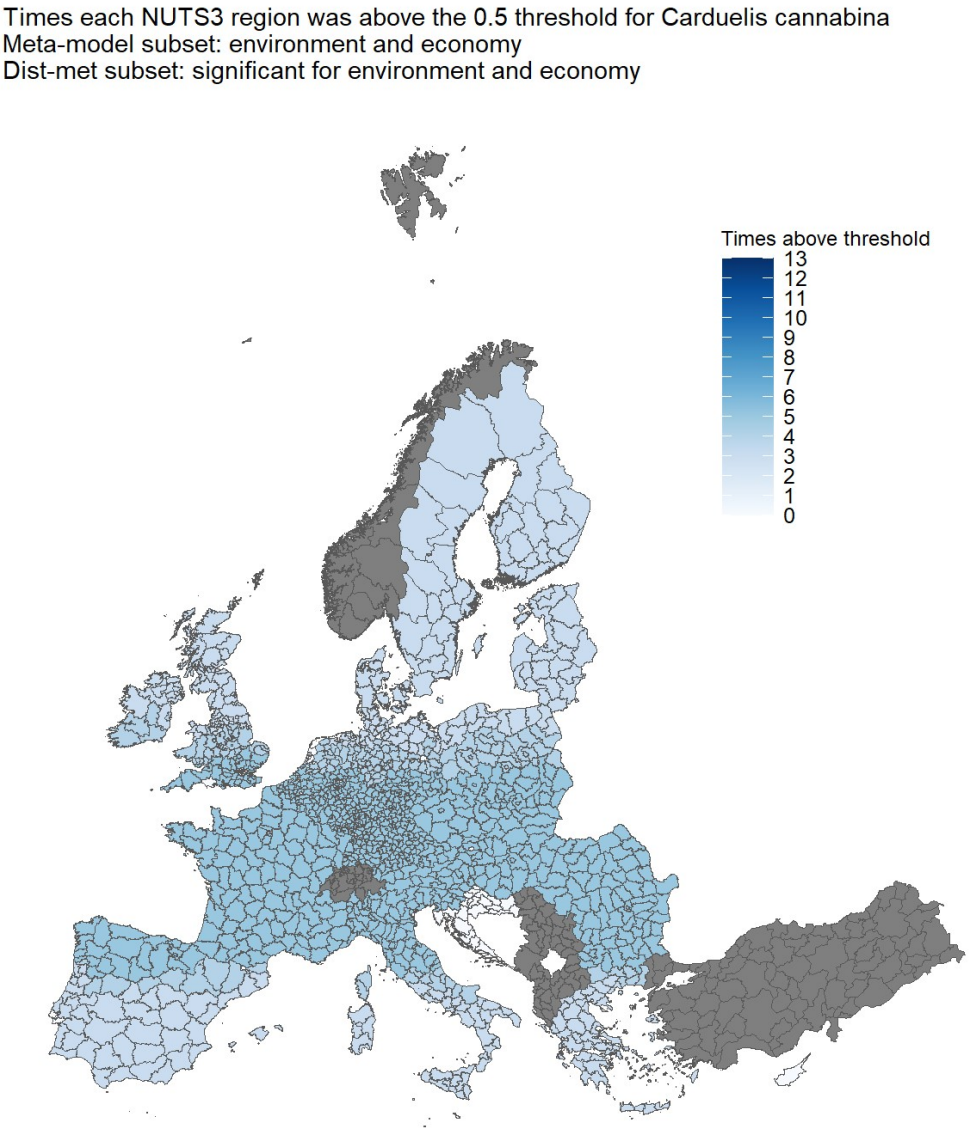

Figure 72: *Transferability map for the* ***biodiversity (Carduelis cannabina)*** *ecosystem service based on* ***significant environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

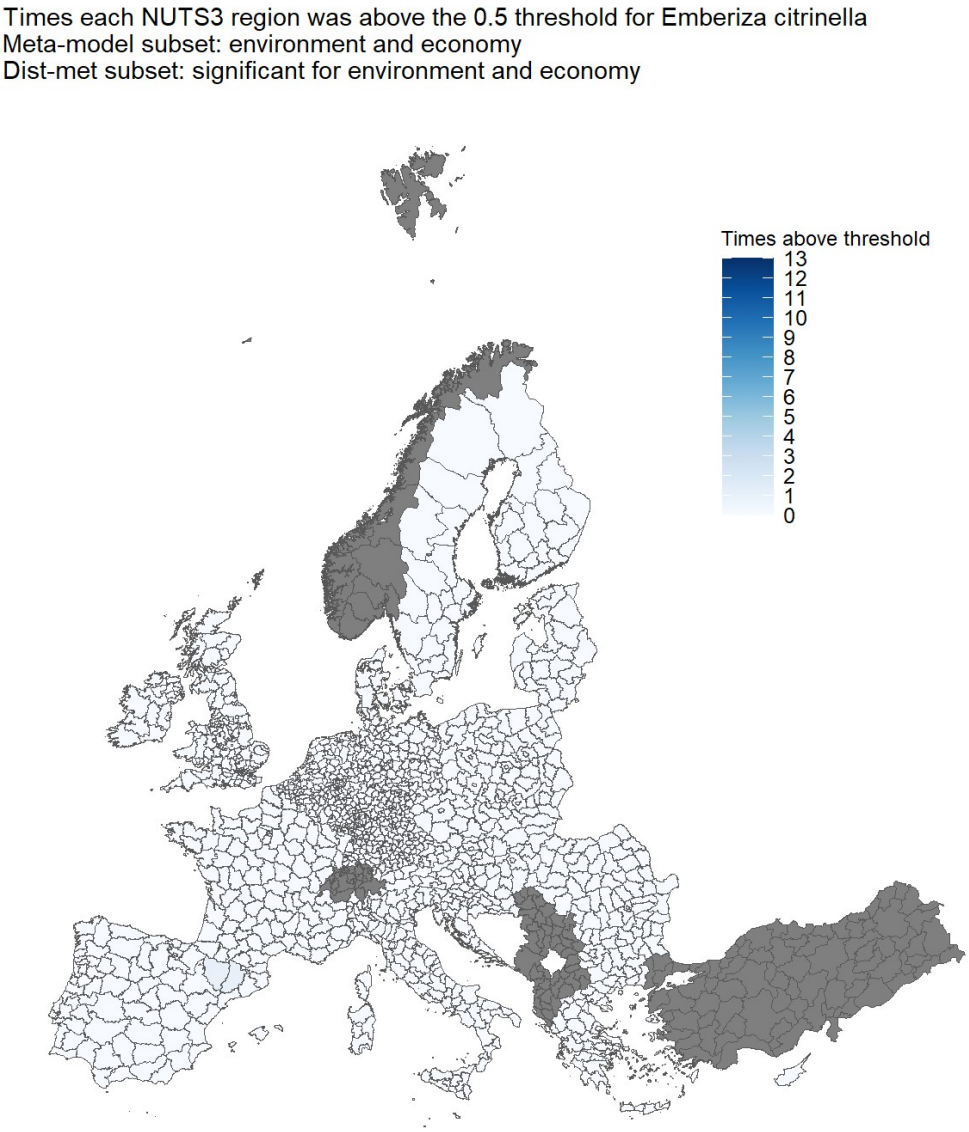

Figure 73: *Transferability map for the* ***biodiversity (Emberiza citrinella)*** *ecosystem service based on* ***significant environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

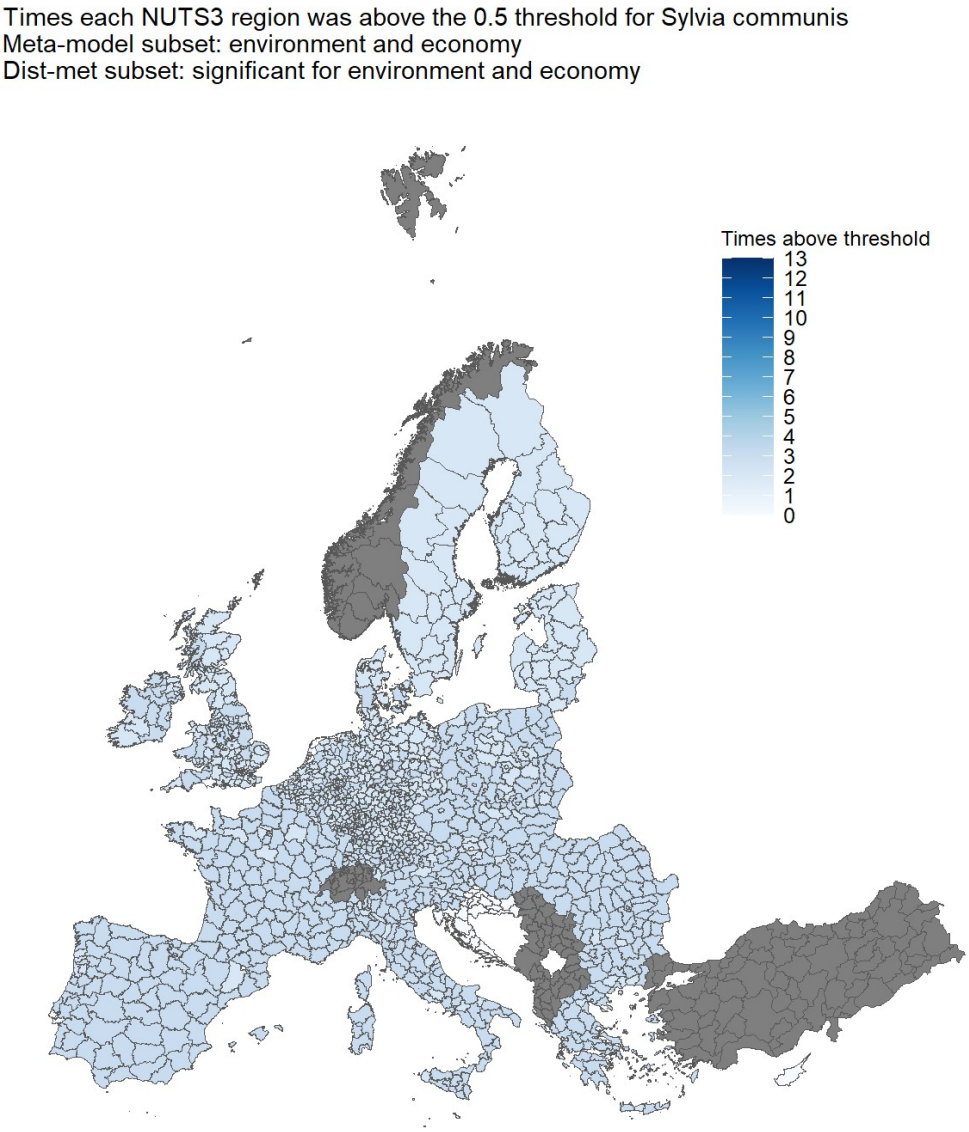

Figure 74: *Transferability map for the* ***biodiversity (Sylvia communis)*** *ecosystem service based on* ***significant environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

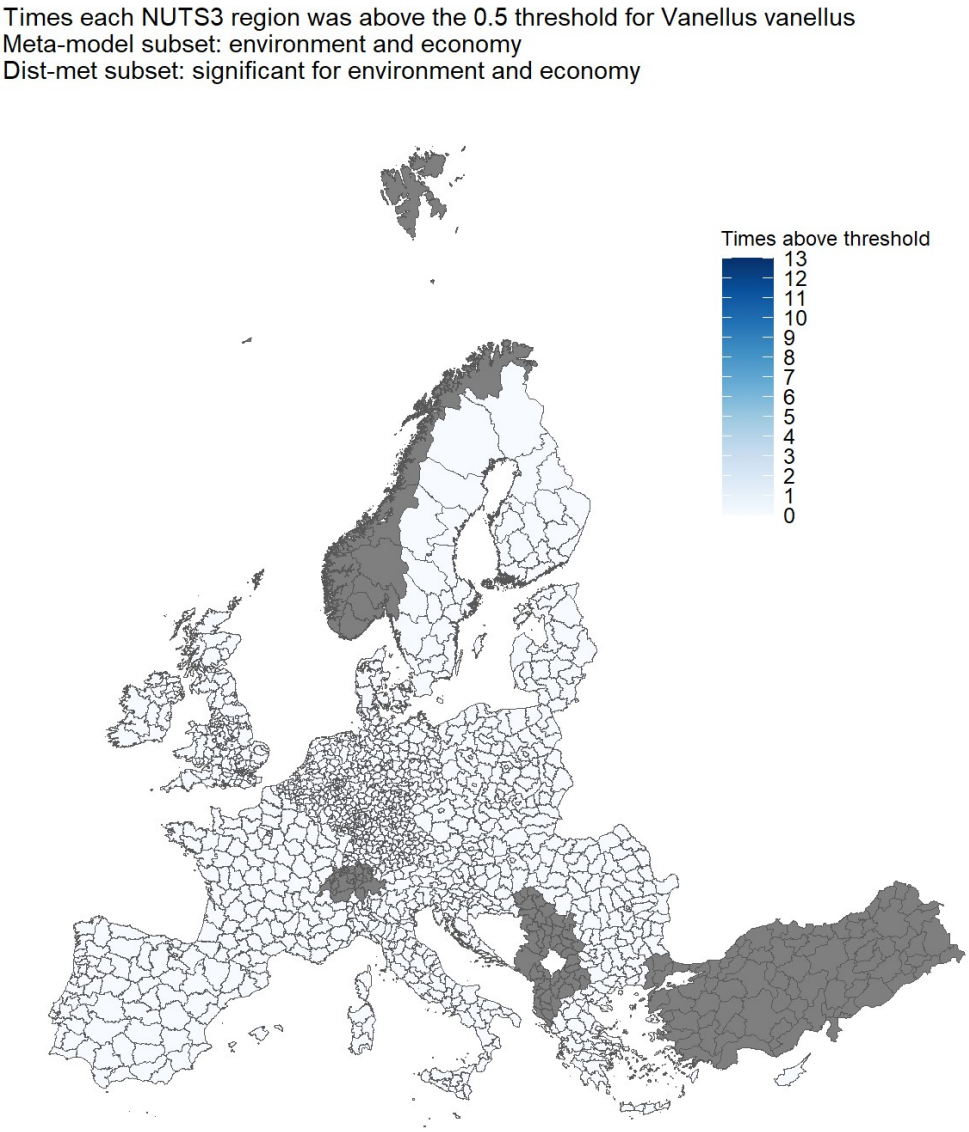

Figure 75: *Transferability map for the* ***biodiversity (Vanellus vanellus)*** *ecosystem service based on* ***significant environmental and economic*** *variables. The shaded areas are regions with a lack of economic data.*

5. Transferability potential

5.1 Transferability potential based on environmental variables

When including all the transferability diagrams with a significant decreasing trend (i.e. showing the hypothesised negative relationship between meta-model strength and Minkowski distance) calculated based on all the environmental variables, we found that 10 diagrams for food (Fig. 4), nine diagrams for phosphorus (Fig. 7) and 11 diagrams for nitrogen (Fig. 6) have the potential for transferability. Of the 19 available transferability diagrams per ESS, this represents approximately 50% of the diagrams. However, for the carbon model, only one diagram from Serbia (RS121) meets the criteria for transferability (Fig. 5), suggesting that our selection of environmental predictors is not suitable for this ecosystem service. None of the biodiversity models, representing the occurrence of five bird species, had any transferability based on the criteria. This may again suggest the selection of predictors for biodiversity was not useful. Considering transferability estimates of the food ecosystem service across Europe, our results indicate the strongest transferability potential in the latitudinal band between 45 and 52°N, where the number of spatial overlaps of individual transferability maps ranges between eight to 10 (Fig. 40). Likely associated with climate (i.e. the combination of temperature and precipitation), the transferability potential decreases with latitude and ceases completely in the southernmost parts of Europe (Andalusia, Murcia, southern Sardinia, Sicily, Peloponnese peninsula, south-western Anatolia) where environmental conditions are too different from those present in our CS for estimating food ecosystem services. When estimating the transferability potential for nutrient uptake (nitrogen and phosphorus combined), our maps show a relatively high potential for transferability in much of Europe (the number of individual maps is approximately seven) except for the Alpine arc, the Balkans, central Turkey and northern Spain, where new research (i.e. case studies) is needed and our results cannot be translated into current agri-environmental policy (Figs. 42 and 43). Unlike food and nutrients, the models of carbon (Fig. 41) and biodiversity show no potential for transferability.

Accounting only for significant variables/predictors, the ‘suitable’ transferability diagrams are much fewer in number (from zero to five; Figs. 13-21) compared to diagrams based on all environmental variables. Therefore, only 5-25% of all diagrams for carbon, nitrogen and phosphorus can be used for spatial estimates of transferability potential (Figs. 50-52). Interestingly, nutrient uptake is consistent for both nitrogen and phosphorus, and has five overlaps in central, south-western and western Europe. When only using significant predictors for the different biodiversity species, some of the graphs met the criteria - something that did not occur when using ‘all’ variables. Three out of 16 (18.75%) diagrams met the criteria for *Carduelis cannabina* (Fig. 45), with one of 16 (6.35%) meeting it for *Emberiza citrinella* and *Sylvia communis*, respectively (Figs. 46 and 47). *Vanellus vanellus* and *Alauda arvensis* did not succeed in meeting the criteria (Figs. 44 and 48).

5.2 Transferability potential based on environmental and economic variables

Compared to the previous set of variables, which covered a larger area of Europe, the limited economic data from FADN and Thunen datasets provided information for a slightly smaller area, which allowed the production of only 16 transferability diagrams (no information for Norway, Switzerland or the Balkans). In any case, we found that the number of 'suitable' transferability diagrams decreases greatly when all environmental and economic variables are included, i.e. also economic size and type of farm specialization. In fact, although the food ecosystem service contains at least six (<40%) of all diagrams with transferability potential (Fig. 22), only two and three diagrams for nitrogen and phosphorus can be used for this type of analysis (Figs. 24-25). The carbon ecosystem service shows no diagrams with a significant downward trend, preventing any estimates of the distribution of transferability (Fig. 23). Also, none of the biodiversity diagrams show a significant downward trend. Regarding the food ESS, at least four to six individual maps overlap in central, western and northern Europe (Fig. 58). To a much lesser extent (two to three overlaps) this pattern is also evident for nitrogen and phosphorus, although the area covered is much smaller and limited to isolated areas in the Czech Republic, Saxony and parts of the southern United Kingdom (Figs. 60 and 61).

Despite focusing only on the significant predictors, the transferability diagrams for carbon, nitrogen and phosphorus (Figs. 32-34) essentially do not differ, except for the food production model where only two diagrams can be used for transferability potential (Fig. 31). Again, transferability potential is the highest in central and western Europe together with Nordic countries for food (Fig. 67) and in more isolated territories of these regions for nitrogen and phosphorus (Figs. 69-70). However, similar to using only significant environmental variables, just using significant environmental and economic variables for biodiversity shows that the criteria was sometimes met: *Carduelis cannabina* (Fig. 36) has five diagrams (31.25%) that show a significant downward trend, with the subsequent area covered ranging from Ireland in the north to central Italy in the south. *Sylvia communis, Alauda arvensis,* and *Emberiza citrinella* meet the criteria three, one, and one times, respectively (Figs. 56, 53, and 55).

5.3 Transferability challenges

As discussed in the previous sections (see 5.1 and 5.2), much of the difference in transferability potential results from the use of only environmental variables in combination with economic data. Although the R^2 values from the models (the Y-axis for the transferability diagrams) are relatively high and comparable, the combination of environmental and economic variables appears to be less useful for any transferability estimates. This is mainly because the economic variables do not cover as many NUTS3 regions as the environmental variables, as we lacked economic data for Switzerland, Norway and Serbia. Moreover, the transferability diagrams for the Spanish case study of Catalonia reveal predominantly

upward linear trends, yet we were unable to identify a causal link for such a discrepancy. It should also be noted that this behaviour may be related to outliers, which can strongly influence the slope of the linear trend.

The selection of which variables to use for transferability diagrams is also an important factor that has associated challenges. This is clear when comparing, for example, food and biodiversity, just considering environmental variables. When 'all' environmental variables were used for food production there were 32 predictor variables (including seasonal data, and both means and standard deviations) that were used to calculate the distance metric. The resulting map showed good coverage of Europe. However, a reduction of predictors to a 'significant' set resulted in the food model having virtually no transferability potential. Conversely, when 'all' predictors (10, in total) were used for biodiversity, there was no transferability potential identified, while using only 'significant' predictors increased the potential for transferability. This indicates the importance of choosing the appropriate set of environmental variables. The situation becomes even more challenging when economic data are included, as seen by far fewer graphs meeting the criteria per ESS than with the 'environmental-only' data counterparts. However, this effect is likely caused not by the fact that these variables add no relevant information but rather by the quality of the economic data. The considered economic variables (Table 2), extracted for each European NUTS3 region from the FADN and Thunen datasets, are only partial equivalents of the socioeconomic variables used for the ESS models developed for BESTMAP case studies.

Acknowledgements

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References

Anon (2019) Farm Accountancy Data Network Public Database. Available at: http://data.europa.eu/88u/dataset/farm-accountancy-data-network-public-database [Accessed September 12, 2023].

Cord A, Roilo S, Beckmann M, Paulus A, Schneider K, Lugonja P, Nikolić T, Langerwisch F, Bednář M, Václavík T, Evans P (2023) D3.3 Ecosystem service, biodiversity and socio-economic models for each case study. ARPHA Preprints

European Commission (2019) Definitions of Variables used in FADN standard results. Committee for Farm Accountancy Data Network (FADN). Brussels

Grant Hokit D, Ascunce M, Ernst J, Branch LC, Clark AM (2010) Ecological metrics predict connectivity better than geographic distance. Conservation Genetics 11, 149-159

Johann Heinrich von Thünen Institute (2020) Conversion and transmission of national farm returns to the Farm Accountancy Data Network of the European Union (FADN) and methodological developments in terms of policy advice. Project TI-BW-08-PID1532 2012-2020 funded by Federal Office for Agriculture and Food (BLE)

Johnson JB, Omland KS (2024) Model selection in ecology and evolution. Trends in ecology & evolution 19, 101-8

Langerwisch F, Václavík T, Bednář M, Ziv G, Gunning J, Gosal A, Paulus A, Brdar S, Lugonja P, Stojkovic S, Roilo S (2023) D3. 5 Farming System Archetypes for each CS. ARPHA Preprints.

QGIS (2023) QGIS Geographic Information System. QGIS Association. http://www.qgis.org

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Václavík T, Beckmann M, Bednář M, Brdar S, Breckenbridge G, Cord AF, Domingo-Marimon C, Gosal A, Langerwish F, Paulus A, Roilo S, Šarapatka B, Ziv G, Čejka T (in revision) Farming system archetypes help explain the uptake of agri-environment practices in Europe. Environmental Research Letters

Václavík T, Langerwisch F, Cotter M, Fick J, Häuser I, Hotes S, Kamp J, Settele J, Spangenberg J, Seppelt R (2016). Investigating potential transferability of place-based research in land system science. Environmental Research Letters 11, 095002.

Appendix

Appendix 1. Explanation of symbols on the map.