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Analysis

Full speed ahead or floating around? Dynamics of selected circular bioeconomies in Europe

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ABSTRACT

Measuring the progress of the circular bioeconomy requires quantifying a range of indicators. Contrary to previous studies that analyzed only a few indicators, we devise a method that can accommodate any number of them. Our objective is to empirically investigate whether the circular bioeconomies in ten selected European Union Member States were progressing or regressing over 2006–2016 as measured by 41 indicators. We model the development of the intra-distribution of the indicators using Markov transition matrices. We find that the ten circular bioeconomies mostly progressed. Moreover, research and development quickly progressed in the private sector but regressed in the public sector, suggesting substitution between them. Our cross-country comparison reveals that Germany is the front-runner in the circular bioeconomy, but circular bioeconomies in Slovakia, Poland, and Latvia also developed quickly.

1. Introduction

The size of a country's economy is commonly measured by its gross domestic product (GDP) and other comparable indicators (Kubiszewski et al., 2013). A part of the economy is the bioeconomy, which entails all economic sectors and systems linked to biological resources and their functions and principles (European Commission, 2018). Measuring the development of the bioeconomy requires quantifying a range of indicators to determine its impact on the economy, the environment, and society (Wesseler and von Braun, 2017).

The bioeconomy in the European Union (EU) can potentially tackle economic, environmental, and social problems if the transition from a fossil-based economy is approached in the right way (O'Brien et al., 2017). Sustainable land use and natural capital preservation within the bioeconomy could be promoted by following the principles of a circular economy, which is defined as an economy "[...] where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised" (European Commission, 2015, p. 2). Applying the principles of a circular economy in the bioeconomy, the advancement of the circular bioeconomy can contribute to sustainable development by reducing the use of raw fossil materials to mitigate climate change, forming new value chains to promote economic growth, and creating jobs, especially in rural areas. Recent European heatwaves in 2018, 2019, and 2020 and an increasing trend of heatwaves since the 1970s have heightened the urgency to tackle climate change (Zhang et al., 2020). The circular bioeconomy is expected to mitigate the effects of climate change by reducing fossil fuel consumption and adapt to it by reducing heat stress and flood risks by increasing tree and vegetative cover (Bell et al., 2018). However, the transition to a circular bioeconomy requires the sustainable use of natural resources, high expenditures on research and development (R&D) of new technologies, and education for new and restructured jobs (Purkus et al., 2018). These challenges emphasize the need for policy actions to steer this transition in a structured and sustainable way. Hence, the EU and several EU Member States (MSs) as individual countries have launched and adopted bioeconomy policy strategies to achieve long-term sustainable development, such as the EU Green Deal in December 2019 (European Commission, 2019a; German Bioeconomy Council, 2018).

The bioeconomy policy strategies show that the transition to a circular bioeconomy is a political aim deepened by the world's pressing environmental problems. Still, it comes with economic, environmental, and social impacts that must be considered, so the progress of circular bioeconomies in EU MSs should be tracked and compared (Jander and Grundmann, 2019). In the last decade, several large frameworks have been developed to monitor the trends and progress of various policy objectives, such as the United Nations (UN) Sustainable Development Goals (SDGs).

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Many indicators can measure various development characteristics of a trend, such as the transition from a fossil-based economy to a bio-based one. For example, there are 27 indicators to support the Europe 2020 Strategy, 100 EU SDGs indicators, 232 UN SDGs indicators, or 1600 World Bank World Development Indicators. In the same vein, Bracco et al. (2019) reviewed existing monitoring approaches to the bioeconomy and collected 269 distinct indicators from 19 sources that measured a wide range of impact categories, such as food security, biodiversity conservation, and the resilience of biomass producers. Among others, Lier et al. (2018) proposed 161 indicators and the BioMonitor project[1] 84 indicators for a bioeconomy-monitoring framework.

In previous quantitative assessments of circular bioeconomy development, researchers have selected a few economic and social indicators to track their developments. Ronzon and M'Barek (2018) examined the temporal dynamics of the EU bioeconomy and provided a spatial analysis of the EU circular bioeconomy, comparing different EU MSs and grouping them according to the labor market specialization and the apparent labor productivity of their circular bioeconomies. Ronzon and M'Barek (2018) considered only four indicators: the number of people employed, turnover, value added, and apparent labor productivity. D'Adamo et al. (2020) compared the socio-economic performance status of bioeconomy sectors in EU MSs using the same indicators as Ronzon and M'Barek (2018) except for apparent labor productivity. Furthermore, they introduced a new composite dimensionless indicator to measure and compare socio-economic performance between EU MSs. Efken et al. (2016) measured the importance of the bioeconomy within the economy as a whole in Germany from 2002 to 2010 using employment and gross value added as indicators. Other studies have also been limited to economic indicators and employment (e.g., Piotrowski et al., 2016) or provided only snapshots in time instead of temporal development (e.g., Iost et al., 2019).

Unlike to the previous literature, we devise a theoretical framework that accommodates any number of well-defined quantitative indicators and empirically analyze 41 of them. We investigate their distribution to find patterns in the evolution of the circular bioeconomies of ten selected EU MSs. A similar approach to ours has been used in other fields of economics with a single indicator for many regions or sectors. Quah (1993, 1996) was the first in the cross-country growth and income literature to investigate patterns in income distributions using Markov transition matrices. Later, many researchers adopted this approach to analyze trade-specialization patterns by estimating the intra-distribution dynamics of trade-specialization indices over time (e.g., Zaghini, 2005; Alessandrini et al., 2007; Fertö and Soós, 2008; Chiappini, 2014). Zaghini (2005) analyzed the probability of new EU MSs moving between different degrees of trade specialization. He examined the intra-distribution dynamics of the Lafay index, considering the difference between the exports and imports of 208 sectors. The variation of the relative ranking of sectors by the Lafay index over time depicts these intra-distribution dynamics.

In our exploratory research, we paint a picture of the development of the EU circular bioeconomy between 2006 and 2016 and analyze its specificities in Finland, France, Germany, Italy, Latvia, The Netherlands, Poland, Portugal, Slovakia, and Spain. Our research objective is to investigate whether the circular bioeconomies in these countries are progressing or regressing over the ten-year period. We selected these EU Member States, from now on referred to as the EU-10, on several grounds. First, we considered the (potential) importance of the circular bioeconomy to their economies. Countries such as The Netherlands and Finland already have highly competitive agricultural and forestry sectors and consider the circular economy an approach to consolidate their positions and be more environmentally sustainable (van Ministerie, 2013; Ministry of Employment and the Economy, 2014). Others, such as Latvia and Italy, focus on increasing per capita income competitiveness in their bioeconomy sectors (Italian Presidency of Council of Ministers, 2017; Latvian Ministry of Agriculture, 2018). Second, the selected countries cover the whole range of agricultural intensification, from intensive agriculture in The Netherlands and Germany to extensive agriculture in Latvia and Portugal (European Commission, 2019b). Third, we wanted to achieve good geographical coverage across the EU, including the distinction by the entry date into the EU—before and after 2004. Finally, we were constrained by the availability of coherent data for the included indicators. The data sources of Eurostat did not contain consistent time series for all indicators, in all EU Member States, and all years. Therefore, our choice of the countries and the period is a result of a compromise that respects the three qualifications above. That said, our framework allows including additional countries and years if the necessary data is available.

Our article contributes to the current literature by including a wide range and a high number of indicators to provide a more comprehensive view of the circular bioeconomy's progress and economic, social, and environmental impacts in ten EU countries. Our analysis of the dynamics of circular bioeconomies is unique by examining the intra-distribution of indicators.

2. Background

2.1. Circular bioeconomy policy actions

The circular bioeconomy is high on the political agenda, and many policymakers have proposed and already implemented policy actions to support and steer its development. Table 1 presents an overview of policy actions related to the bioeconomy in the EU and the EU-10. Policymakers in the EU have made the bioeconomy a priority to reduce the use of petrochemicals, mitigate and adapt to climate change, reduce dependency on imports of natural resources, and promote rural development (European Commission, 2018). At the EU level, this is reflected in a multitude of EU policy initiatives and research programs, including the EU Bioeconomy Strategy and the European Bio-Based Industries Joint Undertaking (Wesseler and von Braun, 2017). At the MS level, most countries in this study have developed dedicated bioeconomy strategies or other policy initiatives and research programs related to the bioeconomy from 2006 to 2016. The exceptions are Italy and Latvia, who published their bioeconomy strategies only afterwards in 2017, and Slovakia and Poland, who have not yet developed a bioeconomy strategy while it is under development (Joint Research Centre, 2019). However, in Slovakia and Poland, bioeconomy development is recognized in regional and smart specialization strategies (RIS3 SK, 2013; Sosnowski et al., 2014).[2]

While bioeconomy strategies target the whole bioeconomy, policy actions can also target specific policy areas. An example of the latter is the German *Erneuerbare Energien Gesetz* (EEG), which targeted the promotion of renewable energy. The promotion of bioenergy in the EEG then affected other parts of the bioeconomy, such as agriculture and electricity production.

2.2. Measuring performance with indicator frameworks

Governments have taken numerous policy actions on the circular bioeconomy that they must monitor, such as the SDGs. Policymakers have used monitoring frameworks with a diverse set of indicators for many policy objectives. The 17 UN SDGs are a widely used framework and include 232 indicators to measure progress towards 169 corresponding targets. However, measuring progress towards the SDGs is complicated by the fact that there are no specific targets for SDG indicators (United Nations, 2017). Nevertheless, three prominent methods to measure SDG performance have been developed: the Bertelsmann

[1] www.biomoitor.eu

[2] We are grateful to an anonymous reviewer for pointing this out.

Table 1
Overview of actions related to the bioeconomy from 2007 to 2017 by countries in this study.

Title	Type	Level	Target policy area	Year
European Union				
En route to the Knowledge-Based Bioeconomy	Consultation document	Supra-national	Yes	2007
Innovating for Sustainable Growth: A Bioeconomy for Europe	Policy Strategy	Supra-national	No	2012
Bio-based Industries Consortium	Investment program	Supra-national	No	2012
Germany				
Erneuerbare Energien Gesetz 2009	Policy measure	National	Yes	2009–2011
Erneuerbare Energien Gesetz 2012	Policy measure	National	Yes	2012–2016
Nationale Forschungsstrategie BioÖkonomie 2030	Research strategy	National	No	2010–2016
Bioeconomy. Baden-Württemberg Path Towards a Sustainable Future	Policy strategy	Regional	No	2013
Nationale Politikstrategie Bioökonomie	Policy strategy	National	No	2014
Finland				
The Natural Resource Strategy	Policy strategy	National	No	2009
Distributed Bio-Based Economy – Driving Sustainable Growth	Policy strategy	National	No	2011
Sustainable Bioeconomy: Potential, Changes and Opportunities for Finland	Policy strategy	National	No	2011
The Finnish Bioeconomy Strategy – Sustainable growth from bioeconomy	Policy strategy	National	Yes	2014
The Finnish Bioeconomy Strategy	Policy strategy	National	No	2014
The Netherlands				
Groene Groei – Van Biomassa naar Business	Innnovation contract	National	Yes	2012
Framework Memorandum on the Bio-Based Economy	Framework paper	National	Yes	2012
Groene Groei: voor een sterke, duurzame economie	Green growth strategy	National	Yes	2013
France				
National Biodiversity Strategy 2011–2020	Research & innovation	National	Yes	2011
The new face of Industry in France	Research & innovation	National	Yes	2012
France Europe 2020	Research & innovation	National	No	2014
Stratégie nationale de transition écologique vers développement durable	High-tech	National	No	2014
A Bioeconomy Strategy for France	Holistic bioeconomy development	National	No	2017
Italy				
Bioeconomy in Italy: A unique opportunity to reconnect economy, society, and the environment	Holistic bioeconomy development	National	No	2017
Spain				
Horizon 2030	Holistic bioeconomy development	National	No	2016
Extremadura 2030	Regional bioeconomy development	Regional	No	2017
Portugal				
Estrategía Nacional para o Mar	Blue economy	National	Yes	2013–2020
Latvia				
Latvian Bioeconomy Strategy 2030 (LI-BRA)	Holistic bioeconomy development	National	No	2017

Poland and Slovakia did not implement an action related to the bioeconomy in this period. Source: German Bioeconomy Council (2018)

Index (BI) by Bertelsmann Stiftung and the Sustainable Development Solutions Network (Lafortune et al., 2018; Sachs et al., 2018), the Organisation for Economic Co-operation and Development's (OECD) distance measure (OECD, 2016), and progress measures based on Eurostat's report (Eurostat, 2019). Substantial discrepancies exist between these methods (Miola and Schiltz, 2019); the normalization of indicators is a significant one.

The SDG indicators must be normalized to enable aggregation and comparison because they measure different economic, environmental, and social targets and therefore have different units and dimensions. Accordingly, researchers subtract the minimum value across all countries from the indicator value and divide the difference by the range of values across all countries for the BI (Lafortune et al., 2018). This procedure generates a score which relates to the indicator values in all included countries but means little for the development of a single country independently. For the OECD's distance measure, the latest value of an indicator is subtracted from the target value and is divided by the standard deviation across all countries (OECD, 2019). Again, the resulting score is related to all included countries, and importantly, target values for each indicator are necessary. The progress measure based on Eurostat's report linearly interpolates the value of a specific indicator for 2030. For that, the difference between the latest and the first observation is divided by the difference in years and then multiplied by the difference between 2030 and the latest observation and added to the value of the latest observation (Miola and Schiltz, 2019). All indicator values are then rescaled between zero and one and aggregated to obtain a performance measure at the goal level. This method is sensitive to outliers in the time-series data because only two observations are included in its calculation. The z-score (standard score) is another method for normalization and is common for composite indices of development, which integrate various social, political, and economic aspects of the development of a country (Booysen, 2002). Its calculation is straightforward and uses the mean and standard deviation of an indicator (see Section 4 for details).

For our framework, we needed to normalize because of our selected data and methodology. We analyzed the development of the circular bioeconomy in the EU and its MSs independently and compared the development among countries, but targets were not available for a significant number of indicators, so we used z-scores to normalize the indicators. Before we could do that, we needed to gather and prepare our dataset, which the following section describes.

3. Data

We used time-series data from Eurostat's 'indicator set to measure the progress towards the SDGs' and 'monitoring framework on the circular economy.'[3] From the 232 SDG indicators, we chose those related to the bioeconomy according to Ronzon and Sanjuán (2020). To select bioeconomy-related indicators, they identified any meaning-based equivalence or similarity between SDG targets and the EU Bioeconomy Action Plan that is part of the Updated Bioeconomy Strategy 2018.

The selected 41 'bioeconomy-related' and circular-economy indicators cover not only a multitude of aspects of the circular bioeconomy but also different periods. The largest data gaps occur before 2005 and in the recent years 2017–2019. The former data gaps likely come from indicators that were introduced later and for which data collection needed to be implemented in all EU MSs; the latter is likely due to the time it takes to collect the data. For a consistent data set, we finally considered the period of 2006–2016 and filled in remaining data gaps by predicting missing values using linear regression. The indicators from the circular economy monitoring framework were either coded as 'cei' (competitiveness and innovation) or 'wm' (waste management), followed by a classification number. In contrast, SDG indicators were coded as 'sdg' with a goal number between 1 and 17, followed by a classification number.

In most cases, we avoided the same indicator being represented multiple times with different dimensions or measurement units in the data. For example, the indicator 'Employment rates of recent graduates' from SGD 4 – Quality Education contains disaggregated data for males and females, but we only kept the aggregated total. However, we kept the disaggregated data for indicators that can provide additional insights. For instance, we included the indicators disaggregated by sectors as well as the total for 'Share of renewable energy in gross final energy consumption by sector' because they likely move in different directions. Table 2 provides a list of all our indicators and specifies which are aggregated and which are not.

In the next step, we checked the indicators for consistency in their interpretation. For some indicators such as agricultural factor income per annual work unit, a higher value means either the bioeconomy is progressing or has a positive impact on society, while for others such as ammonia emissions from agriculture, a higher value means the bioeconomy is regressing, has a negative impact on society, or both. To make all indicators consistent, we had to ensure that a higher indicator value indicates a move in the desired direction. Therefore, we assigned a negative sign to the indicators whose desired direction was negative. A similar approach was taken, for example, by the OECD (2019) and Ronzon and Sanjuán (2020). In the case of indicators whose optimal value is zero, we took their absolute value and assigned a negative sign to it.[4] In this way, the positive and negative deviations from the optimum were treated equally. Table 2 shows the desired directions of all the indicators; we adopted the directions of SDG bioeconomy indicators from Eurostat (2019). The circular economy indicators are all designed so that an increase means a move in the desired direction. Having prepared our data, we applied our methodology to the indicator framework, as outlined in the following section.

Table 2
List of the indicators used in this study.

Code	Description	Desired Direction
cei_cie010	Value added at factor costs (Mio Euro)	+
cei_cie010	Value added at factor costs (% of GDP)	+
cei_cie010	Gross investment in tangible goods (Mio Euro)	+
cei_cie010	Gross investment in tangible goods (% of GDP)	+
cei_cie010	Persons employed (umber)	+
cei_cie010	Persons employed (% of total employment)	+
cei_wm030	Recycling of biowaste (kg per capita)	+
sdg_02_20	Agricultural factor income per annual work unit	+
sdg_02_30	Government support to agricultural research and development (Mio Euro)	+
sdg_02_30	Government support to agricultural research and development (Euro per inhabitant)	+
sdg_02_40	Area under organic farming - % of utilised agricultural area (UAA)	+
sdg_02_50	Gross nutrient balance on agricultural land by nutrient (nitrogen)	0
sdg_02_50	Gross nutrient balance on agricultural land by nutrient (phosphorus)	0
sdg_02_60	Ammonia emissions from agriculture (tonne)	–
sdg_02_60	Ammonia emissions from agriculture (kg/ha)	–
sdg_04_20	Tertiary educational attainment by sex (total)	+
sdg_04_50	Employment rates of recent graduates by sex (total)	+
sdg_04_60	Adult participation in learning by sex (total)	+
sdg_07_10	Primary energy consumption (Mio tonnes of oil equivalent)	–
sdg_07_30	Energy productivity (Euro per kg of oil equivalent)	+
sdg_07_40	Share of renewable energy in gross final energy consumption by sector (total)	+
sdg_07_40	Share of renewable energy in gross final energy consumption by sector (transport)	+
sdg_07_40	Share of renewable energy in gross final energy consumption by sector (electricity)	+
sdg_07_40	Share of renewable energy in gross final energy consumption by sector (heating and cooling)	+
sdg_08_30	Real GDP per capita – Chain linked volumes (% on previous period, per capita)	+
sdg_08_40	Long-term unemployment rate by sex (total)	–
sdg_09_10	Gross domestic expenditure on R&D by sector – Business enterprise sector	+
sdg_09_10	Gross domestic expenditure on R&D by sector – Government sector	+
sdg_09_10	Gross domestic expenditure on R&D by sector – Higher education sector	+
sdg_09_20	Employment in knowledge-intensive services	+
sdg_09_20	Employment in high- and medium-high technology manufacturing	+
sdg_09_30	R&D personnel by sector - Business enterprise sector (% of active population)	+
sdg_09_30	R&D personnel by sector - Government sector (% of active population)	+
sdg_09_30	R&D personnel by sector - Higher education sector (% of active population)	+
sdg_09_40	Patent applications to the European Patent Office (number)	+
sdg_09_40	Patent applications to the European Patent Office (per million inhabitants)	+
sdg_11_60	Recycling rate of municipal waste (% of total waste generated)	+
sdg_12_41	Circular material use rate (% of material input for domestic use)	+
sdg_13_10	Greenhouse gas emissions (base year 1990)	–
sdg_13_10	Greenhouse gas emissions (tonnes per capita)	–
sdg_14_10	Surface of marine sites designated under NATURA 2000 (km^2)	+

"+" denotes indicators that progress with a higher value; "-"denotes indicators that regress with a higher value; and "0″ denotes indicators whose desired value is zero.

[3] We downloaded the data from the official website of Eurostat, which is freely available at https://ec.europa.eu/eurostat/data/bulkdownload.

[4] An alternative to reverting the sign would be taking the reciprocal of the value. This method would, however, not work for the balance indicators whose desired value is zero.

4. Methodology

4.1. Z-scores

We analyze the evolution of the bioeconomies in Finland, France, Germany, Italy, Latvia, The Netherlands, Poland, Portugal, Slovakia, and Spain in the period of 2006–2016. We first examined the movements over time of all circular bioeconomy indicators together and compared them across countries. We then analyzed the dynamics of circular bioeconomy indicators using Markov transition matrices.

As all indicators have different units and magnitudes, they need to be normalized for meaningful comparison and aggregation. Although several normalization methods exist, they suffer from deficiencies, as pointed out in Section 2. We calculated the z-score (standard score) for each indicator to put our data onto a standardized scale. The z-score of a given indicator in a given year measures how many standard deviations the indicator value is away from the indicator's mean. A positive z-score denotes a value above the mean, and a negative z-score corresponds to a value below the mean over the whole period. The z-score of indicator i in year t is given by

$$z_{it} = \frac{x_{it} - \overline{x}_i}{s_i} \tag{1}$$

where x_{it} is the value of an indicator, $\overline{x}_i$ is the temporal mean of indicator i, and s_i is the indicator's temporal standard deviation. Using Eq. (1) for normalizing our indicators allowed us to aggregate them, giving equal weight to all indicators, and track their movement over time. To rank the normalized indicators according to the 'speed' of their development over time, we calculated the slope parameter of a linear regression of a z-score of indicator i on time as shown in Eq. (2)

$$\widehat{\beta}_i = \frac{Cov[t, z_i]}{Var[t]} \tag{2}$$

We used parameter $\widehat{\beta}_i$ as a measure to rank the indicators and did not examine whether there was a statistically significant relationship. A larger value of $\widehat{\beta}$ corresponds to a faster-progressing indicator.

4.2. Markov transition matrices

To analyze the dynamics of the circular bioeconomy, we needed to understand the development of the intra-distribution of indicators over time. *Z*-scores allowed us to rank the indicators according to their change over years and define a distribution of these changes. We calculated the quartiles of the z-scores across all indicators for each year and used them as boundaries to divide the indicators into quarters: from Q_1, the indicators with the lowest z-scores, to Q_2 and Q_3, with the medium-low and medium-high z-scores, to Q_4, the indicators with the highest z-scores. We then used the quarters to construct Markov transitions matrices.

Following Quah (1993, 1996) and Zaghini (2005), we modeled the development of the intra-distribution of indicators over time using Markov transition matrices. These matrices were used in the cross-country growth literature to analyze income convergence (e.g., Quah, 1993, 1996). To build a Markov chain, we need a transition matrix and an initial distribution. Assuming a finite set $S = \{1, \ldots, m\}$ of states, a real number p_{ij} must be assigned to each pair $(i,j) \in S^2$ of states, ensuring that the properties

$$p_{ij} \geq 0 \quad \forall (i,j) \in S^2 \tag{3}$$

$$\sum_{j \in S} p_{ij} = 1 \quad \forall i \in S \tag{4}$$

are satisfied. The transition matrix **P** can be defined as follows:

$$P = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{pmatrix} \tag{5}$$

where the value of each cell is a transition probability, that is, the probability that an indicator from segment i moves to segment j in the next year. We calculated the transition probabilities for each period by counting the number of transitions between intervals of the relative change of indicator levels.

We compared the mobility (i.e., the extent of indicator movement among quarters) between different periods and countries with two metrics proposed by Shorrocks (1978):

$$M_1 = \frac{n - \mathrm{tr(P)}}{n - 1} \tag{6}$$

and

$$M_2 = 1 - |det(\mathrm{P})|, \tag{7}$$

where n is the order of a square transition matrix P, *tr(P)* is its trace (i.e., the sum of elements on the main diagonal), and det(*P*) is its determinant.

For both metrics, a higher value suggests a higher indicator mobility between segments, while zero indicates no mobility at all. However, both metrics can still lead to different outcomes, as they measure different types of mobility. M_1relates only to the trace of the transition matrix and therefore measures the ratio between diagonal and off-diagonal transition probabilities. The metric M_2 uses the determinant of the transition matrix and therefore measures all changes in the matrix.

5. Results

5.1. The external shape of the distribution of circular bioeconomy indicators

To analyze the movement of all circular bioeconomy indicators, we examined the external shape of the z-score distribution across all countries over time. The graph in Fig. 1 shows that the aggregated distribution comes close to a normal distribution, which results from the calculation of a z-score, and that most indicators have a z-score between −2 and 2. In the graph in Fig. 2, the distribution for each consecutive year shifts to the right and therefore peaks at a higher z-score level. Circular bioeconomy indicators, on average, improve over time for the EU-10 aggregate.

To further describe and analyze the external shape of the distribution of circular bioeconomy indicators, we present brief descriptive statistics for the EU-10 in Table 3. It shows that the EU-10 mean z-score progressed from −0.622 in 2006 to 0.466 in 2016.

This progression is nearly continuous over the whole period except for an interruption between 2008 and 2010. The national bioeconomies' developments confirm this positive trend to varying extents. Germany progressed from a mean of −1.001 in 2006 to 0.769 in 2016; Slovakia increased its mean by 1.504 from 2006 to 2016 and Portugal by 1.186. Finland progressed the least, from a mean of −0.35 in 2006 to only 0.045 in 2016. Latvia, The Netherlands, Poland, Italy, Spain, and France have successively greater progress but still lag behind Germany and Slovakia. The range of z-scores for the EU-10 is generally higher in the first four years of the examined period, then relatively low around 2.5 from 2010 to 2013, before increasing again in 2014 and 2016.

Fig. 3 confirms the generally positive trend as the median (the band inside the box) increases over time in the EU-10. The interquartile range (the width of the box) is comparable to the range and shows a similar picture. In the middle of the period (2010−2012), it is generally lower than at the beginning and end. With some small deviations, the same trend can be seen in the development of circular bioeconomy indicators

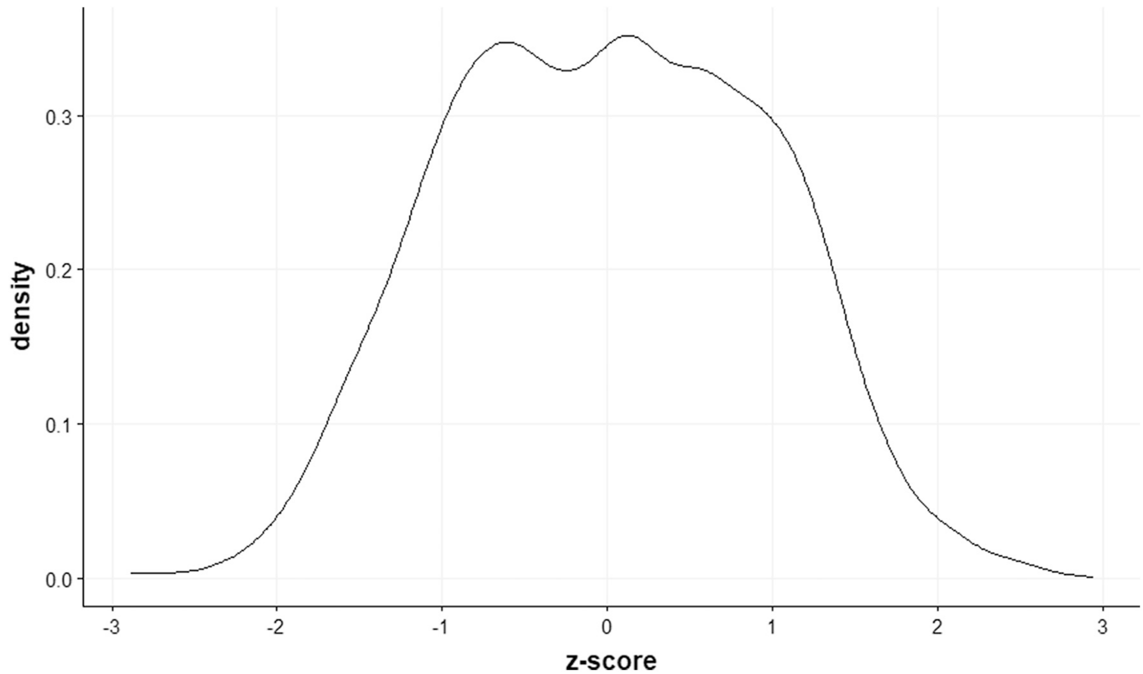

Fig. 1. Indicator distribution over the whole period for all countries (Kernel density estimates).
Note: The graph shows the density estimates for the z-scores aggregated across all indicators and years.

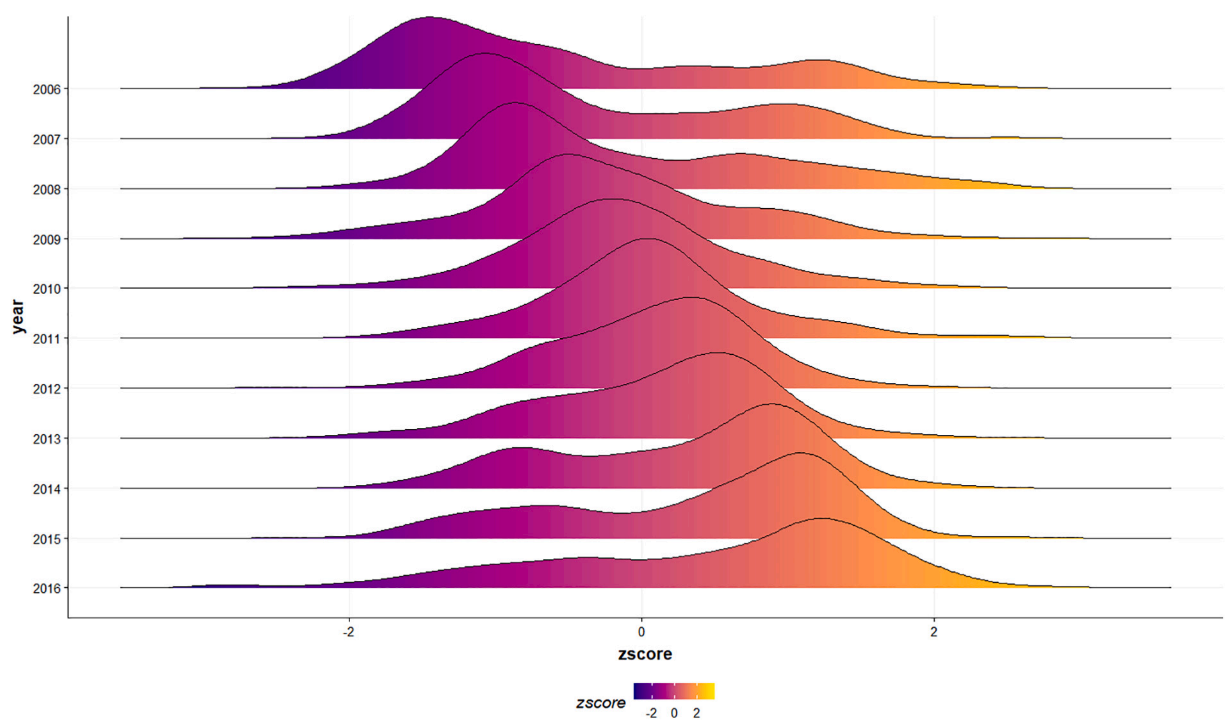

Fig. 2. Indicator distribution by year for all countries (Kernel density estimates).
Note: The graph shows the temporally disaggregated z-scores for all indicators.

in each country (Appendix A).

We ranked all 41 indicators from best to worst according to the development of their z-scores over time. Table 4 presents the five best and worst indicators for all countries, which shows how their circular bioeconomies are progressing or regressing. The rate of progress was among the highest for the share of renewable energy in gross final energy consumption in all countries except Italy. The indicators for the share of renewable energy do not differentiate between the type of renewable energy and do not allow to assess the progress with respect to bioenergy only. However, in 2017, the largest part of renewable energy was still biofuels and renewable waste in all EU-10 countries and

Table 3
Descriptive statistics from the standardized indicator distribution.

EU-10											
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Mean	−0.622	−0.430	−0.122	−0.155	−0.122	0.052	0.081	0.138	0.310	0.405	0.466
Median	−0.954	−0.758	−0.476	−0.248	−0.164	0.029	0.175	0.286	0.555	0.706	0.733
St. dev.	1.113	0.953	1.005	0.842	0.735	0.716	0.677	0.761	0.858	0.941	1.134
Range	5.339	4.972	4.359	5.044	4.885	4.621	4.554	4.800	4.096	4.832	5.747

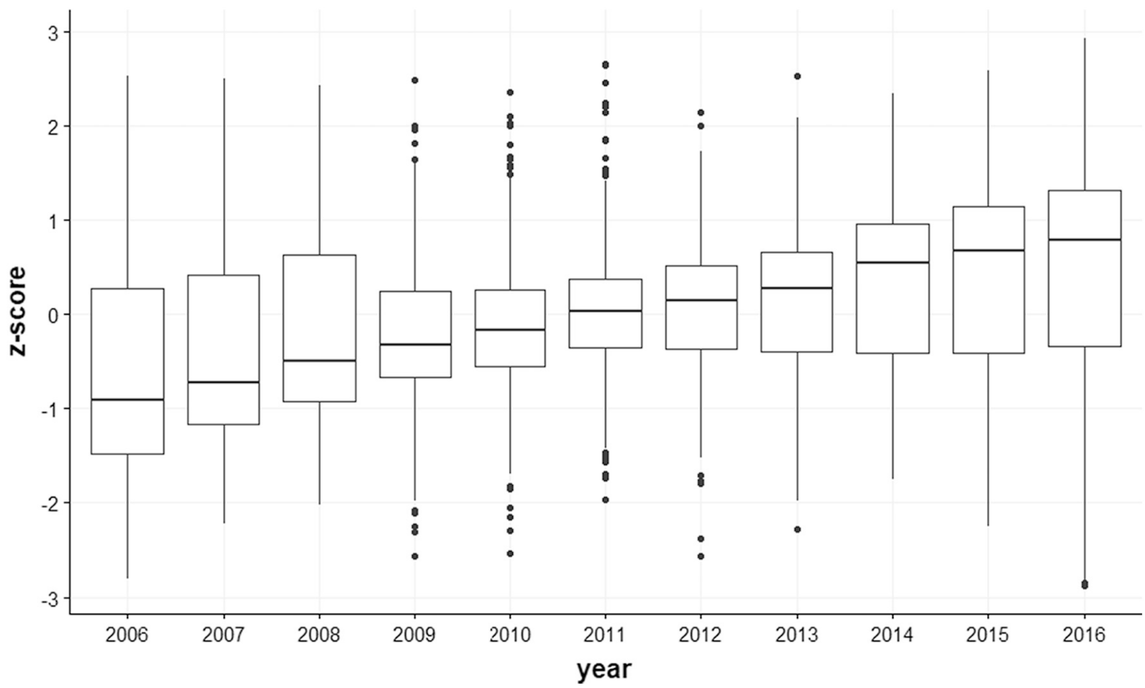

Fig. 3. Development of circular bioeconomy indicators in the EU-10 from 2006 to 2016 as box plots.
Note: A box plot illustrates the z-scores for each year. The band inside the box corresponds to the median and the width of the box to the interquartile range (IQR). The upper (lower) whisker extends from the hinge to the largest (lowest) value no further than 1.5 * IQR from the hinge. The points correspond to outliers beyond the range of the whiskers.

therefore, it is likely that bioenergy played a major role in the progress of the share of renewable energy (Bórawski et al., 2019).[5] Also, biowaste recycling, the recycling rate of municipal waste, and the circular material use rate were among the most-improving indicators in seven of the ten countries. By contrast, a negative development took place for ammonia emissions and the nutrient balance on agricultural land in Germany, Latvia, and Slovakia. At least one economic indicator for private investments, jobs, and gross value added related to circular economy sectors is regressing in six of the ten countries. Two of these economic indicators are among the worst in Italy, Latvia, Portugal, and Slovakia.

In contrast, the percentage of total employment for circular economy sectors increased sharply in Spain, Latvia, and Portugal. This development is ambiguous for indicators related to R&D. The indicators for patent applications are among the worst in Germany, Italy, and France, while they are among the best in Poland. On the one hand, indicators related to public expenditure, agricultural research and development, higher education, and government are among the worst in Spain, Finland, The Netherlands, and Poland, but indicators related to R&D personnel or R&D expenditure in the business enterprise sector are among the best in Germany, France, and Italy.

5.2. Intra-distribution dynamics of the circular bioeconomy

To analyze the dynamics of the selected circular bioeconomies, we model the development of the intra-distribution of indicators over time using Markov transition matrices. The matrices are constructed by tracing how each indicator changes its position relative to other indicators between two periods. To keep things manageable and to ease the interpretation of the results, in each year, we assign the indicators to quarters according to the quartiles for a given year, based on the value of an indicator's z-score. Indicators in the first quarter (Q_1) have the lowest z-scores and those in the fourth quarter (Q_4) have the highest z-scores. The indicators in Q_2 perform better than in Q_1 but worse than in Q_3, which in turn performs worse than in Q_4.

Now we are in a position to follow each indicator between any two points in time (e.g., t and $t + 1$ or $t + 10$) and determine whether the indicator has stayed in the same quarter or has left it for some other quarter. By calculating the proportions of individual moves from a given quarter at time t into any quarter at $t + 1$, we estimate the transition matrices as presented in Table 5.

The left-hand side of Table 5 presents averages of one-year transition matrices in the period 2006–2016, while the right-hand side presents one transition matrix for each country over the whole period (i.e., ten

[5] To further illustrate this point, bioenergy accounted for 90% of total final renewable energy use in Poland in 2010 according to the International Renewable Energy Agency, while the remaining 10% came from hydropower and wind (IRENA, 2015).

Table 4
The most progressing and the most regressing indicators in the period 2006–2016.

Most progressing indicators	$\widehat{\beta}$	Most regressing indicators	$\widehat{\beta}$
Germany			
Share of renewable energy in gross final energy consumption – electricity	0.300	Patent applications to the European Patent Office (total number)	−0.291
Share of renewable energy in gross final energy consumption – all sectors	0.299	Patent applications to the European Patent Office (number per million inhabitants)	−0.288
Employment rate	0.294	Ammonia emissions from agriculture (kg per hectare)	−0.288
Recycling of biowaste	0.293	Ammonia emissions from agriculture (tonnes)	−0.278
R&D personnel – business enterprise sector	0.292	Private investments, jobs, and gross value added related to circular economy sectors – value added at factor cost – % of GDP	−0.172
Finland			
Area under organic farming	0.298	Employment in knowledge-intensive services	−0.295
Recycling rate of municipal waste	0.296	Circular material use rate	−0.294
Share of renewable energy in gross final energy consumption – heating and cooling	0.295	R&D personnel – government sector	−0.277
Share of renewable energy in gross final energy consumption – all sectors	0.292	R&D personnel – higher education sector	−0.272
Employment in high- and medium-high technology manufacturing	0.292	Gross domestic expenditure on R&D – higher education sector	−0.234
The Netherlands			
Share of renewable energy in gross final energy consumption – all sectors	0.296	Government support for agricultural R&D (million euros)	−0.267
Tertiary educational attainment	0.291	Government support for agricultural R&D (euros per capita)	−0.264
Share of renewable energy in gross final energy consumption – heating and cooling	0.286	Long-term unemployment rate	−0.246
Recycling rate of municipal waste	0.284	Private investments, jobs, and gross value added related to circular economy sectors – % of total employment [V16111]	−0.242
Share of renewable energy in gross final energy consumption – transport	0.282	Employment rate of recent graduates	−0.236
France			
R&D personnel – higher education sector	0.302	R&D personnel – government sector	−0.302
R&D personnel – business enterprise sector	0.302	Employment in high- and medium-high technology manufacturing	−0.290
Recycling rate of municipal waste	0.301	Long-term unemployment rate	−0.258
Share of renewable energy in gross final energy consumption – heating and cooling	0.299	Employment rate of recent graduates	−0.253
Employment in knowledge-intensive services	0.298	Gross domestic expenditure on R&D – government sector	−0.250
Poland			
Tertiary educational attainment	0.299	Energy productivity	−0.294
	0.298		−0.293

Table 4 (*continued*)

Most progressing indicators	$\widehat{\beta}$	Most regressing indicators	$\widehat{\beta}$
Share of renewable energy in gross final energy consumption – electricity		Surface of marine sites designated under NATURA 2000	
Patent applications to the European Patent Office (number per million inhabitants)	0.298	Gross domestic expenditure on R&D – business enterprise sector	−0.280
Patent applications to the European Patent Office (total number)	0.298	Adult participation in learning	−0.255
Share of renewable energy in gross final energy consumption – heating and cooling	0.296	Private investments, jobs, and gross value added related to circular economy sectors – value added at factor cost – % of GDP	−0.183
Slovakia			
Tertiary educational attainment	0.297	Private investments, jobs, and gross value added related to circular economy sectors – gross investment in tangible goods – % of GDP	−0.229
Energy productivity	0.295	Adult participation in learning	−0.223
Share of renewable energy in gross final energy consumption – electricity	0.292	Gross nutrient balance on agricultural land – phosphorous	−0.206
Greenhouse gas emissions (index 1990 = 100)	0.290	Private investments, jobs, and gross value added related to circular economy sectors – gross investment in tangible goods – million euros	−0.194
Share of renewable energy in gross final energy consumption – all sectors	0.289	Employment rate of recent graduates	−0.091
Italy			
Recycling rate of municipal waste	0.298	Recycling rate of municipal waste	0.298
Gross domestic expenditure on R&D – business enterprise sector	0.296	Gross domestic expenditure on R&D – business enterprise sector	0.296
Recycling of biowaste	0.296	Recycling of biowaste	0.296
Circular material use rate	0.296	Circular material use rate	0.296
Tertiary educational attainment	0.295	Tertiary educational attainment	0.295
Spain			
Private investments, jobs, and gross value added related to circular economy sectors – % of total employment [V16111]	0.297	Circular material use rate	−0.293
Share of renewable energy in gross final energy consumption – all sectors	0.294	Long-term unemployment rate	−0.267
Share of renewable energy in gross final energy consumption – heating and cooling	0.292	Government support for agricultural R&D (euros per capita)	−0.265
Share of renewable energy in gross final energy consumption – electricity	0.291	Government support for agricultural R&D (million euros)	−0.259
Energy productivity	0.285	Employment rate of recent graduates	−0.252
Portugal			
Employment in knowledge-intensive services	0.300	R&D personnel – government sector	−0.283
Tertiary educational attainment	0.299	Private investments, jobs, and gross value added related to circular economy sectors – gross investment in tangible goods – % of GDP	−0.266
	0.298		−0.249

(*continued on next page*)

Table 4 (*continued*)

Most progressing indicators		Most regressing indicators	
$\widehat{\beta}$		$\widehat{\beta}$	
Share of renewable energy in gross final energy consumption – electricity		Gross domestic expenditure on R&D – government sector	
Share of renewable energy in gross final energy consumption – all sectors	0.294	Private investments, jobs, and gross value added related to circular economy sectors – gross investment in tangible goods – million euro	−0.249
Private investments, jobs, and gross value added related to circular economy sectors – % of total employment [V16111]	0.294	Employment rate of recent graduates	−0.241
Latvia			
Private investments, jobs, and gross value added related to circular economy sectors – % of total employment [V16111]	0.299	Ammonia emissions from agriculture (tonnes)	−0.286
Surface of marine sites designated under NATURA 2000	0.298	Ammonia emissions from agriculture (kg per hectare)	−0.266
Tertiary educational attainment	0.293	Private investments, jobs, and gross value added related to circular economy sectors – value added at factor cost – % of GDP	−0.264
Share of renewable energy in gross final energy consumption – electricity	0.288	Private investments, jobs, and gross value added related to circular economy sectors – ross investment in tangible goods – % of GDP	−0.252
Circular material use rate	0.282	Gross nutrient balance on agricultural land – nitrogen	−0.245

years). To ease the interpretation of results, let us have a look at the one-year transition probabilities of Germany. For example, the value 0.50 (Q_1, Q_1) means that 50% of indicators that were in Q_1 in one year, stayed in Q_1 also in the next year. Similarly, 11% (Q_1, Q_4) of indicators that started in Q_1 in one year improved their performance by moving to Q_4 in the next year. The final example shows that 14% (Q_4, Q_1) of highly-ranked indicators that started in Q_4 in one year worsened their performance by moving to Q_1 in the next year.

The diagonal values of the transition matrices depict how dynamic a circular bioeconomy is in a country. If the diagonal values are higher than the non-diagonal values, more indicators stay in their quarters from one year to the next. Hence, the indicators grow or decline in a homogenous manner.

We can illustrate a country that has been less dynamic in the short term by comparing the one-year transition matrices of Portugal and Germany. For Portugal, the diagonal values are relatively high; for example, 65% of the indicators stayed in the best-performing quarter (Q_4) from year to year. In contrast, in Germany, the probability for indicators to stay in their initial quarters was generally lower, with 53% staying in Q_4 and approximately 25% staying in Q_2 and Q_3. This comparison shows that the intra-distribution of circular bioeconomy indicators fluctuates less in Portugal.

Comparing short- and long-term matrices, it is evident that over a ten-year period, the probability of an indicator to shift from one quarter to another is more likely than over a one-year period. This disparity is intuitive because one would expect that, over a longer period, indicators progress or regress at different speeds. However, what stands out in this table is the extent of the disparity between short- and long-term matrices. Not a single probability exceeds a 50% likelihood of staying in one quarter; the highest is for Poland to stay in Q_2 with a probability of 45%. The probability of staying in the medium-performing quarters (Q_2 and Q_3) is also higher than in the least-performing quarter (Q_1) and the best-performing quarter (Q_4). In contrast, for the short-term matrices, this tendency is, to a lesser extent, the opposite.

Table 6 provides an overview of short-term mobility for one-year matrices (in M_1 and M_2) divided into averages for two periods: 2007–2011 and 2012–2016. This overview allows us to see whether mobility was higher in the first five or second five years of the given period. In 2007–2011, the country with the highest mobility (0.832) was Germany, which decreased to 0.810 in 2012–2016. The table shows a decline in short-term mobility in seven of the ten countries. The decline was especially substantial in Finland and The Netherlands, each going down by 0.18. In Italy, however, short-term mobility was stable; only in Poland and Slovakia did mobility increase by 0.03 and 0.07, respectively. Table 6 also shows mobility indices for one-year and ten-year transition matrices, that is, short-term and long-term dynamics. According to M_1, mobility is higher over ten years than over one year in all countries.

Short-term and long-term mobility						
Country	One-year		Ten-year		Change in Mobility	
	M_1	M_2	M_1	M_2	ΔM_1	ΔM_2
Germany	0.82	0.97	1.13	0.98	0.31	0.01
Finland	0.74	0.98	1.23	0.97	0.49	−0.01
The Netherlands	0.72	0.96	1.10	1.00	0.38	0.03
France	0.75	0.98	1.23	0.98	0.49	0.00
Poland	0.71	0.98	1.11	0.98	0.40	0.00
Slovakia	0.79	0.99	1.24	0.96	0.44	−0.03
Italy	0.73	0.98	1.30	0.99	0.57	0.01
Spain	0.68	0.95	1.20	0.98	0.52	0.03
Portugal	0.65	0.95	1.17	0.97	0.51	0.02
Latvia	0.74	0.95	1.17	0.99	0.43	0.04

Source: Own calculations.

To assess the movement of the whole distribution of z-scores over time, we regressed z-scores on a time variable. The result was a significant slope coefficient for all countries. Fig. 4 depicts the relation between the mobility according to M_1, and the z-score slope. We can observe a general pattern of a higher slope with a higher level of mobility. This pattern is unexpected because we previously found an increase in indicators' z-scores and a decrease in mobility over time.

The graph shows that Germany's and Slovakia's bioeconomies improved the fastest while also maintaining the highest short-term mobility. Portugal and Spain experienced relatively slow progress in their bioeconomies while also maintaining low short-term mobility. In contrast to this trend, Finland's bioeconomy had average short-term mobility but improved the slowest. The remaining countries can be found in the middle of the spectrum.

6. Conclusions

In this quantitative study, we showed the similarities and differences in the dynamic evolution of a wide range of indicators for circular bioeconomies in ten EU Member States. We developed a novel framework in which we normalized indicators with various units and dimensions and then investigated patterns using Markov transition matrices. Our framework allowed us to understand indicators that cover various economic, environmental, and social aspects of a circular bioeconomy.

We found that the evolutions of the EU-10 circular bioeconomies were generally progressive considering all indicators; however, this development was not homogeneous. While most of the EU-10 rapidly progressed in their shares of renewable energy and recycling and circular material use rates, agro-environmental indicators rapidly regressed in Germany, Latvia, and Slovakia. Economic indicators related to circular-economy sectors were among the worst indicators in six countries and among the best in only three countries. The indicators related to R&D generally progressed quickly in the private sector and regressed in the public sector, which suggests that one substituted for the other.

Table 5
Short-term and long-term transition matrices for all countries.

One-year transition matrix					Ten-year transition matrix				
Germany									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q_1	0.50	0.26	0.13	0.11	Q_1	0.00	0.40	0.40	0.20
Q_2	0.17	0.26	0.39	0.18	Q_2	0.00	0.30	0.30	0.40
Q_3	0.17	0.34	0.25	0.24	Q_3	0.10	0.10	0.30	0.50
Q_4	0.14	0.12	0.21	0.53	Q_4	0.82	0.18	0.00	0.00
Ergodic	0.241	0.241	0.244	0.273	Ergodic	0.244	0.243	0.244	0.268
Finland									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q_1	0.50	0.32	0.10	0.08	Q_1	0.00	0.10	0.50	0.40
Q_2	0.32	0.38	0.20	0.11	Q_2	0.00	0.20	0.30	0.50
Q_3	0.13	0.20	0.35	0.32	Q_3	0.20	0.50	0.10	0.20
Q_4	0.04	0.09	0.32	0.55	Q_4	0.73	0.18	0.09	0.00
Ergodic	0.238	0.241	0.246	0.275	Ergodic	0.245	0.243	0.244	0.268
The Netherlands									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q_1	0.50	0.24	0.18	0.08	Q_1	0.00	0.30	0.10	0.60
Q_2	0.34	0.43	0.16	0.07	Q_2	0.10	0.30	0.30	0.30
Q_3	0.07	0.23	0.37	0.33	Q_3	0.10	0.30	0.40	0.20
Q_4	0.09	0.10	0.26	0.55	Q_4	0.73	0.09	0.18	0.00
Ergodic	0.250	0.248	0.242	0.260	Ergodic	0.245	0.244	0.243	0.269
France									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q_1	0.46	0.32	0.12	0.10	Q_1	0.00	0.30	0.50	0.20
Q_2	0.26	0.37	0.22	0.16	Q_2	0.00	0.10	0.30	0.60
Q_3	0.15	0.17	0.42	0.26	Q_3	0.20	0.30	0.20	0.30
Q_4	0.12	0.13	0.24	0.52	Q_4	0.73	0.27	0.00	0.00
Ergodic	0.243	0.243	0.250	0.263	Ergodic	0.245	0.243	0.244	0.268
Poland									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q_1	0.58	0.28	0.09	0.05	Q_1	0.00	0.30	0.40	0.30
Q_2	0.23	0.35	0.23	0.18	Q_2	0.00	0.45	0.27	0.18
Q_3	0.14	0.17	0.38	0.32	Q_3	0.33	0.11	0.11	0.44
Q_4	0.07	0.17	0.20	0.56	Q_4	0.73	0.18	0.00	0.09
Ergodic	0.254	0.242	0.218	0.286	Ergodic	0.252	0.288	0.211	0.249
Slovakia									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q_1	0.47	0.27	0.13	0.13	Q_1	0.00	0.40	0.50	0.10
Q_2	0.27	0.32	0.23	0.17	Q_2	0.10	0.10	0.30	0.50
Q_3	0.14	0.29	0.32	0.25	Q_3	0.20	0.30	0.10	0.40
Q_4	0.11	0.11	0.29	0.50	Q_4	0.64	0.18	0.09	0.09
Ergodic	0.245	0.245	0.243	0.267	Ergodic	0.245	0.244	0.244	0.268
Italy									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q_1	0.55	0.27	0.11	0.07	Q_1	0.00	0.00	0.50	0.50
Q_2	0.26	0.40	0.23	0.11	Q_2	0.10	0.10	0.50	0.30
Q_3	0.12	0.22	0.33	0.33	Q_3	0.30	0.40	0.00	0.30
Q_4	0.06	0.11	0.30	0.53	Q_4	0.55	0.45	0.00	0.00
Ergodic	0.243	0.248	0.244	0.265	Ergodic	0.245	0.243	0.244	0.268
Spain									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q_1	0.53	0.33	0.10	0.04	Q_1	0.30	0.10	0.40	0.20
Q_2	0.28	0.39	0.24	0.09	Q_2	0.00	0.00	0.40	0.60
Q_3	0.13	0.17	0.41	0.29	Q_3	0.30	0.30	0.10	0.30
Q_4	0.05	0.10	0.22	0.63	Q_4	0.36	0.55	0.09	0.00
Ergodic	0.241	0.243	0.242	0.275	Ergodic	0.243	0.245	0.244	0.269
Portugal									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q_1	0.53	0.30	0.13	0.04	Q_1	0.10	0.20	0.50	0.20
Q_2	0.30	0.38	0.19	0.13	Q_2	0.10	0.20	0.20	0.50
Q_3	0.09	0.19	0.48	0.25	Q_3	0.30	0.10	0.20	0.40
Q_4	0.06	0.10	0.19	0.65	Q_4	0.45	0.45	0.09	0.00
Ergodic	0.233	0.234	0.246	0.288	Ergodic	0.244	0.244	0.244	0.268
Latvia									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q_1	0.53	0.22	0.18	0.07	Q_1	0.10	0.10	0.40	0.40
Q_2	0.22	0.37	0.26	0.16	Q_2	0.20	0.10	0.30	0.40
Q_3	0.16	0.26	0.33	0.25	Q_3	0.00	0.60	0.20	0.20
Q_4	0.08	0.14	0.22	0.56	Q_4	0.64	0.18	0.09	0.09
Ergodic	0.243	0.244	0.247	0.267	Ergodic	0.245	0.243	0.244	0.268

Source: own calculations.

Table 6
Mobility metrics.

Short-term mobility in two periods						
Country	One-year 2007–2011		One-year 2012–2016		Change in Mobility	
	M_1	M_2	M_1	M_2	ΔM_1	ΔM_2
Germany	0.83	0.96	0.81	0.98	−0.02	0.02
Finland	0.83	0.98	0.65	0.97	−0.18	0.00
The Netherlands	0.80	0.95	0.63	0.97	−0.18	0.02
France	0.77	0.97	0.73	0.98	−0.04	0.01
Poland	0.68	0.98	0.75	0.99	0.07	0.01
Slovakia	0.78	0.98	0.81	0.99	0.03	0.01
Italy	0.73	0.98	0.73	0.98	0.00	−0.01
Spain	0.69	0.94	0.67	0.96	−0.02	0.02
Portugal	0.72	0.94	0.59	0.96	−0.12	0.02
Latvia	0.80	0.98	0.67	0.92	−0.13	−0.07

Our results show that the circular bioeconomy is multi-faceted and that, while it generally progressed during the study period, not all indicators moved in the desired direction. This pattern is exemplified in Germany's circular-bioeconomy indicators, which progressed the most on average in comparison to the rest of the EU-10. At the same time, intra-distribution dynamics were also high for Germany: indicators sharply differed in their developments, and their relative rankings strongly varied in consecutive years. Indicators, such as patent applications and ammonia emissions from agriculture, even regressed rapidly. We recommend that policymakers consider all indicators and not only a few because a country with highly dynamic indicators seems to progress differently in economic, environmental, and social aspects. Therefore, examining only a few indicators can bias the picture of a country's circular bioeconomy.

Moreover, our cross-country comparison revealed that circular bioeconomies develop at different paces. Circular bioeconomies in Slovakia, Poland, and Latvia developed quickly in comparison to the rest of the EU-10. Their substantial relative progress from 2006 to 2016 was particularly unexpected because their governments have not implemented any policy actions at national level for the circular bioeconomy during that period. However, D'Adamo et al. (2020) found that Slovakia, Poland, and Latvia are still lagging behind the rest of the EU in terms of socio-economic performance. Therefore, the rapid development of circular bioeconomies in Slovakia, Poland, and Latvia may be partly explained by a catch-up effect on highly developed circular bioeconomies such as The Netherlands. This finding is consistent with Ronzon and M'Barek (2018), who emphasized the potential of the bioeconomy in Central and Eastern Europe.

In contrast, the circular bioeconomies in Finland, Spain, The Netherlands, and Portugal improved the slowest, even though they have dedicated national bioeconomy strategies. Moreover, Finland and The Netherlands have additional policy and green-growth strategies. Perhaps the impacts of these policy strategies are limited and more concrete policy actions are needed, such as an economy-wide carbon tax or targeted investments in bio-industrial initiatives (Philippidis et al., 2018). It is also possible that more time is needed for these strategies to take effect.

We faced significant challenges in compiling the data needed for our framework. After we had selected our indicators according to their relevance to the circular bioeconomy and data availability, only 41

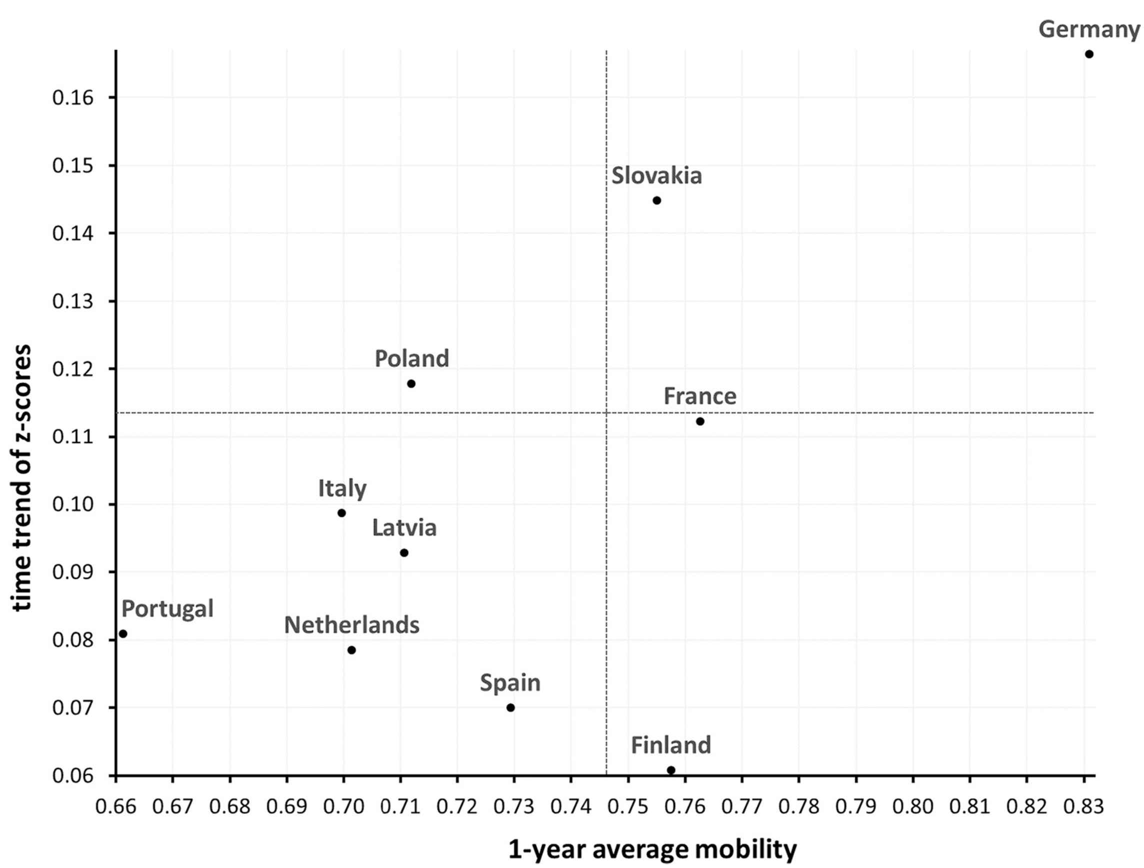

Fig. 4. Correlation of average one-year mobilities (M1) and time trend of z-scores between countries.
Note: The dotted horizontal and vertical lines depict the averages of the minimum and maximum values.

indicators remained. This number of items is feasible but possibly affects the robustness of the results using Markov transition matrices. As soon as additional indicators become available, this issue could be easily addressed by future studies. Moreover, we analyzed the directions, speeds, and dynamics of circular bioeconomies, but we could not assess their initial states with our framework. In an unlikely but theoretically possible case, a circular bioeconomy could already be at its steady state at the beginning of the study period, so zero progress in its indicators' z-scores would not be problematic. This problem could be solved if quantitative targets for all indicators were determined, which would allow us to assess the distance from realizing those targets.

Another limitation of our study is that we mostly use 'bioeconomy-related' indicators from the SDGs because an established comprehensive indicator framework is absent for the bioeconomy. However, contributing to the SDGs is a major objective of policy strategies targeting the circular bioeconomy, such as the 2018 EU Bioeconomy Strategy (European Commission, 2018). A downside of our results is that not all of these indicators are intended to measure the progress or impact of the circular bioeconomy but more general aspects of sustainable development. For instance, the indicators on the share of renewable energy include types other than bioenergy. Therefore, including more indicators specific to the circular bioeconomy would yield more precise results. As comprehensive indicator frameworks for the circular bioeconomy have already been proposed,[6] we expect more indicators to become available in the future.

With more indicators available in the future, creating, for example, economic, environmental, or social indicator groups to compare their developments and dynamics might produce interesting results. We expect the intra-distribution dynamics to be lower for indicators within groups than for ungrouped indicators. More countries should also be added to the analysis, especially countries with large circular bioeconomies outside the EU, such as the United States and China. We anticipate that more circular bioeconomy indicators for current and additional countries will be collected, the evolution of which our framework can help to analyze.

Declaration of Competing Interest

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

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Appendix A. Development of circular bioeconomy indicators in ten selected European Union Member States from 2006 to 2016 as box plots

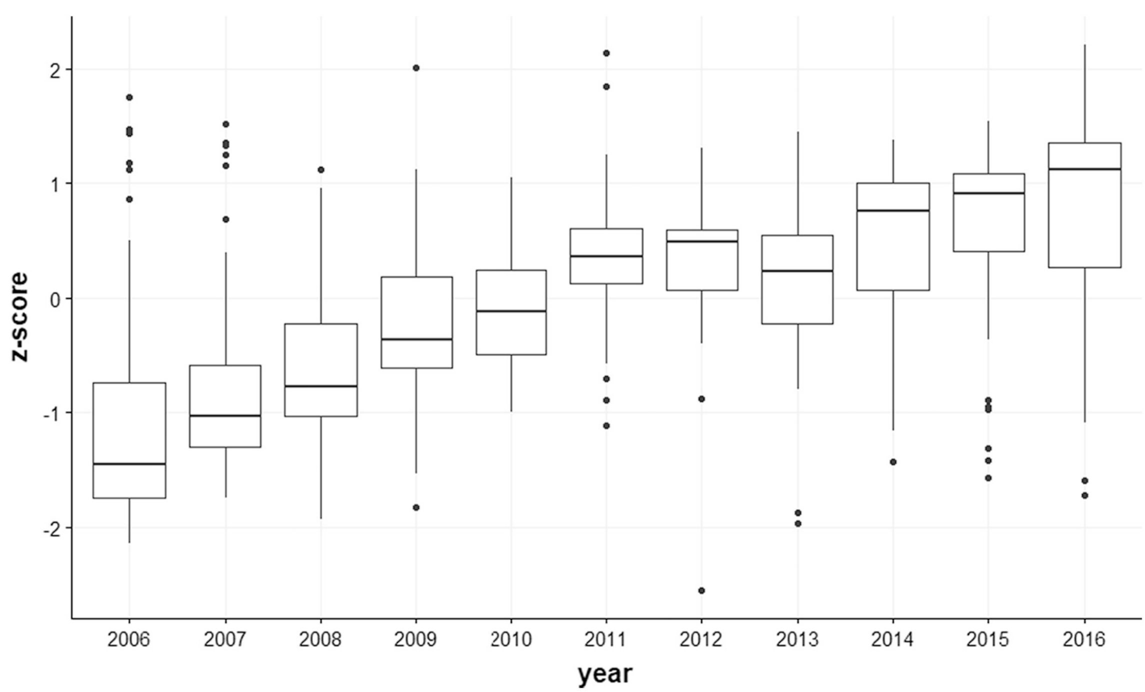

Fig. A.1: Germany.

[6] See, for example, the BioMonitor project, JRC Bioeconomy Monitoring, and the German Systematic Monitoring and Modelling of the Bioeconomy (Symobio) project.

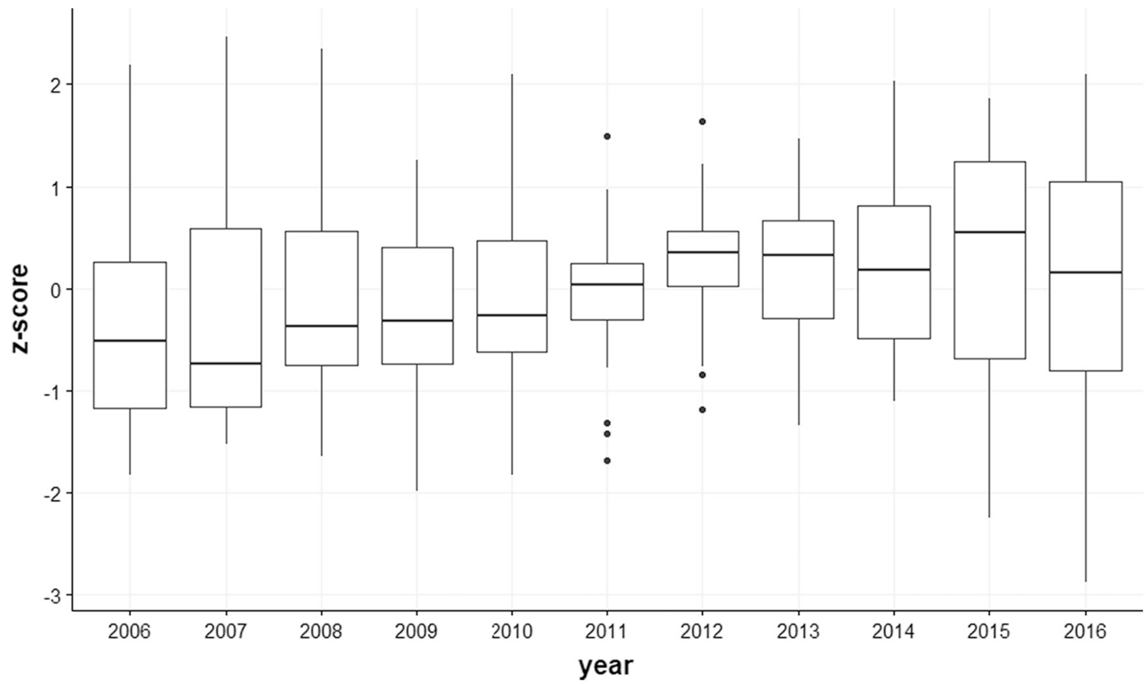

Fig. A.2: Finland.

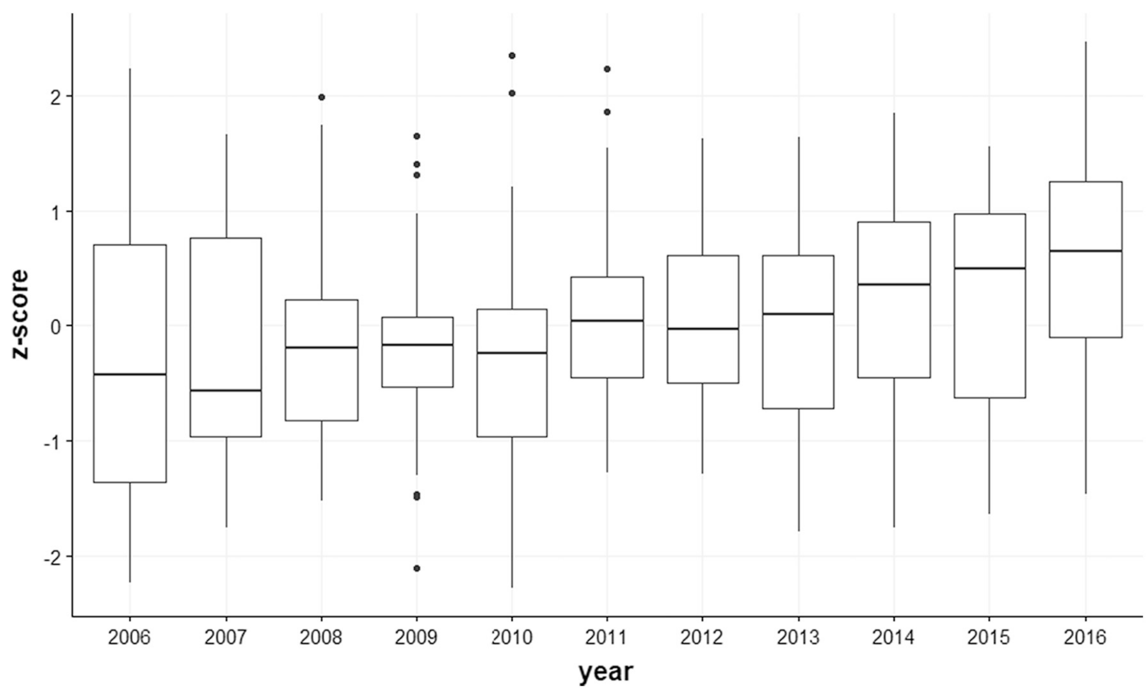

Fig. A.3: The Netherlands.

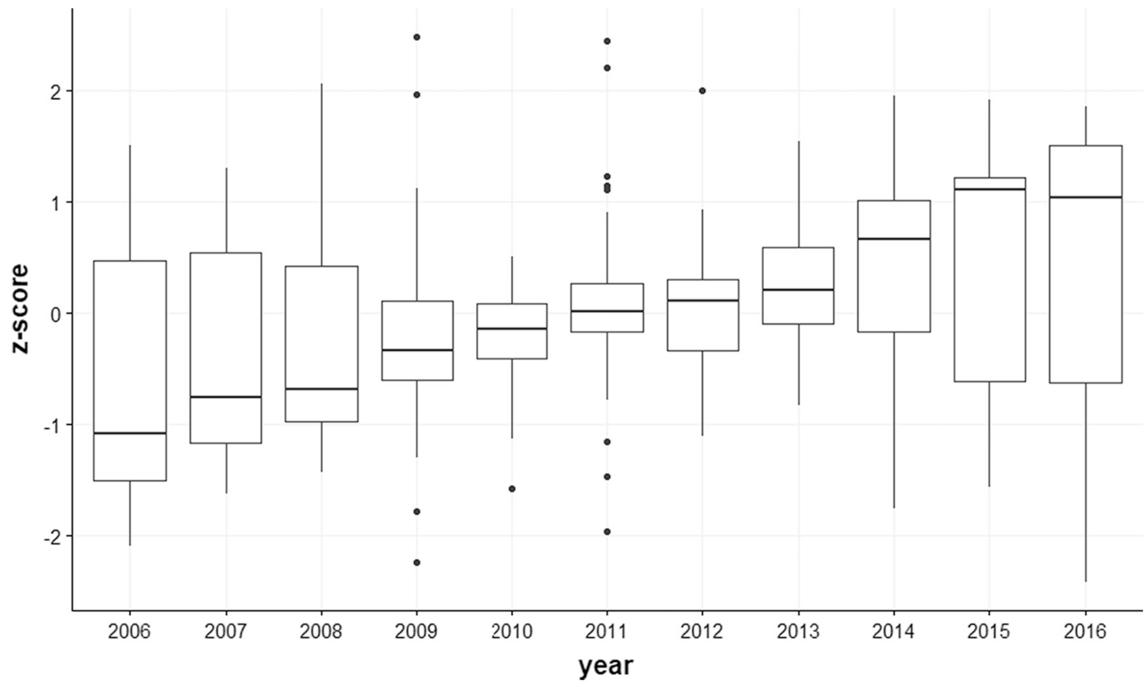

Fig. A.4: France.

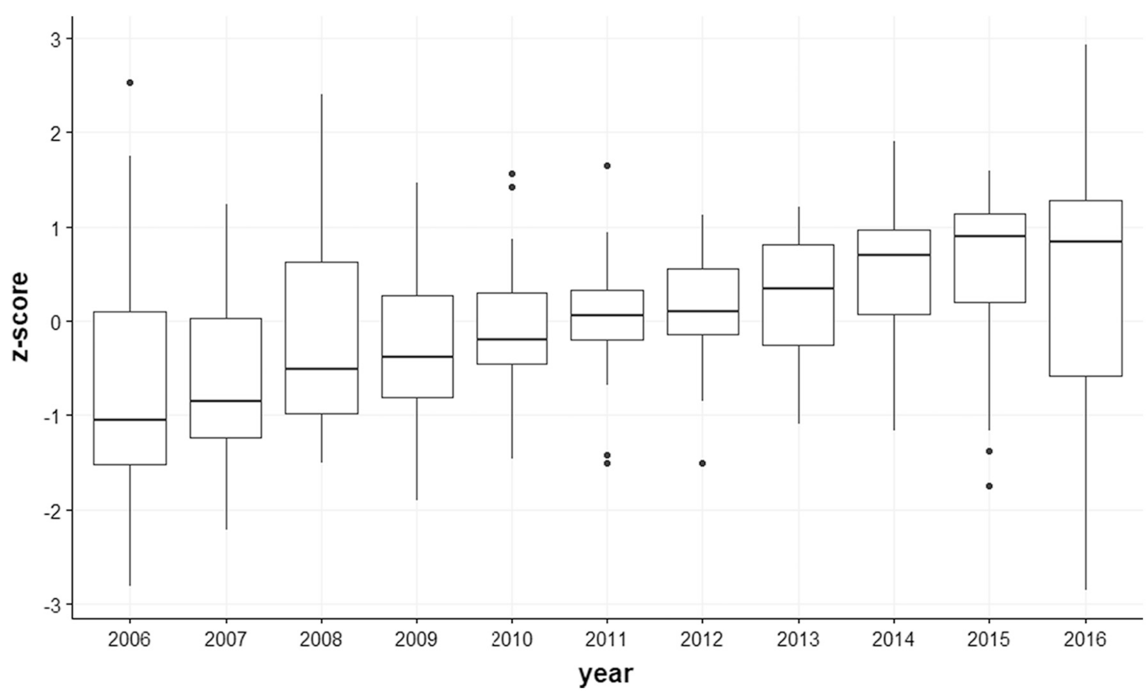

Fig. A.5: Poland.

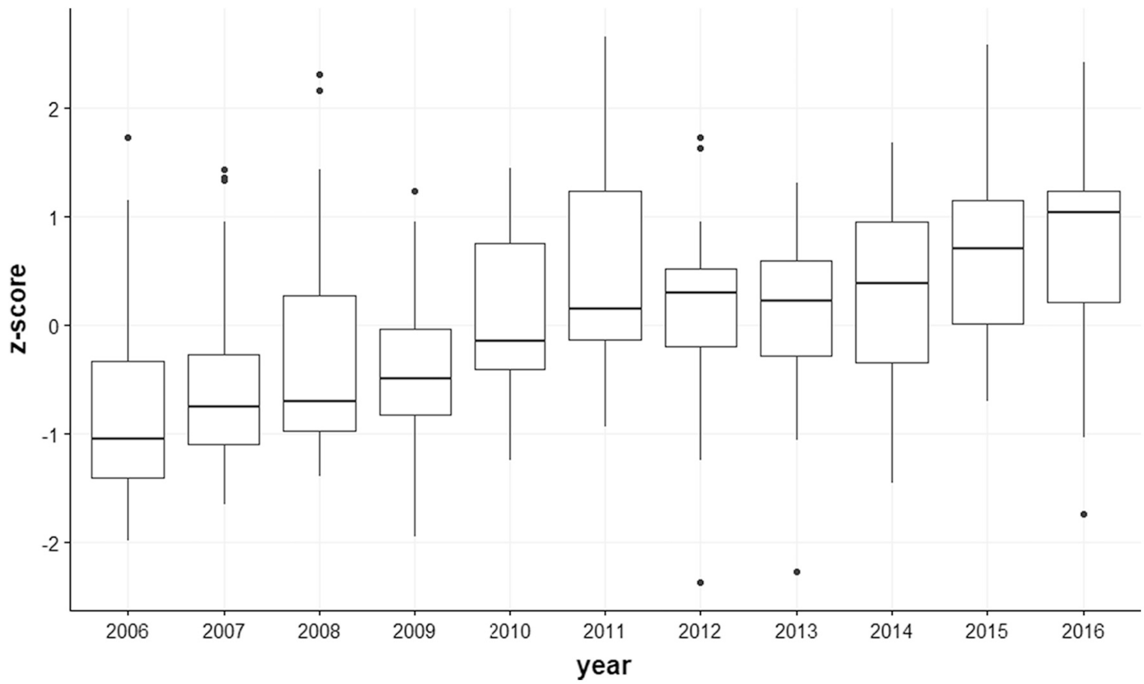

Fig. A.6: Slovakia.

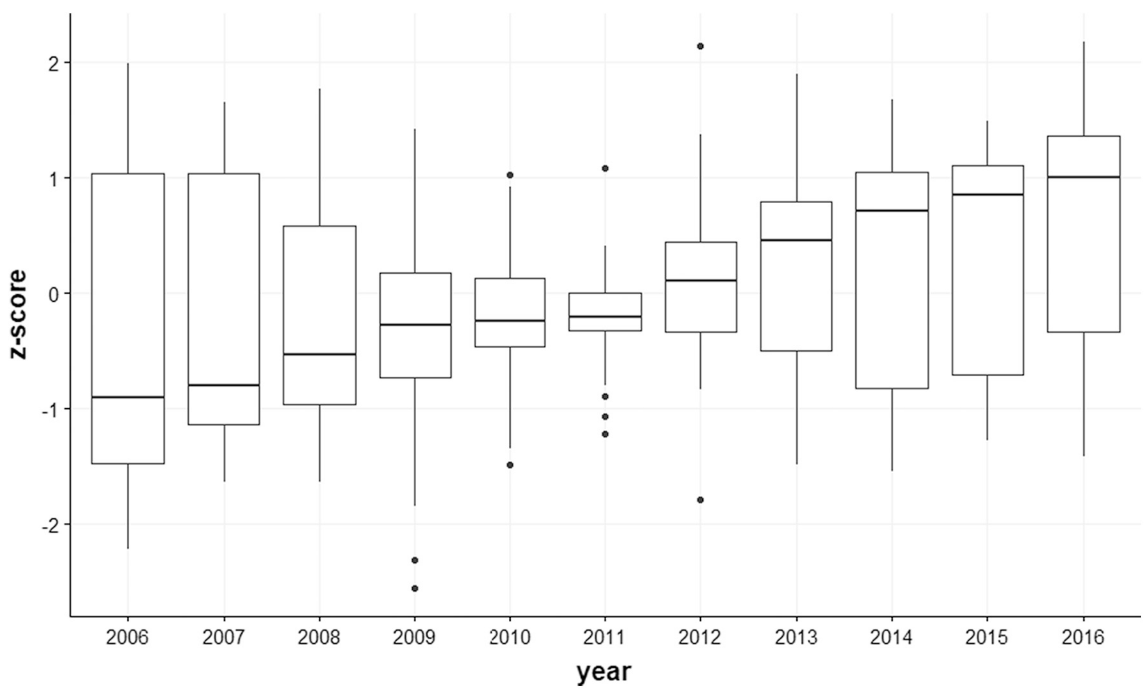

Fig. A.7: Italy.

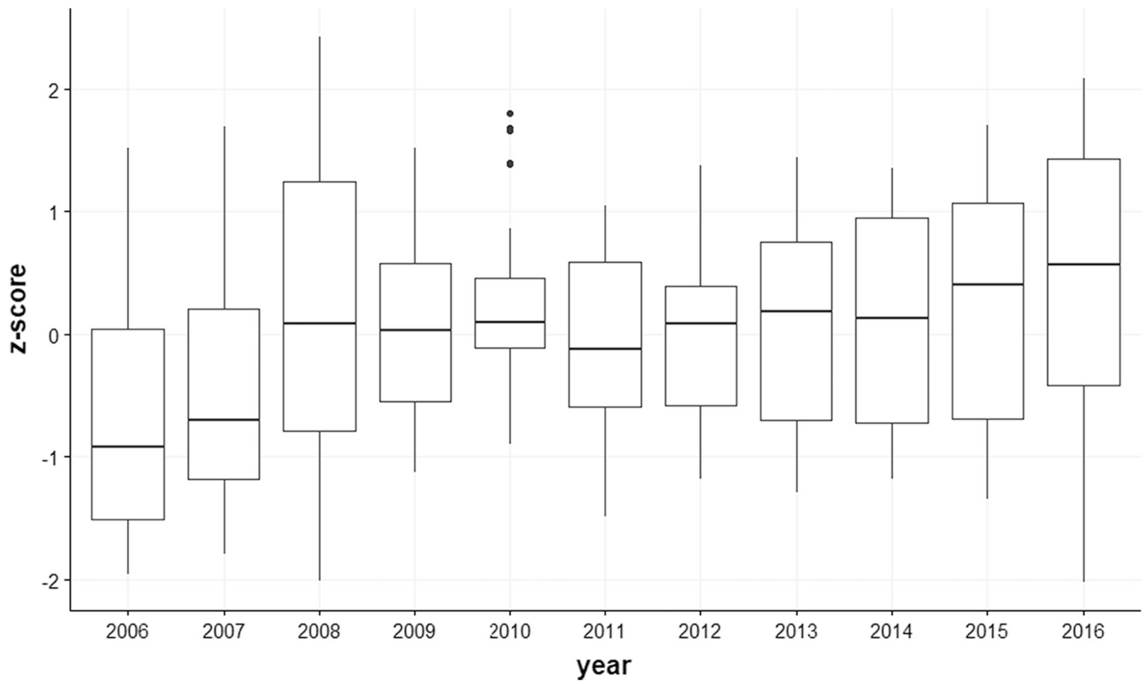

Fig. A.8: Spain.

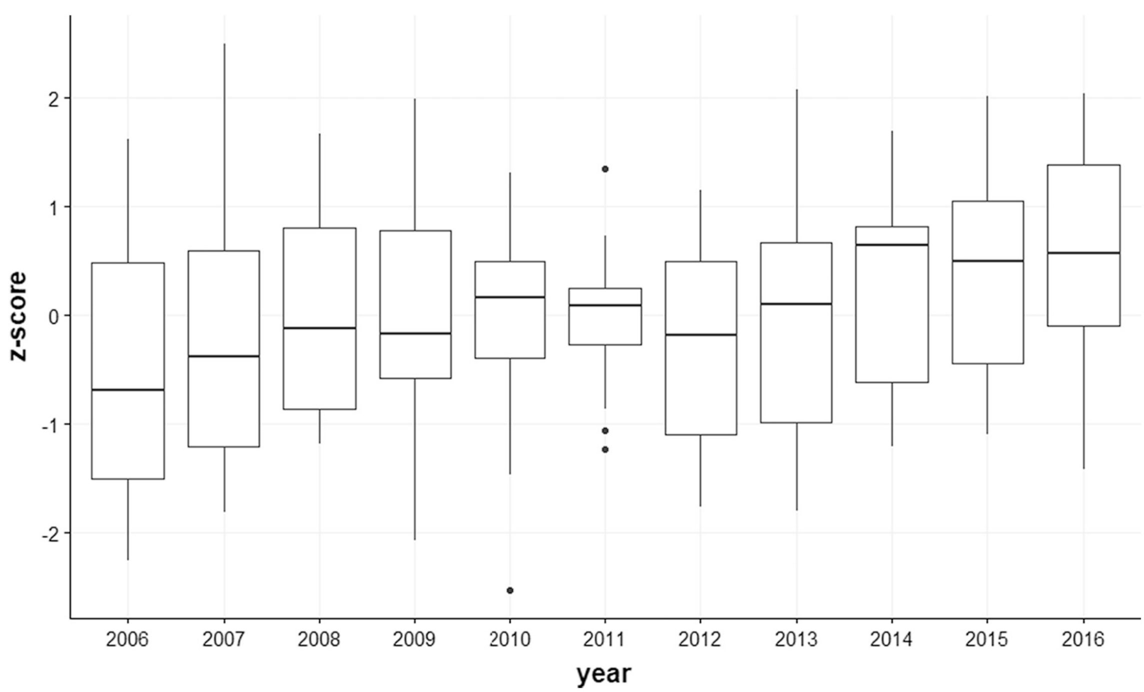

Fig. A.9: Portugal.

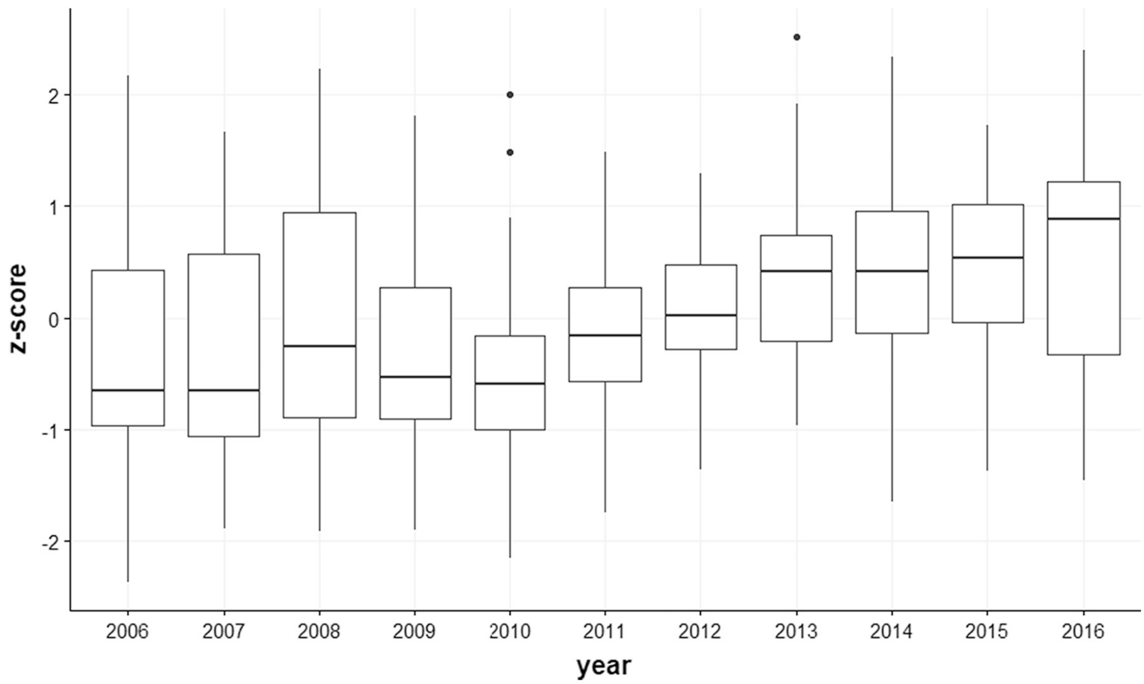

Fig. A.10: Latvia.
Note: A box plot illustrates the z-scores for each year. The band inside the box corresponds to the median and the width of the box to the interquartile range (IQR). The upper (lower) whisker extends from the hinge to the largest (lowest) value no further than 1.5 * IQR from the hinge. The points correspond to outliers beyond the range of the whiskers.

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