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How university students assess the planetary boundaries: A global empirical study

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ABSTRACT

In order to effectively address global environmental problems, it is important that future decision-makers in society are aware of the safe operation space for humans, which is limited by the planetary boundaries. Until now, however, there has been a lack of international studies examining how the planet's boundaries are perceived. In this study, we investigated how students of environmental and sustainability studies in 35 countries ($n = 4140$) assess the planetary boundaries. Based on the rating, using spectral clustering, the 35 countries were assigned to five different clusters. Four indicators (Human Development Index, Legatum Prosperity Index, Natural Resources Income and Forest Area) were used to provide explanations for the clustering result. The indices allow a distinction between the clusters and provide initial explanations for the clustering. The results provide important insights for today's decision-makers, as possible measures for action in the individual countries can be derived from the findings.

1. Introduction

The Earth system is currently undergoing major global changes. The loss of global biodiversity or climate change are just two prominent examples of environmental problems that cause serious consequences (IPCC, 2022; Johnson et al., 2017). Because of these dramatic functional changes in the Earth system which have been caused by humans, a new earth epoch has been proclaimed: The Anthropocene (Crutzen, 2002; Lewis and Maslin, 2015; Ruddiman, 2013).

In order to define the safe operating space in which humans can operate without affecting the functioning of Earth systems, the concept of planetary boundaries was introduced by Rockström et al. (Rockström et al., 2009a). For this purpose, critical Earth system processes, associated control variables and related thresholds were identified. Crossing such a threshold could lead to irreversible environmental change (Rockström et al., 2009b). To define safe operating space for humans, a planetary boundary is not the threshold itself, but a point before that threshold is reached. This provides a buffer for inaccuracy in the placement of the thresholds and allows society to react to warning signals that occur when the threshold is approached. When the planetary boundary is crossed, the safe operating space is left and the zone of uncertainty begins, which increases the risk of impact. If this zone is also surpassed, the dangerous level begins, at which the probability of serious impacts on Earth systems increases significantly with potentially devastating consequences for humanity (Steffen et al., 2015). While on the one hand it is necessary to ensure that the natural thresholds of planetary boundaries are not exceeded, on the other hand humanity must use nature to provide the social foundation for people to have sufficient resources to live a decent life (Raworth, 2012). The planetary boundaries are not independent of each other, but the effect on one planetary boundary can cause a stronger impact on another boundary (Lade et al., 2020). The concept of planetary boundaries is regularly extended and improved by new research results (Persson et al., 2022; Steffen et al., 2015) and the framework is useful for both terrestrial and marine Earth systems (Nash et al., 2017; Newbold et al., 2016).

If global environmental problems are to be addressed, the perception of society must also be taken into account. Especially the perspective of future leaders, decision-makers, land managers or politicians is particularly important, as they have a far reaching influence on society with their decisions. In this context, universities play an important role, as they teach and train the next generation of decision-makers (Alshuwaikhat and Abubakar, 2008; Bellou et al., 2017; Lozano et al., 2013). Although important positions in society can be reached without a university education, the knowledge and skills that universities provide improve the chances of reaching such a position (Vicente-Molina et al., 2013). Therefore, students in the environmental field are an essential group, as they are likely to become future decision-makers in the environmental field whose decisions will not

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only affect society in their own country, but will have a lasting global impact.

While studies on the perceptions of (future) decision-makers already exist for other relevant concepts dealing with the management of global problems (Bain et al., 2019; Kleespies and Dierkes, 2022), such as the Sustainable Development Goals of the United Nations (United Nations 2015), there is still a lack of similar studies for planetary boundaries. This study aims to answer the question of how students of environmental and sustainability studies in different regions of the world perceive the state of the planetary boundaries. For this purpose, students in a total of 35 countries ($n = 4140$) were asked about their assessment of the crossing of the planetary boundaries. In order to determine influences on the rating, data was grouped into clusters of similar assessment by a spectral clustering algorithm. Different country-specific indices were used to find explanations for the clustering results. The Human Development Index (HDI) and the Legatum Prosperity Index (LPI) were selected as indicators, as they represent the wealth of a country. These indicators take wealth further than purely monetary wealth and also include other important factors such as education. In addition, Natural Resources Income (NRI) and Forest Area (FA) of a country were selected as indicators. The results of our analysis can provide guidance to today's decision makers on what actions are needed in different countries to optimize the perception of planetary boundaries and on this way address global environmental problems.

2. Methods

2.1. Data collection procedure

Using an online questionnaire, a total of 4140 students of environmental and sustainability studies (e.g., biology, ecology and conservation, environmental sciences, natural resources management, etc.) in 35 countries were surveyed (64.18% female, 33.84% male, 0.87% diverse 1.11% no answer). The respondents were on average 22.53 years old and in their fourth semester of study. For data collection, professors, researchers and lecturers at universities in the countries surveyed were contacted by email. The email explained the background and objectives of the study and asked to distribute the questionnaire among students. In a cover letter for the students, there was a link to the survey as well as an information text about the aims of the study, the voluntary nature of participation, data protection, and the ethical approval. Since the survey was conducted on a voluntary basis, there may be some bias in the sample. For example, students who are particularly interested in this topic may have been more likely to complete the questionnaire than students who are not interested. However, as the same survey method was used in all countries and any possible bias applies equally to all countries, this does not pose a methodological problem and the results between countries remain comparable. A list of the surveyed countries including sample size can be found in the appendix Table 2. Data collection took place between September 2020 and July 2021.

The survey was conducted in one of the official languages of the surveyed countries. All questionnaires were translated by native speakers and verified by another person. The study was reviewed and approved by the ethics committee of the science didactic institutes and departments of the [authors university] under approval number [blinded]. If additional approval from a local ethics committee was required due to local regulations, this approval was obtained.

In the questionnaire, a short introductory sentence was presented to the students explaining that the earth has natural limits. The students were asked to assess how far they thought the limits of our planet had already been reached or exceeded by human activity today. Their answer was to be given on a six-point scale from limit not yet reached through limit slightly exceeded up to limit severely exceeded. Since the planetary boundaries for "novel entities" and "atmospheric aerosol loading" were not yet quantified at the time of data collection, these two planetary boundaries were not included in the survey. The two subcategories of biochemical flow were combined into one item (similar to Persson et al. (Persson et al. (2022)) and "genetic diversity" was used as a representative for "biosphere integrity".

2.2. Analysis

To find appropriate clusters, scikit-learn's spectral clustering algorithm with a radial basis function (RBF) kernel was used (Pedregosa et al., 2011). To assign class labels, the discretization technique is used because it is known to be robust against random effects (Yu and Shi, 2003). While being less known than classical clustering approaches like PCA, spectral clustering is the appropriate choice to find clusters on data in which a certain community structure is supposed to exist (Damle et al., 2019) and the geometry of a single cluster might be non-convex. Furthermore, it is applicable to medium sizes of data points with a small number of desired clusters. This is the case for the data underlying this study. Spectral clustering algorithms do not initially make assumptions about the global structure of data but they first decide locally whether two data points look similar. The global clustering then emerges in such a way that the local relations between data points are well preserved in low-dimensional projections (Yu and Shi, 2003). In the current study, for each country the mean and its standard deviation of the scores for each planetary boundary is computed across all questionnaires. Thus, each country is represented by a point in a 14-dimensional Euclidean space. While the mean is a straight-forward choice, the standard deviation allows distinguishing between homogeneous countries and inhomogeneous countries with the same mean and thus contains valuable information. The spectral clustering algorithm now assigns a label (the number of the cluster) to each such point. As it requires the number of desired clusters as an input, a result needs explicit inspection and validation. A standard approach is to iteratively increase the number of clusters and analyze the algorithm's output. In the current study, five clusters are identified as stable and if the spectral clustering algorithm is allowed to create six clusters, it still discriminates only five clusters during the discretization step which indicates the stability of the five clusters found.

2.3. Indices

Four global indices were used to explain the clustering results:

- Human Development Index from 2020 (HDI): The HDI consists of three components: Life expectancy at birth, expected and mean years of schooling, and gross national income per capita (United Nations Development Programme 2020a). The index is published regularly by the United Nations in the Human Development Report and is an important indicator of prosperity (United Nations Development Programme 2020b).
- Legatum Prosperity Index from 2021 (LPI): The LPI evaluates the prosperity of a country under consideration of three domains: inclusive society, open economy and empowerment of people. For this purpose, a total of 300 indicators are evaluated in 12 subcategories (Legatum Institute 2021).
- Natural Resources Income in percent of the gross domestic product from 2020 (NRI): The NRI indicates the percentage of a country's gross domestic product derived from oil, natural gasses, coal, minerals and forests. The contribution of natural resources to economic output is seen as an important factor in the sustainable development framework (World Bank 2020).
- Forest Area in percent of land area from 2020 (FA): Area of land with trees that are at least 5 m tall. Trees in agricultural use and trees in urban parks or gardens are not included (World Bank 2020).

3. Results

Finding causal clusters on unordered data is a challenging task. This study tackles the problem by spectral clustering, a technique that is de-

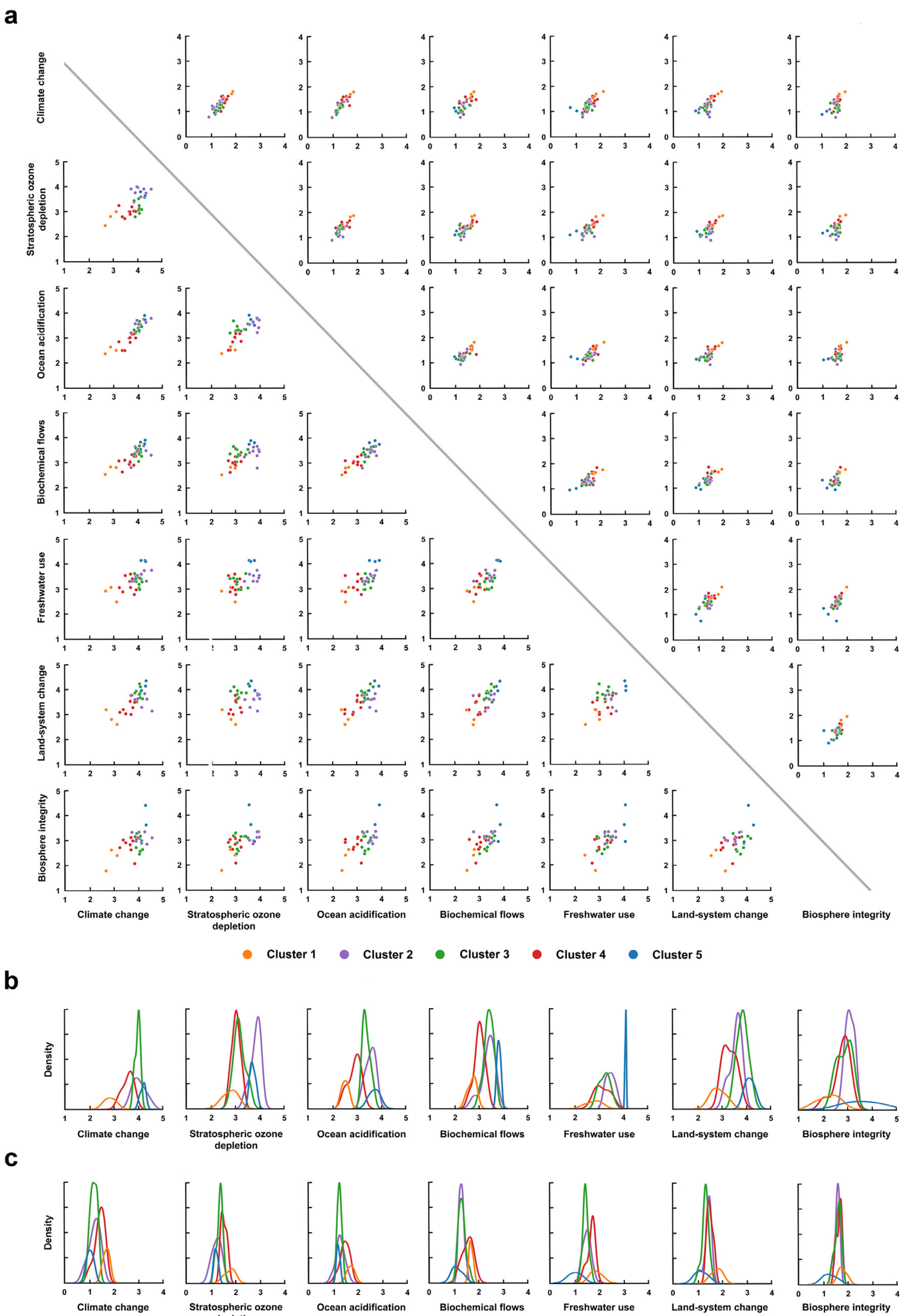

Fig. 1. Representation of the five clusters as identified via the spectral clustering algorithm. (a) pairwise two-dimensional projection of the average (bottom left) and standard deviation (top right) of the questionnaires of the countries. Clusters are highlighted. (b) distribution of the averages of the planetary boundaries inside the clusters; (c) corresponding distribution of the standard deviations.

Table 1
Mean (M) and standard deviation (SD) of planetary boundaries for each country divided by clusters. The mean and standard deviation of the cluster values in bold are average values of the countries belonging to the cluster.

	Climate change		Stratospheric ozone depletion		Ocean acidification		Biochemical flows		Freshwater use		Land-system change		Biosphere integrity	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Cluster 1	**2.82**	**1.72**	**2.79**	**1.72**	**2.54**	**1.67**	**2.72**	**1.64**	**2.81**	**1.81**	**2.76**	**1.74**	**2.23**	**1.77**
Federal Republic of Nigeria	2.99	1.81	2.94	1.86	2.55	1.81	2.82	1.69	2.40	2.00	2.41	1.94	2.23	1.94
Russian Federation	2.70	1.58	2.52	1.46	2.43	1.52	2.51	1.57	2.97	1.63	3.16	1.47	1.85	1.66
Kingdom of Saudi Arabia	2.78	1.78	2.91	1.83	2.63	1.67	2.83	1.66	3.05	1.81	2.70	1.80	2.60	1.72
Cluster 2	**3.56**	**1.45**	**2.98**	**1.50**	**2.88**	**1.45**	**3.00**	**1.52**	**3.11**	**1.66**	**3.27**	**1.49**	**2.66**	**1.65**
Islamic Republic of Pakistan	3.80	1.51	3.18	1.37	3.13	1.36	3.20	1.42	3.47	1.63	3.29	1.43	2.87	1.64
Japan	3.37	1.25	2.79	1.44	2.51	1.63	2.56	1.59	2.86	1.66	3.20	1.38	2.93	1.74
Kingdom of Morocco	3.19	1.56	2.85	1.56	2.46	1.43	3.08	1.28	3.25	1.80	2.71	1.60	2.58	1.69
People's Republic of China	3.20	1.42	3.21	1.38	2.81	1.46	3.08	1.44	3.01	1.48	3.05	1.41	2.65	1.49
Republic of Ireland	3.86	1.61	3.04	1.45	3.18	1.50	2.92	1.65	2.79	1.73	3.48	1.53	2.04	1.67
Republic of Kenya	3.60	1.63	2.75	1.69	2.81	1.65	3.14	1.72	2.64	1.89	3.42	1.71	2.65	1.83
Republic of Korea	3.72	1.00	2.96	1.40	2.87	1.08	3.00	1.25	3.04	1.33	2.98	1.30	2.60	1.44
Republic of South Africa	3.72	1.39	3.07	1.55	3.17	1.29	3.13	1.71	3.70	1.73	3.82	1.36	2.90	1.75
Republic of the Philippines	3.58	1.64	2.99	1.65	2.99	1.63	2.90	1.63	3.26	1.67	3.48	1.65	2.72	1.62
Cluster 3	**4.02**	**1.18**	**3.08**	**1.35**	**3.33**	**1.27**	**3.38**	**1.30**	**3.19**	**1.44**	**3.80**	**1.28**	**2.87**	**1.57**
Canada	4.12	1.08	3.08	1.42	3.40	1.21	3.46	1.29	3.27	1.51	3.79	1.34	2.74	1.75
Commonwealth of Australia	3.91	1.34	2.76	1.44	3.23	1.27	3.30	1.23	3.30	1.38	3.96	1.26	2.75	1.56
Federative Republic of Brazil	4.02	1.32	3.51	1.26	3.52	1.25	3.48	1.30	2.98	1.36	4.20	1.22	3.16	1.48
French Republic	3.94	1.32	2.94	1.45	3.11	1.31	3.57	1.32	3.31	1.33	3.45	1.41	3.16	1.41
Kingdom of Sweden	4.02	1.29	2.85	1.46	3.53	1.33	3.68	1.17	3.25	1.49	4.08	1.24	3.27	1.58
Portuguese Republic	4.04	1.12	3.15	1.35	3.19	1.33	3.31	1.45	2.87	1.53	3.75	1.29	2.96	1.60
Republic of China	3.89	0.92	3.45	1.09	3.36	1.10	3.40	1.08	3.61	1.24	3.83	1.03	3.07	1.40
Republic of Singapore	4.05	1.12	3.01	1.36	3.33	1.22	3.07	1.37	3.22	1.37	3.82	1.29	2.42	1.63
United Kingdom of Great Britain and Northern Ireland	4.04	1.07	3.12	1.19	3.32	1.19	3.32	1.22	2.96	1.61	3.66	1.23	2.56	1.67
United States of America	4.15	1.25	2.96	1.45	3.33	1.44	3.18	1.59	3.13	1.61	3.51	1.52	2.56	1.62
Cluster 4	**4.06**	**1.22**	**3.77**	**1.23**	**3.49**	**1.31**	**3.37**	**1.30**	**3.44**	**1.48**	**3.53**	**1.36**	**3.04**	**1.57**
Commonwealth of Puerto Rico	4.55	0.75	3.76	1.01	3.72	1.03	3.20	1.29	3.65	1.22	2.93	1.51	2.89	1.64
Dominican Republic	3.80	1.46	3.68	1.43	3.44	1.49	3.58	1.29	3.63	1.48	3.55	1.45	2.88	1.67
Kingdom of Thailand	3.75	1.18	3.87	1.08	3.06	1.47	2.89	1.32	3.13	1.75	3.77	1.17	3.38	1.60
Kingdom of Spain	4.35	0.98	3.71	1.25	3.61	1.21	3.44	1.25	3.29	1.43	3.60	1.40	2.80	1.65
Republic of Colombia	4.22	1.31	3.88	1.31	3.75	1.29	3.75	1.29	3.56	1.61	3.84	1.42	3.17	1.64
Republic of Peru	4.04	1.15	4.01	1.07	3.4	1.23	3.50	1.15	3.31	1.45	3.58	1.18	3.08	1.44
Republic of Poland	4.07	1.26	3.58	1.28	3.49	1.29	3.36	1.34	3.51	1.41	3.22	1.53	2.92	1.58
Slovak Republic	3.85	1.33	3.39	1.33	3.32	1.16	3.18	1.34	3.24	1.53	3.60	1.39	3.08	1.47
United Arab Emirates	3.92	1.59	4.04	1.33	3.61	1.58	3.42	1.39	3.67	1.40	3.71	1.23	3.14	1.43
Cluster 5	**4.20**	**1.05**	**3.65**	**1.14**	**3.70**	**1.16**	**3.77**	**1.14**	**4.05**	**1.09**	**4.07**	**1.14**	**3.59**	**1.24**
Federal Republic of Germany	4.34	0.87	3.58	1.12	3.93	1.12	3.71	1.31	4.10	1.22	4.09	1.34	4.38	0.97
Republic of India	3.96	1.22	3.75	1.00	3.43	1.21	3.73	1.05	3.98	1.02	3.89	1.09	2.84	1.50
United Mexican States	4.29	1.07	3.62	1.29	3.74	1.15	3.87	1.05	4.06	1.02	4.25	1.00	3.54	1.24

signed specifically to find clusters in data with an underlying causal structure. Fig. 1 shows the distribution of the data points with five as necessary and stable identified clusters in a pairwise two-dimensional projection.

Important differences, but also similarities, were found in the assessment of the planetary boundaries between the clusters (Table 1). In all clusters, every single planetary boundary was evaluated as outside the safe operating space, including those that had not yet been currently crossed. Within the clusters, there was no strong distinction between the individual planetary boundaries, but they were estimated to be similarly exceeded. In cluster 1, compared to the other clusters, the exceeding of the planetary boundaries was estimated to be rather moderate. All boundaries are in the zone of uncertainty, including those such as genetic diversity and biochemical flows, which in reality are already beyond the zone of uncertainty. In cluster 2, all planetary boundaries are at the end of the zone of uncertainty. Climate change, land-system change and freshwater use are rated as slightly beyond the zone of uncertainty. In the third cluster, all planetary boundaries, with the exception of genetic diversity, are rated as beyond the zone of uncertainty. In cluster 4, similar to cluster 3, all planetary boundaries, except genetic diversity, are beyond the zone of uncertainty, in the high risk area. Compared to the previous cluster, however, the planetary boundaries are estimated to be further beyond the zone of uncertainty. In cluster 5, all planetary boundaries are well within the dangerous zone with a high risk of serious impact. Land use change, water use, and climate change are rated particularly high. Even planetary boundaries that are actually not yet exceeded, such as freshwater use or ocean acidification, are assessed as highly exceeded in this group (Fig. 2).

Four global indices were selected in order to gain possible explanations for the cluster formation and to be able to distinguish the clusters from each other. Cluster 3 is characterized by high wealth indices of the countries included: This cluster consists almost exclusively of countries with a high HDI and high LPI. Cluster 1 is distinguished from the other clusters by its high NRI. Clusters 2, 4 and 5 differ significantly in terms of FA. While cluster 2 includes countries with a low FA, cluster 4 and 5 contains countries with a large FA (Fig. 3).

4. Discussion

Spectral clustering methods require visual inspection and verification of the clusters' found. As can be seen in Fig. 1 (a), in every column there is at least one projection in which a clear separation of one color from the others is visible. This corresponds to the necessity of the cluster represented by this color. Fig. 1 (b, c) shows a kernel density estimation of the distribution of any planetary boundary per cluster. All distributions are close to β-distributions without severe indentations which indicates that the distributions are natural and do not seek to be a conjunction of multiple distributions which would corre-

Table 2
Sample size and values of the selected indices for each country.

	Sample size	Human Development Index (2020)	Legatum Prosperity Index (2021)	Natural resources income,% of GDP (2020)	Forest area,% of land area (2020)
Commonwealth of Australia	104	0.944	78.76	10.10	17.40
Federative Republic of Brazil	96	0.765	59.57	5.90	59.40
Canada	190	0.929	88.37	2.20	38.70
People's Republic of China	105	0.761	62.23	1.40	23.30
Republic of Colombia	120	0.767	58.04	4.30	53.30
Dominican Republic	112	0.756	58.7	2.40	44.40
French Republic	115	0.901	76.34	0.00	31.50
Federal Republic of Germany	108	0.947	80.57	0.10	32.70
Republic of India	57	0.645	53.57	1.90	24.30
Republic of Ireland	74	0.955	79.63	0.00	0.50
Japan	59	0.919	77.72	0.20	68.40
Republic of Kenya	61	0.601	51.09	1.20	6.30
United Mexican States	159	0.779	59.15	2.70	33.80
Kingdom of Morocco	46	0.686	55.97	0.40	12.90
Federal Republic of Nigeria	85	0.539	43.02	6.20	23.70
Islamic Republic of Pakistan	101	0.557	44.13	0.90	4.80
Republic of Peru	122	0.777	60.81	4.40	56.50
Republic of the Philippines	265	0.718	56.75	1.40	24.10
Republic of Poland	503	0.88	70.32	0.90	31.00
Portuguese Republic	209	0.864	74.21	0.20	36.20
Commonwealth of Puerto Rico	57	n/a	n/a	0.00	56.00
Russian Federation	104	0.824	59.1	11.00	49.80
Kingdom of Saudi Arabia	120	0.854	58.59	18.30	0.50
Republic of Singapore	127	0.938	79.05	0.00	22.00
Slovak Republic	131	0.86	70.56	0.20	40.10
Republic of South Africa	30	0.709	56.69	5.40	14.10
Republic of Korea	48	0.916	73.52	0.20	64.50
Kingdom of Spain	294	0.904	75.44	0.10	37.20
Kingdom of Sweden	49	0.945	83.11	0.90	68.70
Republic of China	184	n/a	76.9	n/a	n/a
Kingdom of Thailand	66	0.777	60.51	1.30	38.90
United Arab Emirates	60	0.89	67.31	11.90	4.50
United Kingdom of Great Britain and Northern Ireland	98	0.932	79.6	0.40	13.20
United States of America	81	0.926	77.15	0.50	33.90

spond to more clusters. This is also supported by running the algorithm allowing one more cluster but still only the five present clusters are identified.

The conducted survey and the following cluster analysis provide important information about the perceptions of students in environmental and sustainability studies on global environmental problems and the capacities of our planet. Based on the analysis, valuable recommendations for action can be derived for today's decision makers in education and politics, which can help to contribute to the preservation of Earth Systems on a global scale. Independent of the cluster, it is shown that all planetary boundaries were considered to be exceeded, even if this is not the case at the moment (Rockström et al., 2009b; Steffen et al., 2015). Despite the fact that this is a misconception and a massive overestimation in some cases, it is a positive result, as it proves that students worldwide recognize the important environmental problems and evaluate them as such.

In all clusters, the loss of biodiversity is rated as least exceeded compared to the other planetary boundaries, although this planetary boundary is one of the highest exceeded in reality (Rockström et al., 2009b; Steffen et al., 2015). Currently, the extinction rate of species is 1000 times higher than the background rate of extinction, with a projected upward trend (Pimm et al., 2014). This loss of biodiversity may have a negative effect on the stability of ecosystems and reduces ecosystem services that are important to humans (Cardinale et al., 2012), which negatively impacts human well-being (Díaz et al., 2006). These findings suggest that environmental students worldwide need to be more educated about the loss of biodiversity and its consequences. On a global scale, there should be more communication about the worldwide loss of biodiversity, similar to the current communication for climate change (Nerlich et al., 2010). Since there was little differentiated perception of planetary boundaries across all clusters, the differences between each planetary boundary should be more extensively included in university curricula.

The perception of environmental problems in different countries is a complex process on which a wide variety of variables have an influence (Bi et al., 2010; White and Hunter, 2009). Therefore, it is often difficult to understand why people in one country perceive an environmental problem differently than people in another country. In this study we present some possible explanations that can help to understand the different perceptions between countries.

When attitudes towards or concern about environmental problems are studied, a country's wealth is often considered as a possible explanatory variable. In this context, reference is often made to Inglehart's findings (Inglehart, 1995). He describes that in countries where postmaterialist values are more prevalent, people are more willing to protect the environment than in nations where materialist values predominate. With increasing prosperity, nations change more and more from materialist values to postmaterialist values. Numerous empirical studies have confirmed that people in wealthier countries are more concerned about environmental problems (Franzen, 2003; Franzen and Meyer, 2010; Franzen and Vogl, 2013). However, there are also studies that have shown that addressing environmental problems is seen as more important in less wealthy countries (Kleespies and Dierkes, 2022) or that there is no connection between wealth and these environmental attitudes (Boeve-de Pauw and van Petegem, 2010).

In this research, a particularly large number of wealthy countries with a high HDI and LPI are grouped in cluster 3. This indicates that there is a connection between the wealth of a nation and the perception of the planetary boundaries, even though this relationship is not as clear and linear as in previous studies. Most wealthy countries assess the plan-

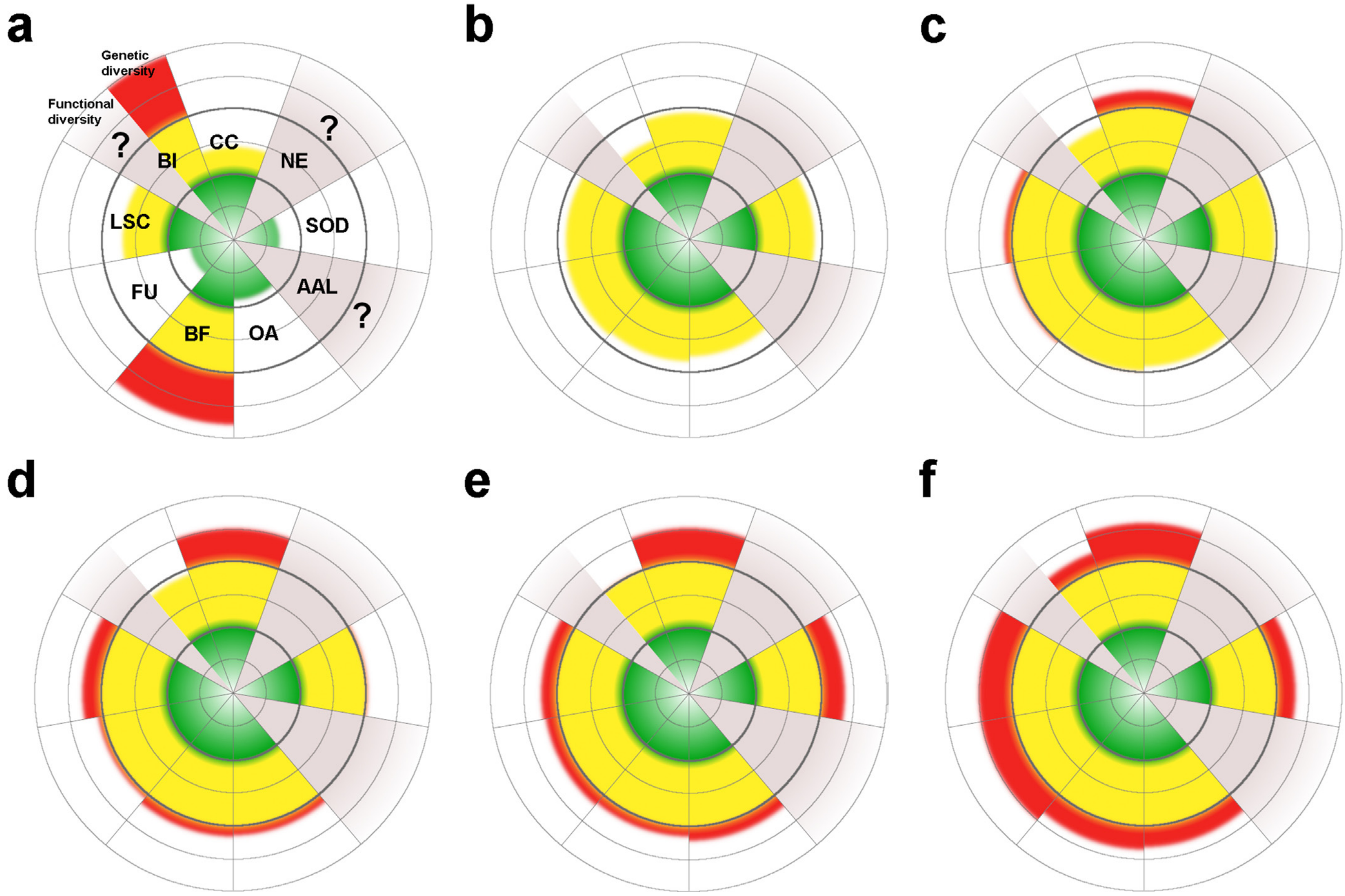

Fig. 2. Assessment of the different planetary boundaries (BI: biosphere integrity; CC: climate change; NE: novel entities; SOD: stratospheric ozone depletion; AAL: atmospheric aerosol loading; OA: ocean acidification; BF: biochemical flows; FU: freshwater use; LSC: land-system change) in the five identified clusters. Green represents the zone in which the planetary boundary has not yet been crossed (safe operating space), yellow the zone of uncertainty, in which the planetary boundary has been exceeded and the risk for change of the Earth systems is increasing, and red is the area beyond the zone uncertainty with high risk for impact. (a) Status of Planetary Boundaries according to Steffen et al. (2015) (b) Cluster 1: Russian Federation, Kingdom of Saudi Arabia, Federal Republic of Nigeria (c) Cluster 2: People's Republic of China, Republic of Ireland, Japan, Republic of Kenya, Kingdom of Morocco, Islamic Republic of Pakistan, Republic of the Philippines, Republic of South Africa, Republic of Korea (d) Cluster 3: Commonwealth of Australia, Federative Republic of Brazil, Canada, French Republic, Portuguese Republic, Republic of Singapore, Kingdom of Sweden, Republic of China, United Kingdom of Great Britain and Northern Ireland, United States of America (e) Cluster 4: Republic of Colombia, Dominican Republic, Republic of Peru, Republic of Poland, Commonwealth of Puerto Rico, Slovak Republic, Kingdom of Spain, Kingdom of Thailand, United Arab Emirates (f) Cluster 5: Federal Republic of Germany, Republic of India, United Mexican States.

etary boundaries to be at the transition between the zone of increasing and high risk.

In addition to the level of wealth in a country, there are other factors that allow a distinction to be made between the clusters. Cluster 1, for example, contains countries where a comparatively high proportion of the gross domestic product is derived from natural resources. It is plausible that in countries where nature is more utilized and used to produce a large proportion of a country's wealth, environmental problems are seen as having less of an impact, as acknowledging these problems would compromise the prosperity in the country.

Clusters 2, 4 and 5 can be differentiated well from each other by the forest area in percent of the total land area of a country. Countries with higher forest area tend to accumulate in clusters 4 and 5, while countries with a small forest area tend to be found in cluster 2. In clusters 4 and 5, the planetary boundaries are considered to be more critically crossed than in cluster 2. The forest areas in a country might offer the population the opportunity to have direct contact with nature. This can strengthen various environmental psychological variables, such as connection with nature (Schultz, 2002) or environmental attitudes (DeVille et al., 2021), which in turn influence the perception of environmental problems. It is also possible that in countries with a higher forest area, society sees nature as more worthy of protection and thus the concern about environmental problems and planetary boundaries is greater. However, it should be noted that while attitudes about environmental problems and behaviors toward the environment are not independent, attitudes do not translate directly into behaviors (Marcinkowski and Reid, 2019). This means that the perceptions of planetary boundaries collected here do not yet allow for a direct statement about the students' environmental behaviors.

The clusters generated provide valuable insights into the perception of the limits of our planet on a global scale. The study fits well with existing research (Franzen, 2003; Franzen and Meyer, 2010; Franzen and Vogl, 2013; Kleespies and Dierkes, 2022) and can serve scientists as a possible starting point for further international research on perceptions of environmental problems. The results can also help today's politicians or decision-makers in universities, schools or politics when designing courses or curriculums, as they show the inaccuracies in the perception of planetary boundaries in different countries.

Since planetary boundaries were assessed to be very symmetrically crossed regardless of the cluster, globally the different states of the boundaries should be more specifically communicated. In countries in clusters where the planetary boundaries were rather underestimated

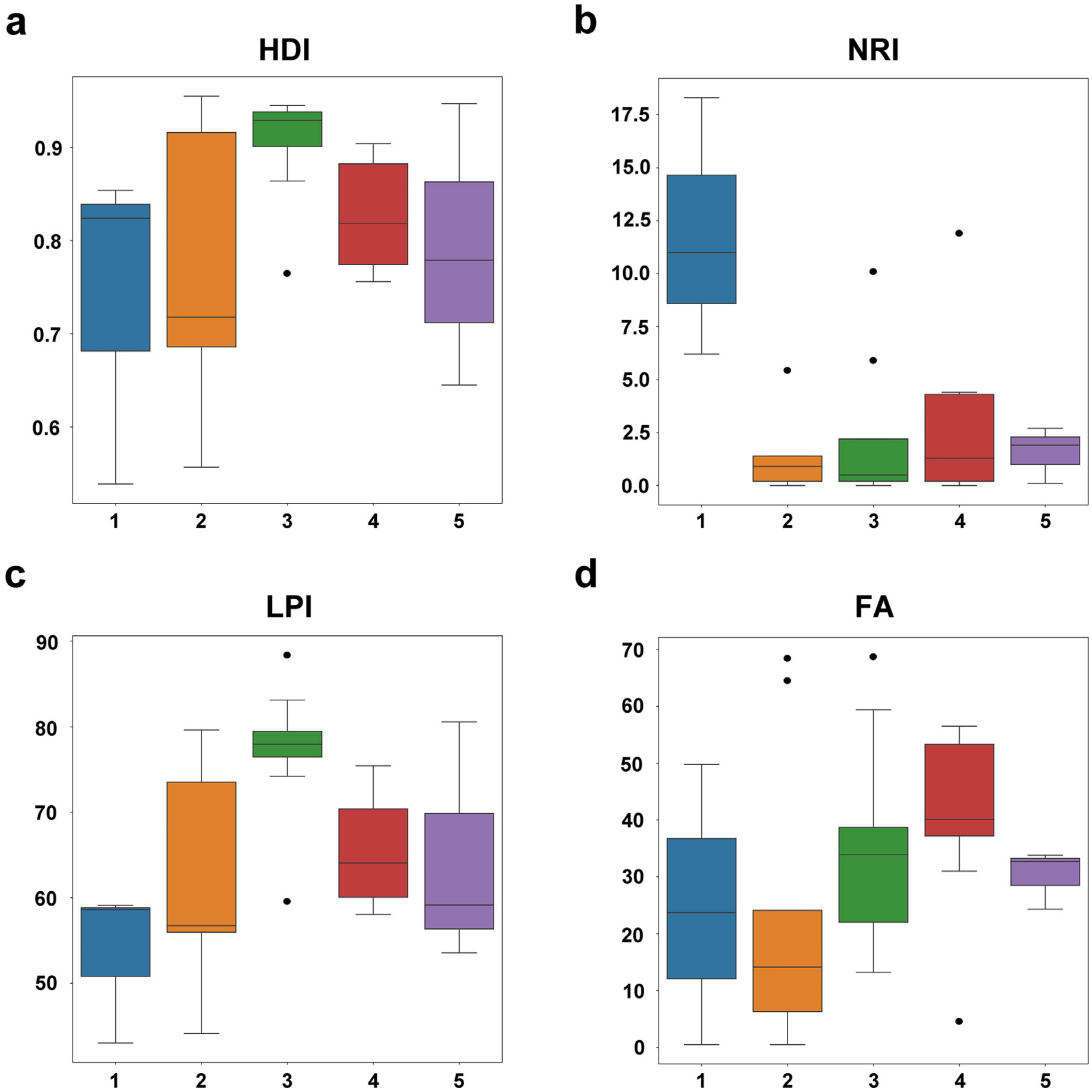

Fig. 3. Distribution of the indices in the five clusters. The five clusters are shown on the x-axis, and the value of the indices on the y-axis. (a) Human Development Index (HDI) (b) Natural Resources Income in percent of the gross domestic product (NRI) (c) Legatum Prosperity Index (LPI) (d) Forest Area in percent of land area (FA).

(cluster 1–2), education and awareness measures should be provided to inform students about the current state of environmental problems. In countries where all planetary boundaries are considered to be strongly exceeded (cluster 3–5), a more pronounced perception of planetary boundaries should be taught in schools and universities and the different state of the boundaries should be highlighted. In this context, it might also be worth promoting other environmental psychological variables, such as connection to nature or environmental attitudes, in addition to knowledge. One way of doing this, for example, would be to create more opportunities for contact with nature (Soga and Gaston, 2016) or to promote active perception of nature (Richardson et al., 2022).

Author contributions

Conceptualization: MWK, PWD; data collection: MWK; methodology: MHK, MWK, PWD; validation, formal analysis, investigation: MWK, MHK, PWD; figures: PWD, MWK, MHK; writing – original: MWK and MHK; writing – review and editing: MWK, MHK, PWD, funding acquisition: PWD. All authors contributed to the article and approved the submitted version.

Ethical approval

The study was reviewed by the ethics committee of the science didactic institutes and departments of the Goethe University Frankfurt am Main under approval number 15-WLSD-2104.

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.

Data availability

Data will be made available on request.

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Supplementary materials

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