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Scale sensitivity of drivers of environmental change across Europe

J. Tzanopoulos^{a,*}, R. Mouttet^b, A. Letourneau^b, I.N. Vogiatzakis^c, S.G. Potts^d, K. Henle^e, R. Mathevet^{b,g}, P. Marty^f

^aDurrell Institute of Conservation and Ecology, School of Anthropology and Conservation, University of Kent, Marlow Building, Canterbury CT2 7NR, UK

^bUMR 5175 – CEFE, CNRS, 1919 route de Mende, 34293 Montpellier Cedex 5, France

^cSchool of Pure & Applied Sciences, Open University of Cyprus, PO Box 12794, 2252 Latsia, Nicosia, Cyprus

^dSchool of Agriculture, Policy and Development, Reading University, Reading RG6 6AR, UK

^eUFZ – Helmholtz Centre for Environmental Research, Department of Conservation Biology, Permoserstr. 15, 04318 Leipzig, Germany

^fUMR 6250, Littoral, Environnement et Sociétés – LIENSs, Université de La Rochelle – CNRS, La Rochelle, France

^gStockholm Resilience Centre, Stockholm University SE-106 91 Stockholm, Sweden

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ABSTRACT

The development of effective environmental management plans and policies requires a sound understanding of the driving forces involved in shaping and altering the structure and function of ecosystems. However, driving forces, especially anthropogenic ones, are defined and operate at multiple administrative levels, which do not always match ecological scales. This paper presents an innovative methodology of analysing drivers of change by developing a typology of scale sensitivity of drivers that classifies and describes the way they operate across multiple administrative levels. Scale sensitivity varies considerably among drivers, which can be classified into five broad categories depending on the response of 'evenness' and 'intensity change' when moving across administrative levels. Indirect drivers tend to show low scale sensitivity, whereas direct drivers show high scale sensitivity, as they operate in a non-linear way across the administrative scale. Thus policies addressing direct drivers of change, in particular, need to take scale into consideration during their formulation. Moreover, such policies must have a strong spatial focus, which can be achieved either by encouraging local–regional policy making or by introducing high flexibility in (inter)national policies to accommodate increased differentiation at lower administrative levels. High quality data is available for several drivers, however, the availability of consistent data at all levels for non-anthropogenic drivers is a major constraint to mapping and assessing their scale sensitivity. This lack of data may hinder effective policy making for environmental management, since it restricts the ability to fully account for scale sensitivity of natural drivers in policy design.

1. Introduction

Although environmental change has always been a part of Earth's functioning and evolution it is currently acknowledged that at present it is taking place at a faster pace and with greater intensity than in the past mainly accelerated by human activities (Schröter et al., 2005). The need for the protection of the natural environment is universally acknowledged (Chapin et al., 2000;

Spangenberg, 2007) and has been the focus of extensive basic and applied research, especially over the last 40 years (Forbes et al., 2004). Despite repeated calls for action and agreed targets under various international initiatives (Millennium Ecosystem Assessment, Convention on Biological Diversity), environmental systems continue to be under threat (Butchart et al., 2010). Managing environmental change is a complex task that needs to take into account ecological, economic and social parameters as well as their interactions (Nelson et al., 2007; Palmer et al., 2004). In many cases environmental conservation and management has been ineffective mainly due to an approach in environmental research that largely separated humans from nature (Berkes and Folke, 1998; Ludwig, 2001).

Responding to this, scientists are increasingly focusing their research on the analysis of socio-ecological systems (Berkes et al., 2003; Young et al., 2006). A fundamental issue is the identification of the drivers of change that determine the status of ecosystems

* Corresponding author at: Durrell Institute of Conservation and Ecology, University of Kent, 14b Marlowe Building, Canterbury CT2 7NR, UK. Tel.: +44 01227 823146; fax: +44 01227 827289.

E-mail addresses: j.tzanopoulos@kent.ac.uk (J. Tzanopoulos), raphaelle.mouttet@gmail.com (R. Mouttet), Aurelien.LETOURNEAU@cefe.cnrs.fr (A. Letourneau), ioannis.vogiatzakis@ouc.ac.cy (I.N. Vogiatzakis), s.g.potts@reading.ac.uk (S.G. Potts), klaus.henle@ufz.de (K. Henle), raphael.mathevet@cefe.cnrs.fr (R. Mathevet), pascal.marty@univ-lr.fr (P. Marty).

and their socio-ecological resilience (Nelson et al., 2006; Folke et al., 2007). Social and ecological resilience assessment would benefit from analysis of socio-economic dynamics acting as root causes of environmental change so that public policies around those issues can be integrated into nature conservation strategies.

Addressing drivers of change and determining their impact on ecosystems and more broadly on the environment is a major challenge. First of all, the polysemy of the concept “driver of change” and its consistency depend on the conceptual framework of analysis adopted (Maxim et al., 2009). Terms such as ‘direct drivers’, ‘indirect drivers’, ‘pressures’ and ‘threats’ are often used in a confusing way. Secondly, numerous and diverse drivers – human induced activities as well as natural phenomena and interactions among them – may affect ecosystems. Thirdly, the challenge of addressing the drivers of change is not only related to the identification and description of all relevant social-economic-cultural and environmental drivers, but must also include the choice of the appropriate spatial level of the analysis. Socio-economic drivers of change, operating at various administrative and temporal scales and their interactions, determine the intensity of anthropogenic and natural processes and their impacts on biodiversity, ecosystems and the environment in general (Satake et al., 2008). Moreover the way drivers operate or appear across scales is sometimes non-linear (Holling et al., 1998; Alessa and Chapin, 2008). As Cash et al. (2006) have stated “*there is a long history of disappointments in policy, management and assessment arising from the failure to take into proper account the scale and cross-scale dynamics in human-environment systems*”. Policy interventions to regulate or modify drivers of change (especially socio-economic drivers) are formulated and implemented at various levels of the administrative scale (local, regional, national, international) (Henle et al., 2010), but the challenge is to identify the relevant set of drivers at each level. Therefore, it is important to analyse and describe the way drivers of change operate across multiple administrative levels.

The main objective of this work is to analyse the scale sensitivity of drivers of environmental change across the European Union. To this end we develop an innovative methodology that consist of the following main steps: (i) compilation of a list of the most important drivers of environmental change through literature review; (ii) mapping appropriate indicators for these drivers; and (iii) development of a typology of scale-sensitivity of drivers that classifies and summarises the behaviour of drivers across multiple administrative levels. Based on these three steps, we discuss how the new typology of drivers can better inform policy making for nature conservation.

2. Methodology

2.1. Conceptual framework

One of the initial challenges for the development of a typology of drivers is the large number of concepts and terms previously used to define drivers of change. A comprehensive overview of the different terms, definition and conceptual frameworks of drivers of change is provided by Anastasopoulou et al. (2009). There is an inconsistency across terminologies, which does not allow for a systematic comparison of the numerous studies on drivers of environmental change. We identified two main approaches on defining drivers of change that are often used among researchers and practitioners: the Millennium Ecosystem Assessment (MEA) (MEA, 2005) approach and the European Environment Agency (EEA, 1995) approach. According to the MEA approach, drivers are defined as “any natural or human induced factor that directly or indirectly causes a change in an ecosystem” and are subsequently divided into two categories: (i) ‘direct drivers’, which have a direct

impact on ecosystems, and (ii) ‘indirect drivers’ whose impacts are more diffuse (Nelson et al., 2006). According to the EEA approach, drivers are divided into ‘driving forces’ and ‘pressures’ with the former corresponding to ‘indirect drivers’ and the latter corresponding to ‘direct drivers’ of the MEA. The EEA approach is built on the Driver-Pressure-State-Impact-Response (DPSIR) framework (EEA, 1995). Despite differences in terminology, both aforementioned approaches are very similar in describing drivers of environmental change. However, the DPSIR framework uses the term “pressures” which we find problematic because it is not a neutral term; it carries an implicit value and places the emphasis on the negative impacts of human activity on ecological systems, which, though often is the case, is not always so. Therefore, we consider the MEA framework more appropriate for socio-ecological studies as it provides a more flexible definition and analysis of drivers.

2.2. Data acquisition

Using an extensive literature review we compiled a list of the most important drivers that affect ecosystems (Table 1) and identified indicators for each driver. The review included published work from scientific journals, databases, and reports on the drivers of change and the impacts of policies on anthropogenic and natural processes. This produced a list of approximately ninety indicators. Only a subset of twenty-seven indicators (Table 2) describing mainly anthropogenic driving forces of environmental change (MEA, 2005; Anastasopoulou et al., 2009) was finally selected, based on the criteria of data availability for all four levels of the European NUTS nomenclature (from NUTS 0 to NUTS 3). The term NUTS stand for “Nomenclature of territorial units for statistics” where NUTS 0 indicates countries, NUTS 1 major socio-economic regions, NUTS 2 basic regions and NUTS 3 small regions (see http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction). EUROSTAT of the European Commission and CORINE land cover (CLC) of the EEA were the primary data sources for indicators since they are the commonly used currency of harmonised data by EU Member States. All indicator data were compiled into a GIS database and a set of four maps per indicator was produced, one for each administrative level (NUTS0, NUTS1, NUTS2 and NUTS3). Since all NUTS belonging to a particular level do not have the same extent, indicators were standardised by area in order to generate comparable values across Europe. We plotted the standardised values of all 27 drivers for all four NUTS levels.

2.3. Quantification of scale sensitivity

A standardised method ensuring comparability between both administrative levels and indicators was implemented to measure numerically the scale sensitivity of drivers. The method consisted of the assessment of the variation of two key variables across administrative levels: change in intensity and change in evenness.

Evenness is a measure of how similar the values of an indicator are for different regions within a larger unit. We used Shannon’s evenness index (E) which is derived from Shannon’s diversity index. These indices are widely used in ecology to measure species diversity, but it can be applied in different contexts to measure the diversity of landscape patterns (Hung et al., 2010) or physical properties of the earth surface (Benito-Calvo et al., 2009). In this study, Shannon’s evenness index measures the homogeneity of the spatial distribution of indicator values within different regions by comparing Shannon’s diversity index with its value if indicator values would be evenly distributed in the considered regions (Begon et al., 2006). Thus, it is appropriate for characterising the change of the drivers’ spatial distribution across scales.

Table 1
Data availability for important drivers of environmental change.

Drivers		Indicators	Data availability (NUTS 0–3)	
Demographic	Population	Total population size	Yes	
		Population density	Yes	
	Age population distribution	Population growth	Yes	
		Age structure (3×)	Yes	
	Mortality	Mortality rate	Yes	
	Fertility	Total fertility rate (TFR)	No	
		Life expectancy	No	
	Migration	Under five mortality rate [MDG]	No	
		Net internal migration rate	No	
	Economic	Economy – production	GDP	Yes
Employment in services			Yes	
Unemployment			Yes	
Industry		Average household income	No	
		Employment in industry	Yes	
		Types of industrial activities	No	
Agriculture		Arable area	Arable area	Yes
			Permanent crops area	Yes
		Grasslands area	Grasslands area	Yes
			Farm size	Yes
		Utilised agricultural area (UAA)	Utilised agricultural area (UAA)	Yes
			Employment in agriculture	Yes
		Farm size	Farm size	Yes
			Livestock density (LSU)	Yes
		% of land/agricultural area under irrigation	% of land/agricultural area under irrigation	Yes
			Use of agricultural pesticides	No
		Fertiliser consumption	Fertiliser consumption	No
			% Holdings with area under organic farming	No
		Agricultural production index	Agricultural production index	No
			Area under organic farming EEA	No
		Agri-environmental management contracts EEA	Agri-environmental management contracts EEA	No
			% of exports of forestry products	No
		Forestry	Wood harvesting intensity	No
			Intensity of forest resource use	No
Tourism		Number of beds	Yes	
Consumption		Motor vehicles per 000 pop	Motor vehicles per 000 pop	No
			Food & livestock trade – import-quantity	No
		Food & livestock trade – export-quantity	Food & livestock trade – export-quantity	No
			Food & livestock trade – import-value	No
		Food & livestock trade – export-value	Food & livestock trade – export-value	No
			Materials consumption per capita	No
		Change in consumption patterns	Per capita caloric intake	No
			Balance of trade in goods and services	No
		Trade	Percent of population living below the poverty line	No
		Poverty	Gini index of income inequality	No
			Total air passengers traffic	No
		Increased mobility	Final energy consumption EEA	No
Primary energy consumption by fuel EEA			No	
Energy consumption		Renewable electricity consumption EEA (R class)	No	
		Renewable primary energy consumption EEA (R class)	No	
Total primary energy intensity EEA (R class)		Total primary energy intensity EEA (R class)	No	
		The makeup of participants	Share of women in economically active population	Yes
Share of women in wage employment in the non-agricultural sector			No	
Proportion of seats held by women in national parliament			No	
The mechanisms of dispute resolution		Number of ADR (alternative dispute resolution) schemes	No	
	Role of the state relative to the private sector	PPPs (Public–private partnerships)	No	
Education	Public spending on education, total (% of GDP)	No		
Cultural – religious	Change in life-style	No		
	Environmental awareness	No		
Science & Technology	Innovation and technological change	Number of students	No	
		Number of universities/superior schools	No	
		R&D scientists and technicians per 1000 people	No	
		Human resources in science & technology	No	
		Expenditure in R&D as a % of GDP	No	
	Agricultural science and technology	Farmers training level	Yes	
		Technology	Patent application	No
	Information technology	Internet use	No	
	Cleaner technologies	Share of renewable energy	No	
	Climate change		No	

Table 1 (Continued)

Drivers	Indicators	Data availability (NUTS 0–3)	
Plant nutrient use	Nitrogen use and trends	Nitrogen balance	No
	Phosphorus use and trends	Phosphorus balance	No
	Potassium use and trends	Potassium balance	No
Land conversion	Deforestation	Deforestation	Yes
	Afforestation	Afforestation	Yes
	Agricultural conversion	Agricultural conversion	Yes
	Wetland loss	Wetland loss	Yes
	Urbanisation	Urbanisation	Yes
Biological invasions	Number of recorded alien species	No	
Natural disasters	Fire	Forest fire hazard potential	No
	Floods	Flood hazard potential	No
	Droughts	Large scale drought occurrence	No
	Landslides	Exposition to landslide hazard	No
Pollution	Exposure of ecosystems to acidification, eutrophication and ozone EEA	No	
	Emissions of acidifying substances	No	
	Emissions of ozone precursors	No	
	Emissions of primary particles and secondary particulate matter precursors EEA	No	
	Exceedance of air quality limit values in urban areas	No	
Mining	Production of selected minerals	No	
Water stress	Intensity of use of water resources OECD	No	
Waste	Generation and recycling of packaging waste EEA	No	

Shannon's evenness index (Hill, 1973) is defined as follows:

$$E_i = P_j \times \frac{\ln(P_j)}{\ln(N_i)}$$

where E_i is the evenness at NUTS level i ($0 \leq i \leq 3$), N_i is the total number of territorial units within NUTS level i , and P_j is the relative value of the indicator in territorial unit j ($1 \leq j \leq N_i$). $P_j = D_j/D_k$, where D_j is the indicator value in territorial unit j and D_k is the sum of the indicator value in the total number of territorial units.

The Shannon's Evenness Index is constrained between zero and one and the closer evenness is to 1, the more the regions within a NUTs level are similar in terms of the values of the indicator.

Change in intensity (I) was assessed by measuring the relative change in the median of an indicator at a given administrative level compared to NUTS level 0 and defined as follow:

$$I_i = \frac{\tilde{X}_i - \tilde{X}_0}{\tilde{X}_0} \times 100,$$

where I_i is the change in intensity at NUTS level i ($0 \leq i \leq 3$), \tilde{X}_i is the median of the indicator at NUTS level i .

Intensity is equal to zero at NUTS level 0 and can either be positive or negative in other levels. Intensity measures how low or high values of an indicator are over- or under-represented within regions from one NUTS level compared to NUTS level 0. A negative

Table 2
List of indicators used in the analysis.

Indicator	Unit	Data source
Afforestation	% of total area	CLC change 1990–2000
Age structure (3×)	% of population within each age class	Eurostat (decade 2000–2010)
Agricultural conversion	% of total area	CLC change 1990–2000
Arable area	% of total area	CLC 2000
Deforestation	% of total area	CLC change 1990–2000
Employment in agriculture	% of total active population	Eurostat (decade 2000–2010)
Employment in industry	% of total active population	Eurostat (decade 2000–2010)
Employment in services	% of total active population	Eurostat (decade 2000–2010)
Farm size	Hectares	Eurostat (decade 2000–2010)
Farm standard gross margin	European size units/utilised agricultural area	Eurostat (decade 2000–2010)
Farmers training level	% of farmers with full agricultural training	Eurostat (decade 2000–2010)
Forest area	% of total area	CLC 2000
Gross Domestic Product (GDP)	Purchasing power standard per inhabitant	Eurostat (decade 2000–2010)
Irrigation	% of utilised agricultural area	Eurostat (decade 2000–2010)
Livestock density	Livestock units/utilised agricultural area	Eurostat (decade 2000–2010)
Mortality	Number of deaths per 1000 inhabitant	Eurostat (decade 2000–2010)
Pasture area	% of total area	CLC 2000
Permanent crop area	% of total area	CLC 2000
Population density	Number of inhabitants per km ²	Eurostat (decade 2000–2010)
Tourism infrastructure	Number of beds in hotels per km ²	Eurostat (decade 2000–2010)
Unemployment	Unemployment rate	Eurostat (decade 2000–2010)
Urbanisation	% of total area	CLC change 1990–2000
Utilised agricultural area	% of total area	Eurostat (decade 2000–2010)
Wetland loss	% of total area	CLC change 1990–2000
Women in active population	% of total active population	Eurostat (decade 2000–2010)

1 country, 2 regions, 4 counties

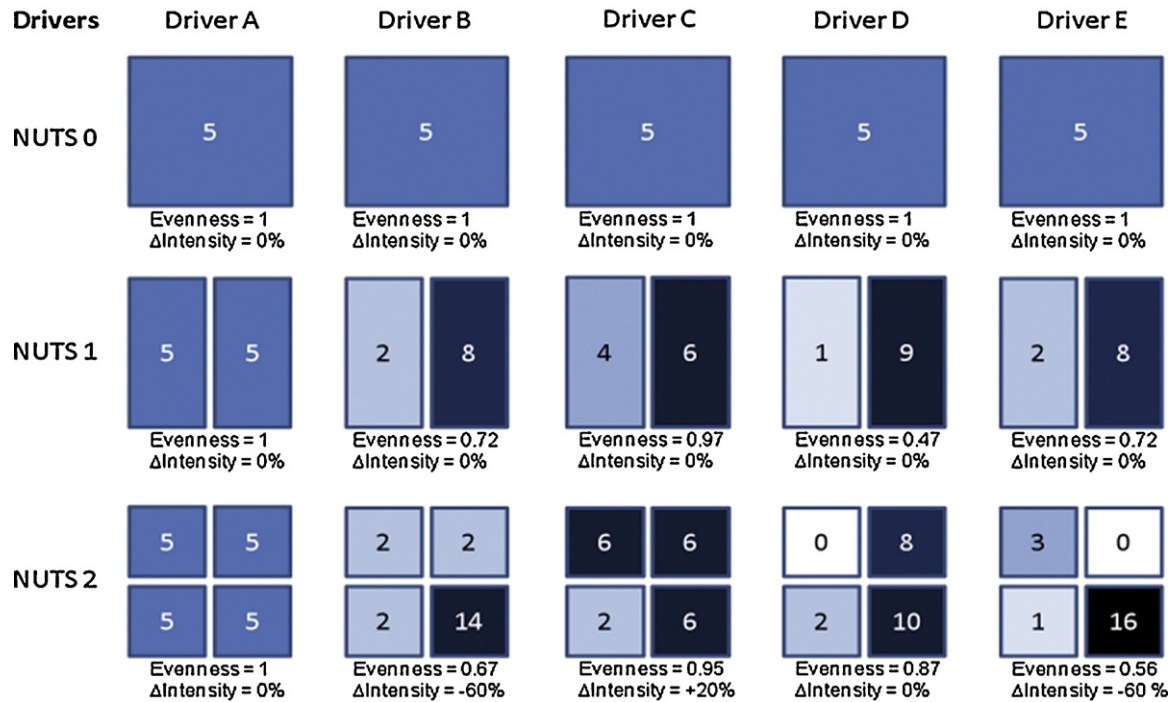


Fig. 1. Conceptual framework to assess scale sensitivity of random drivers (A, B, C, D and E) over multiple scales. Evenness is computed based on Shannon's index of evenness and the change in intensity is based on the difference of the median between different scales for the considered driver. NUT: Nomenclature of territorial units for statistics (EUROSTATS): NUT 0: countries; NUTS 1: major socio-economic regions; NUTS 2: basic regions; NUTS 3: small regions.

value of intensity stands for an over-representation of low values of the indicator whereas a positive one stands for an over-representation of high values. We have chosen to use NUTS level 0 as the baseline in order to make all other changes among NUTS levels and among drivers comparable. Furthermore, measuring the evenness and intensity of the drivers is independent of the number of regions within NUTS levels as well as the units of the indicators: thus, the use of these variables (as shown in the example in Fig. 1) defines a general framework for assessing scale sensitivity.

2.4. Development of a scale sensitivity typology

In order to produce a typology of drivers according to their scale sensitivity we first used cluster analysis in order to identify groups of drivers that show similar patterns in the way they change across scales. The robustness of the cluster analysis outcome was subsequently tested.

More specifically, firstly an ascendant hierarchical clustering (AHC) procedure was performed on centred and scaled data of evenness and intensity across administrative levels to identify and qualify groups of similar indicators. Ward's hierarchical clustering method was used to identify mutually exclusive subsets in which the within-cluster variance was minimised (Ward, 1963). Ward's algorithm can generate clusters of small size (only few objects assigned into a cluster) and thus, it can effectively identify outliers or minor patterns within the data. This ability to cluster makes Ward's algorithm particularly suitable for the analysis of drivers as the main interest is in identifying and separating clusters of indicators with unique attributes regardless of the actual size of the cluster. Moreover, the accuracy of Ward's algorithm has been tested and compared against other clustering methods and has been shown to be robust and efficient in identifying clusters of

dissimilar characteristics (Scheibler and Schneider, 1985; Hirano et al., 2004).

In order to further test the robustness of our typology we used two approaches: a bootstrap technique for the Ward algorithm, which was then followed by a comparison of the outcome of the Ward cluster analysis with the K -means cluster analysis. So first we compared our classification based on the set of 27 indicators with a classification obtained from a resampled set of indicators. The resampling consisted of 21 out of 27 indicators chosen randomly. This comparison was repeated 100 times with random subsets of drivers.

In a second step, we compared the Wards classification with multiple K -means classification over the whole set of 27 indicators. In K -means classification, the indicators belong to the cluster with the nearest mean (i.e. centroids). The initial centroids of clusters are determined randomly. Therefore, two K -means cluster analysis over the same set of indicators can yield different classifications. Thus, the K -means cluster analysis was run 100 times with the whole set of indicators.

3. Results

3.1. Visualisation of indicators across administrative levels

The visual examination of maps at administrative levels from NUTS 0 to NUTS 3 illustrates some differential break-up patterns of indicator values through the European territory. Fig. 2 presents a sample of those maps, which capture the three main disaggregation patterns across the administrative levels; the whole set of 108 maps is available at <http://www.scales-project.net/>. One pattern of driver downscaling shows homogeneity across administrative levels, as is the case of employment in services in the United Kingdom. Other drivers exhibit less homogeneous

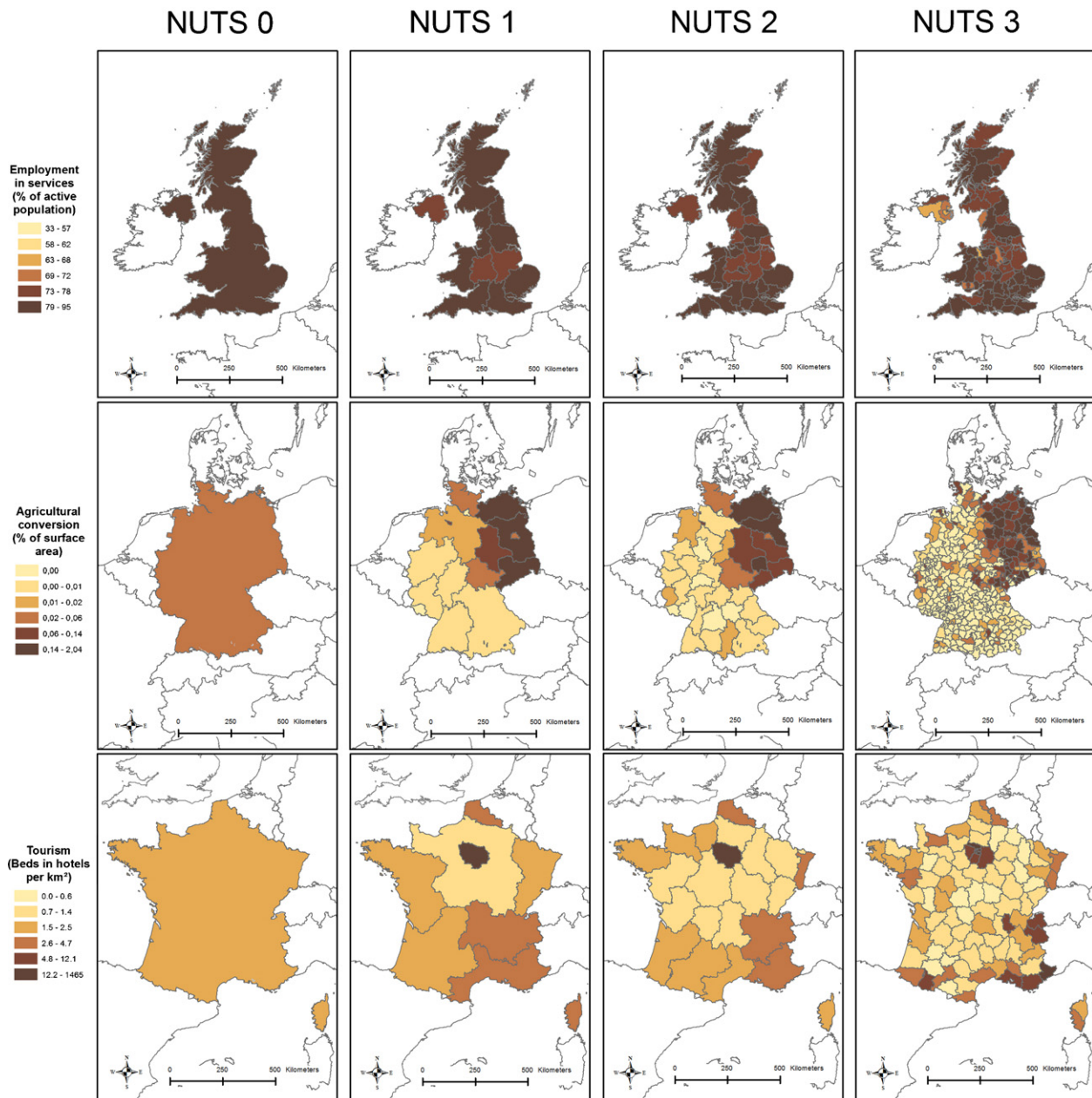


Fig. 2. Visualisation of indicators across administrative levels. Examples with three indicators; employment in services in the United Kingdom, agricultural conversion in Germany, tourism in France. Quantile discretisation from EU wide values at NUTS level 3. Source: Eurostat.

distributions, with clusters of contrasting values revealed at finer levels, as exemplified by the marked east-west polarisation of agricultural conversion values in Germany. Conversely, clusters of similar values can show a scattered pattern across an administrative unit, as seen for tourism infrastructure in France that shows multiple clusters of high values in several places (essentially big cities and coastal areas).

3.2. Quantification of drivers' sensitivity to scale effects

Values of evenness and change in intensity were plotted for each indicator on a two-axis graph, either simultaneously or individually (Figs. 3 and 4). Fig. 3 illustrates the overall variation of evenness and intensity of the 27 indicators evaluated across administrative levels, providing evidence of scale sensitivity for

some drivers. Breaking down Fig. 3 into individual indicators (Fig. 4) allows a clearer representation of the spectrum of scale sensitivity profiles displayed by individual indicators. Indeed, variations of evenness and intensity can vary greatly in direction and amplitude, with the resulting pattern closely linked to the level analysed (Fig. 4). For example, afforestation (Fig. 4i) and urbanisation (Fig. 4xxiv) display contrasting variations of intensity across administrative levels with a decrease of intensity for the former and an increase for the latter when moving to finer administrative levels. Other indicators can show similar qualitative variations of evenness and intensity, though significant differences in amplitude can be seen. This is the case for urbanisation and population; both exhibit the same shape of sensitivity profile, but urbanisation has a greater amplitude than population (Fig. 4xxiv and xxi). Furthermore, an indicator can exhibit contrasting variations of evenness

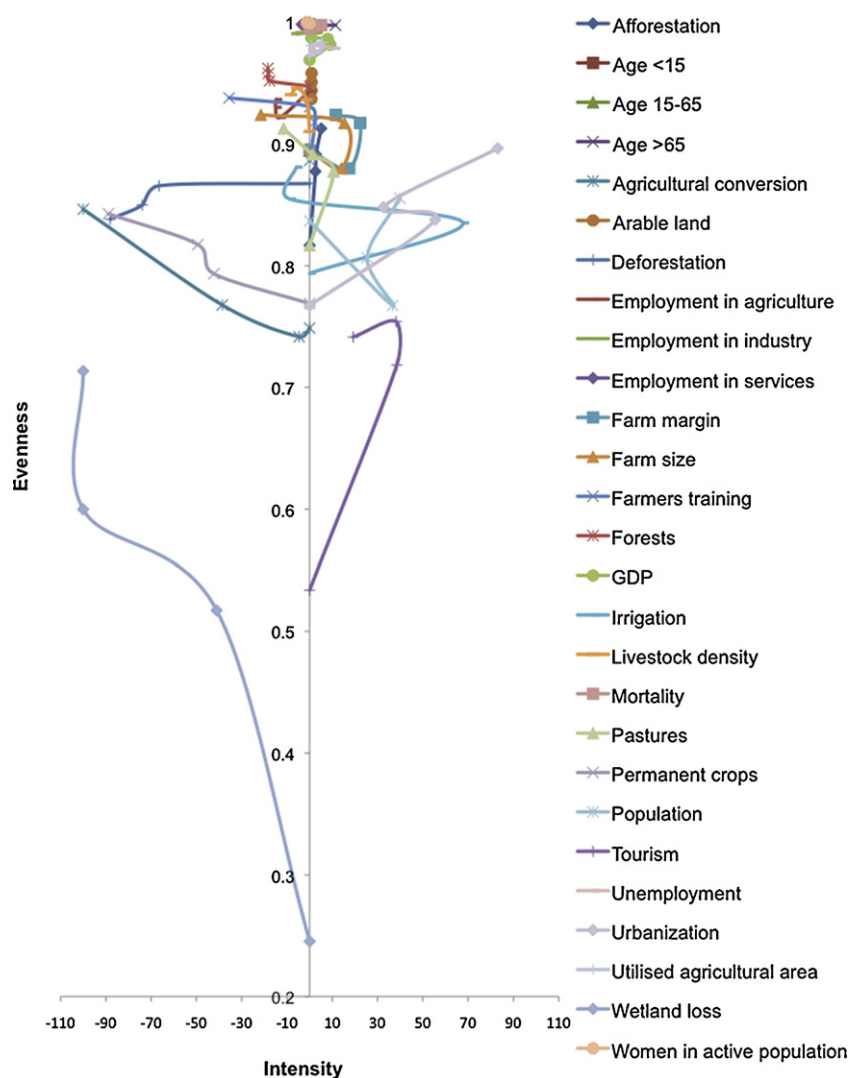


Fig. 3. Simultaneous scale sensitivity of indicators: variation of evenness (vertical axis) and intensity (horizontal axis) across administrative levels. Indicators are listed along a decreasing gradient of evenness at NUTS level 0; arrows begin with values at NUTS level 0 and end with values at NUTS 3 level.

and intensity across administrative levels. Tourism infrastructure is a clear illustration with an increase in intensity observed between NUTS levels 0 and 1, but a decrease in intensity between NUTS levels 2 and 3 (Fig. 4xxii). In addition, there is a group of indicators that do not show much scale sensitivity, such as GDP (Fig. 4xv).

Although the scale sensitivity of a single driver can be efficiently explored using graphical representation of its evenness and intensity variations across administrative levels, when dealing with a whole set of indicators, a typology that captures the multifaceted nature of scale sensitivity is needed to identify drivers that share common characteristics.

3.3. Classification of drivers

The ascendant hierarchical clustering performed on evenness and intensity values of indicators produces a cluster dendrogram from which five classes have been extracted (Fig. 5). Using mean values of evenness and change in intensity, Fig. 6 presents the scale sensitivity profiles of each of the five classes across administrative levels. In class 1, the change in evenness and intensity is very limited. Class 2 exhibits a similar behaviour with increased amplitude, and the differentiation across administrative levels are

more apparent; the overall evenness is lower than in class 1 and tends to increase when moving to finer levels. Classes 3–5 are characterised as much more scale sensitive. Class 3 displays both an increase in evenness and an increase in intensity when moving to finer levels. In contrast, classes 4 and 5 show an increase in evenness, but exhibit a decrease in intensity at finer administrative levels. Classes 4 and 5 differ in their amplitude of variation, with class 5 having much stronger variation.

The categorisation of indicators within these classes follows a thematic logic rather than being random (Table 3). Indicators within each class do not only share common patterns of evenness and intensity change across levels but they do also show a high homogeneity in terms of socio-economic properties. Class 1 groups together most of the indicators related to demographic and economic indirect drivers; those indicators show a rather homogeneous pattern across EU countries and across different administrative levels. This pattern is expected to a certain extent since most of the EU Member States are among the most developed globally and thus, if compared to other countries across the globe, they do appear rather homogenous in terms of economic development. Indicators in class 2 are mainly related to changes in the agricultural sector and rural areas (e.g. farm size, livestock density pasture area). Indicators in classes 3–5 are more scale

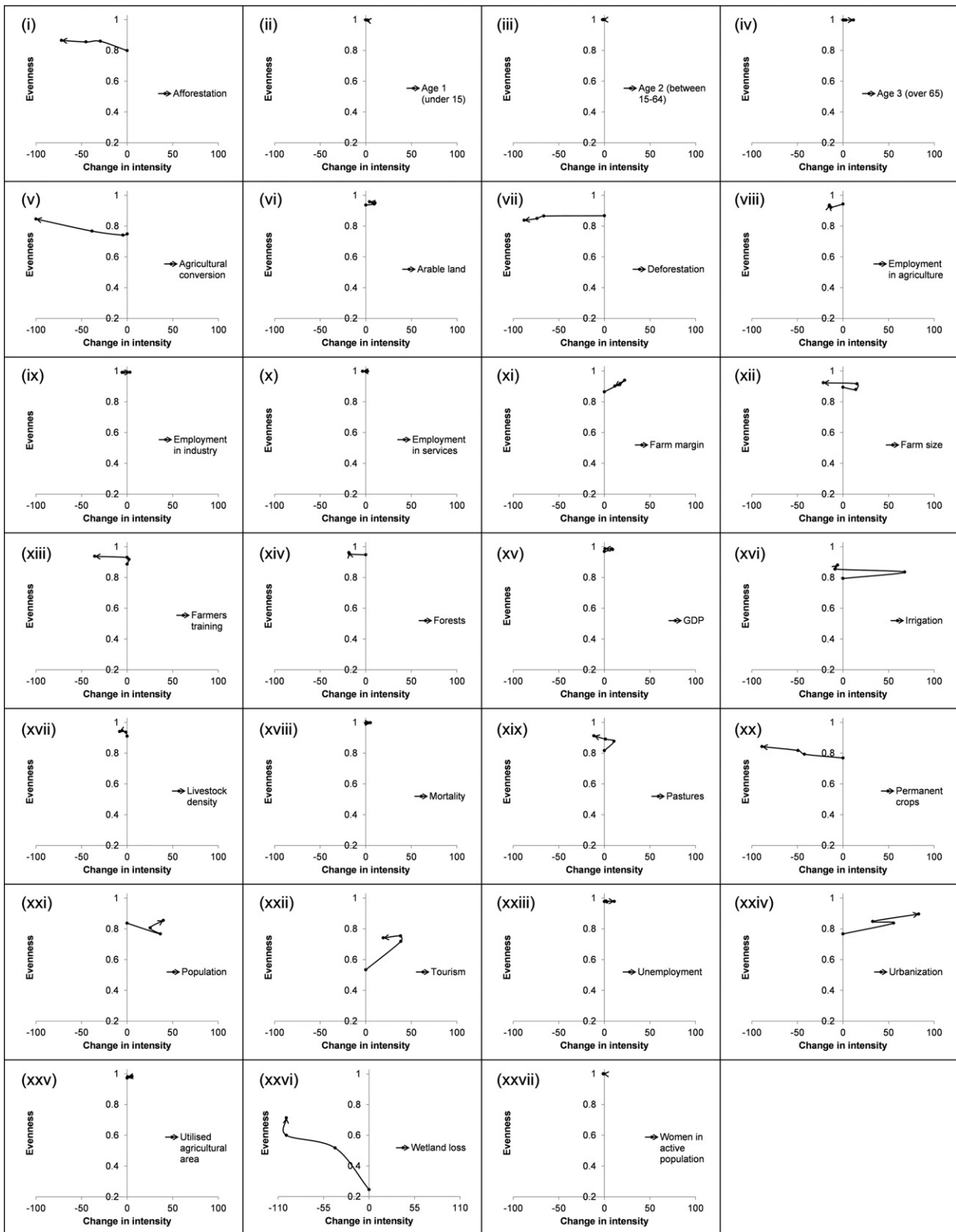


Fig. 4. Individual scale sensitivity of indicators: variation of evenness and intensity across administrative levels (arrows begin with values at NUTS level 0 and end with values at NUTS level 3). E: evenness; I: intensity. Drivers: (i) afforestation, (ii) age structure 1 (<15), (iii) age structure 2 (15–64), (iv) age structure 3 (>65), (v) agricultural conversion, (vi) arable area, (vii) deforestation, (viii) employment in agriculture, (ix) employment in industry, (x) employment in services, (xi) farm margin, (xii) farm size, (xiii) farmers training, (xiv) forest area, (xv) Gross Domestic Product, (xvi) irrigation, (xvii) livestock density, (xviii) mortality, (xix) pasture area, (xx) permanent crop area, (xxi) population density, (xxii) tourism infrastructure, (xxiii) unemployment, (xxiv) urbanisation, (xxv) utilised agricultural area, (xxvi) wetland loss, (xxvii) women in active population.

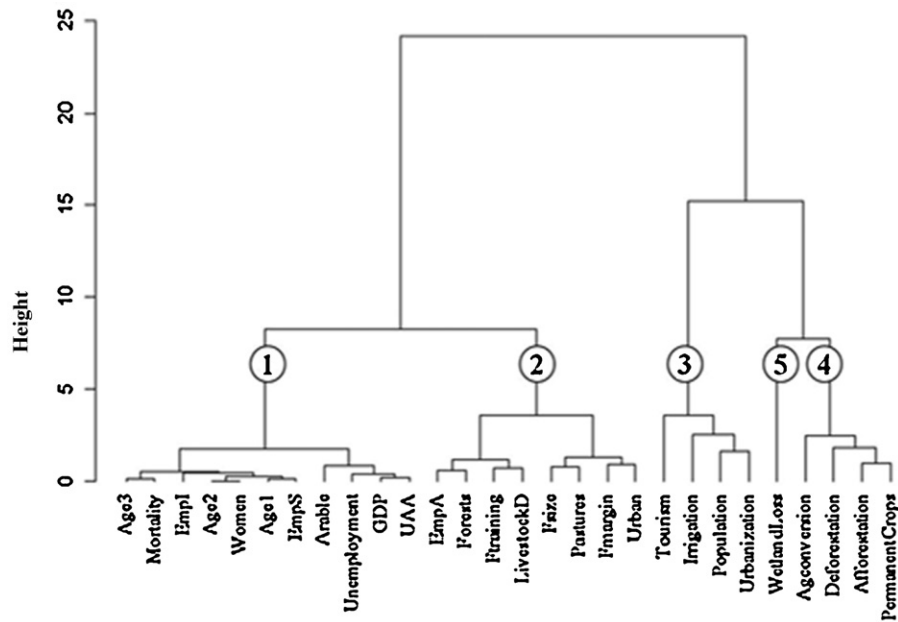


Fig. 5. Cluster analysis dendrogram (numbers delineate the five classes that were opted for the typology).

sensitive. Most of the indicators in class 3 refer to geographical dynamics of urban areas (e.g. urbanisation, population density, tourism infrastructure). Urban dynamics traditionally appear spatially clustered in specific locations across Member States. However, over the last few decades such drivers appear more diffused (and thus of moderate scale sensitivity) across the EU as a

result of increased urbanisation pressure. Finally, indicators related to land conversion are found within classes 4 and 5. The high scale sensitivity of the indicators in those groups indicates that land conversion is taking place in a rather spatially clustered pattern with very different geographical signatures among EU regions.

Bootstrapping showed that the clustering results are robust. Over the 100 runs, we obtained an average agreement of 95.5% and 56 runs had an agreement of 100%. Over the 100 runs of the K-means based sensitivity analysis, none reached an agreement of 100% but we obtained an average agreement of 85.3%.

4. Discussion

The results show that the presented typology of scale sensitivity is robust despite the limited set of drivers considered in the classification process. Besides, this typology is dynamic, not closed and rigidly defined since new drivers can be analysed, and then ascribed to one of the classes when data become available in the future.

4.1. Scale sensitivity and policy implications

It is well known that human activities (Vitousek et al., 1997), and in particular land use and land cover change, have a significant effect on ecosystems and include such activities as destruction of habitats, alteration of nutrients cycles, and conversion of land use. The development of effective nature conservation and environmental management plans and policies requires a sound understanding of all the actors and driving forces involved in shaping and altering habitats, ecosystems, and species presence and abundance (Young et al., 2005; Henle et al., 2008). Anthropogenic drivers operate at multiple levels of the administrative scale and may show non-linearity across scales (Cash et al., 2006; this study). Moreover, geographical information can be represented differently depending on the scale of analysis (Syphard et al., 2011). Thus, spatial analyses across scales are essential to understand what makes a driver scale sensitive (Dungan et al., 2002; Ravera et al., 2011) and reduce mismatches between the scale at which drivers operate and at which they are

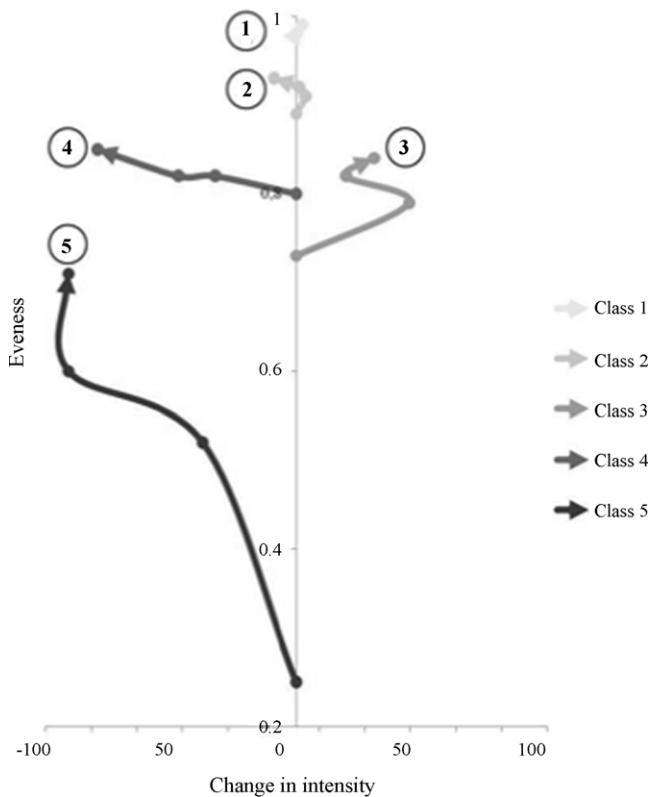


Fig. 6. Scale sensitivity of clusters: mean variation of evenness and intensity across administrative levels. (Arrows begin with values at NUTS level 0 and end with values at NUTS level 3.)

Table 3
Scale sensitivity typology of drivers of change.

Class	Indicators	Scale sensitivity	Evenness	Intensity
1	Age structure Mortality GDP Employment in industry Employment in services Unemployment Women in active population Utilised agricultural area Arable area	Very low	Almost no change	Almost no change
2	Employment in agriculture Farm margin Farm size Farmers training Livestock density Forest area Pasture area	Low	Slight increase	Almost no change
3	Population density Tourism infrastructure Urbanisation Irrigation	Moderate	Moderate increase	Moderate increase
4	Permanent crop area Afforestation Deforestation Agricultural conversion	High	Moderate increase	Large decrease
5	Wetland loss	Very high	Large increase	Large decrease

addressed by policy and management (Cumming et al., 2006; Henle et al., 2010). Our study shows that there are different geographical signatures of drivers of change. This geographical signature can thus influence the efficiency of any nature conservation policy depending on the sensitivity of the drivers and the scale-matching of policies and management.

Furthermore, the analysis developed here shows that scale sensitivity varies considerably among drivers and that drivers can be classified into five broad categories of scale sensitivity depending on the response of evenness and change in intensity across administrative levels. Generally speaking, indirect drivers tend to show low scale sensitivity, although there are some exceptions, such as tourism. In contrast, most of direct drivers show high scale sensitivity with characteristic examples being deforestation, agricultural conversion, and wetland loss. This confirms previous analyses in agricultural landscapes that show strongly temporal and spatial differences in changes in agricultural practices, forestry, and wetland management across Europe (reviewed by Niemelä et al., 2005; Young et al., 2005; Henle et al., 2008). Moreover, scale sensitive drivers can be further divided into (i) drivers whose intensity decreases (e.g. agricultural conversion), and (ii) drivers whose intensity increases (e.g. urbanisation) across administrative levels. The trends observed here suggest that non-scale sensitive drivers have a rather diffuse distribution, whereas scale sensitive drivers have a non-diffuse distribution across Europe. Among scale sensitive drivers, those whose intensity decreases tend to be clustered within relatively few areas, while those whose intensity increases tend to be more scattered.

The presence of scale sensitivity has important implications for policy making (Cumming et al., 2006). Policies addressing direct drivers of change, such as land conversion, need to be scale sensitive (i.e. to take scale into consideration during formulation) to better respond to scale differentiation that is observed across administrative levels (Henle et al., 2010).

Scale sensitivity of drivers of environmental change has two types of consequences for public action. On one hand, as far as knowledge of anthropogenic processes is concerned, focusing on large or medium scale (e.g. NUTS 0 or 1) allows the identification of the main regional contrasts based on indirect drivers. Maps, in particular, show the extent of convergence or divergence of regions in terms of socio-economic factors. However, this large/medium scale focus is less relevant for direct drivers because it fails to capture their strong local contrasts (Young et al., 2005; Cash et al., 2006). On the other hand fine scale focus (NUTS 2 or 3) is less relevant for indirect drivers; even though European space is not socio-economically homogeneous, the 27 Member States are among the most developed countries in the world, and their regions share many similar socio-economic characteristics. The fine scale focus, in contrast, is very relevant for direct drivers whose differences are strongly dependent on local historical and environmental conditions, or for drivers linked to activities that are geographically polarised (e.g. tourism in coastal or mountain regions). Therefore at a fine scale, direct drivers allow local anthropogenic contexts for environmental management and nature conservation to be defined (Young et al., 2005; Cash et al., 2006; Henle et al., 2008).

When it comes to policy making, the low scale sensitive indirect drivers are generally addressed in sectorial policies that operate at large scale (countries or large regions in Member States with a federal structure). In contrast, the existence of a clear scale sensitivity of direct drivers has a high relevance for regional/local policies based on specific measures. This phenomenon advocates for flexibility and a degree of autonomy in regional/local decision making for environmental management and planning (Young et al., 2005). The observed scale sensitivity of drivers of change across scales can be tackled by multi-level governance (Cash et al., 2006): for instance Member States, following the EU strategic choices, could first support low scale sensitive policies in favour of nature conservation, such as supporting employment in agriculture, as maintaining

agricultural landscapes is necessary to launch measures aimed at improving the conservation status of many habitats and species (Bignal and McCracken, 2000; Chamberlain et al., 2000). Policies could also, however, support targeted actions adapted to local contexts (e.g. regional/local measures to limit urban spread or to support some types of land use) (Mühlenberg and Slowik, 1997). To help improve existing ones and to develop new scale sensitive policies, further research is needed to investigate the efficacy and suitability of different policy instruments to address and regulate scale sensitive drivers of change.

4.2. Data gaps

Over the last 10 years significant progress has been made on the development of appropriate indicators of drivers of change (OECD, 1999; Campling et al., 2003; Niemi and McDonald, 2004; Butchart et al., 2010), but the same has not been the case on the compilation of data for most of those indicators, especially at multiple administrative levels. Several indicators are detailed up to NUTS level 2, if not just up to NUTS 0, which reflects the standard level of data availability for European-scale regional statistics.

Data availability at NUTS level 3 is relatively satisfactory for indicators related to demography and some economic factors. Data relevant to indicators of other indirect drivers, such as socio-political and science and technology, are only available at NUTS level 0 (national level) with only few exceptions – though such data may be regionally and locally available but usually not open access and difficult to locate. However, the lack of data is even more severe when it comes to direct drivers of change. Apart from the data that can be derived from land use maps, no data are available for any other direct driver. For example, “plant nutrient use” indicators can only be assessed down to NUTS level 2, while data on biological invasions, pollution, climate change, and water stress are non-existent or restricted to national level only (NUTS 0). The lack of consistent data available at lower administrative levels is a major constraint to mapping and analysing drivers and their indicators across administrative levels. Furthermore NUTS level 3 is still a relatively coarse scale and having easily available harmonised data at sub-municipal or municipal scale (LAU 1 or 2 in the European nomenclature) is of great potential interest to policy development. The need for databases in environmental management and nature conservation is clearly identified (Bisby, 2000; Edwards et al., 2000). However, the integration of socio-economic data in such databases is still an issue. Many studies on environmental or nature conservation issues collect socio-economic data, mainly through interviews or focus groups (Kremen et al., 1999). Richardson et al. (2006) addressed the issue of commercial fishing revenue losses in a study on marine reserve design, and they first used coarse-scale resolution data from official statistics. But when they used fine-scale survey yielded data they found substantial changes in the expected losses linked to the establishment of the marine reserve. Modelling socioeconomic factors can be a solution to cope with such a lack of data (Settele et al., 2005; Haberl et al., 2009). Nevertheless, for socio-economic data relevant for environmental management and showing strong scale sensitivity, it is of great importance to collect data at both coarse and fine scales.

Moreover, socio-economic data are collected on the basis of administrative or statistical units, while on the other hand many databases related to biodiversity issues (e.g. atlas of species, local or regional surveys) and other environmental factors (e.g. climate, land use) are usually available on a grid basis. Therefore a harmonisation of socio-economic and ecological datasets with the use of the common EU standard grid (available by the European Environment Agency is highly recommended to support the

development of more effective policies to tackle the drivers of environmental change at the most appropriate scales).

5. Conclusion

This paper provides an innovative methodology for assessing the scale sensitivity of drivers of environmental change and shows that the spatial distribution of drivers at multiple scales may follow different geographical patterns; as the focal scale of analysis changes certain drivers show an increased unevenness in their spatial distribution, and their intensity may change depending on the location of the spatial units concerned. In that sense it is possible to identify a geographical signature for each driver and thus future work should aim to produce a typology of areas based on such a geographical signature.

Moreover, understanding the scale sensitivity of the drivers of change enables to assess whether existing indicators are scale-relevant with the territorial level of the designed policies and plans. Since drivers of change operate at multiple scales and levels and they often showing strong non-linearity, an analysis of their scale properties is required to better inform environmental policy making.

However, terminological inconsistencies and the lack of consistent data available at all levels is a major constrain to analysing drivers and their indicators across administrative scale. The lack of appropriate data hinders effective policy making, since it does not allow for scale sensitivity to be included into policy design. It is thus imperative that data are collected at the lowest administrative level at least for those drivers that show high scale sensitivity. The scale sensitive typology presented in this paper allows summarising and organising very complex information given by maps at different levels into a hierarchy. It can thus provide an easily interpretable and short description of complex datasets at multiple levels to help support scale sensitive policy formulation.

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