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National innovation systems and sustainable environmental performance: A cross country analysis

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ABSTRACT

This research seeks to understand the role of national innovation systems (NIS) in addressing countries' environmental performance, namely their environmental health, ecosystem vitality, and climate change. The role played by NIS in these societal challenges was tested in 130 countries through cross-sectional models using the updated data from 2022/2021. The major findings of this research revealed that NIS contribute insignificantly to the attainment of meaningful environmental goals, such as enhancing ecosystem vitality or mitigating climate change. Despite making a positive impact towards protecting the population from environmental risks, NIS urgently need to make a paradigm shift towards environmental sustainability.

Introduction

In recent years, a number of studies have warned of the damage caused to our planet, whether in environmental health (Stephen et al., 2018), ecosystem vitality (Edrisi and Abhilash, 2021) or in climate change (Chen and Gong, 2021). Technology and innovation are usually seen as tools to address these challenges and some interesting literature can be found with proposals for cities, regions or specific countries and/or even for some specific economic sectors.

Regardless of these relevant advances, we should be asking if economies are using their national innovation systems (NIS) to address these challenges and whether these systems are aligned to deal with the major problems of protecting environmental health, enhancing ecosystem vitality and mitigating climate change. A holistic approach should be taken when addressing this issue as it remains an academic question. It is therefore essential to broaden knowledge on as many economies as possible so that and policies that consider the idiosyncrasies of each country or region can then be defined.

Given the scant studies linking NIS and environmental domains (at national level), this work aims to bridge this gap and further knowledge in this field. Additionally, we build on the work of Fernandes et al. (2022), which used the environmental performance index (EPI) to examine the NIS role by including the principle factors of EPI (Environmental Health [EH], Ecosystem Vitality [EV] and Climate Change [CC]). In fact, CC was first used as a major factor in the 2022 edition of the Environmental Performance Index Report (CC was a subfactor of EV in the previous editions) and we did not find any previous studies using CC in this way. The inclusion of CC as a major factor marks significant progress in addressing the causes of CC for improved mitigation and monitoring. However, it does not encompass all the environmental issues, challenges, and impacts related to CC.

Innovation systems urgently need information to tackle today's environmental challenges but, due to the lack of national level studies in this domain, the focus should be on making a specific diagnosis that leads to the definition of some lines of action; this is the overriding aim of this work. In addition, it also provides NIS with better guidance on environmental challenges to consolidate the path towards the 2030 sustainability Agenda.

The paper proceeds as follows. We start by describing the main theoretical background underlying the research hypotheses. Next, the methodological section explains the research design, variable metrics, research procedures, and econometric models, before presenting the

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results in the following section. The subsequent discussion analyses the results in light of the theoretical background. Finally, the paper outlines the main practical and theoretical implications and major findings of the study and concludes by addressing limitations and future research.

Literature review and hypotheses

National Innovation Systems (NIS) are viewed as processes where innovations and technological developments take place over time (Johnson and Lundvall, 2013). NIS can make a major contribution when addressing societal challenges (Ghazinoory et al., 2020), and Altenburg and Pegels (2012) added that NIS should be guided by environmental objectives. The bibliometric study provided by Vatananan-Thesenvitz et al. (2019) linking innovation systems and sustainable development reveals these two topics are an emergent trend. In addition, while some authors propose new business models based on innovation for sustainable development (França et al., 2017), others put entrepreneurship and innovation initiatives in the framework of sustainable development as a condition for success (Brás and Moniz, 2021).

Before going further, it should be noted that the sustainability concept comprises three correlated dimensions: environmental sustainability, social sustainability, and economic sustainability (Purvis et al., 2019). However, the bibliometric study conducted by Vatananan-Thesenvitz et al. (2019) highlights the environmental dimension as the basis of sustainable development, just as the study by Mebratu (1998) concluded some years ago. Therefore, the tacit emphasis on environmental usually occurs when the topic is sustainable development.

Some years ago, Green (2005) argued that sustainable development requires a paradigm shift in NIS, and Altenburg and Pegels (2012) called for a desirable green transformation introducing the concept of sustainability-oriented innovation systems. Perhaps as a consequence of these urgent demands, Fernandes et al. (2022, p.1) have recently showed that "NIS can play a decisive role towards an environmentally sustainable future". These authors test the role played by NIS in environmental performance (EP) as a whole, which comprised factors such as: ecosystem vitality, environmental health and, in the 2022 EPI edition, climate change (in previous editions this was a subdomain of ecosystem vitality). In fact, these findings provided the empirical framework to confirm whether (or not) ecosystem vitality, environmental health and climate change of countries are positively influenced by the NIS.

Ecosystem vitality depends on how ecosystems are preserved, protected, and enhanced through biodiversity and habitat, ecosystem services, fisheries, acidification, agriculture or water resources domains (Wolf et al., 2022). "Preserving large, intact areas of natural habitat is a key means of preserving biodiversity" (Alvey, 2006, p.195); given that urban environments put pressure on biodiversity (Kowarik et al., 2020), a reliable framework should be developed for its promotion in the urban ecosystem such that cities become more sustainable and residents' wellbeing is improved (Li et al., 2019; Taylor and Hochuli, 2015). The decline in the overall biodiversity of cities has already been reported (Murphy, 1988) and we know that biodiversity plays a critical role in enabling a long-term ecosystem (Groombridge et al., 2002); promoting biodiversity within the urban ecosystem by engaging city stakeholders is therefore a viable alternative to re-think and re-shape greenspaces for more sustainable cities (Klaus and Kiehl, 2021). Ecological, economic and institutional efforts to protect biodiversity in fact can be viewed as ecosystem services able to exert an influence on the decision-making of individuals, communities, firms, and states (Daily and Matson, 2008). In this vein, putting an end to the ongoing global forest loss since 2001 due to the use of land to produce commodities should be a goal in order to preserve ecosystem vitality (Curtis et al., 2018). Preserving fish resources also contributes to enhancing ecosystem vitality (Wolf et al., 2022), either by assuring the fish stock status (Miqueleiz et al., 2022), controlling the marine trophic index (Su et al., 2021), or avoiding trawl fishing (i.e. catching some organisms unintentionally) (Kennelly and Broadhurst, 2021). Just as the extent of waste water treatment can be considered a response indicator to ecosystem vitality, nitrogen and pesticide use in agriculture can be viewed as pressures to ecosystem vitality (Morse, 2018); in addition, excessive sulphur dioxide (SO2) and nitrous oxide emissions can have a negative impact on ecosystem vitality (Jiang et al., 2020; Tian et al., 2015).

The literature includes some studies which show that NIS have a positive influence on ecosystem vitality, for instance, by protecting agroforestry systems (Borremans et al., 2018), or preserving biodiversity and habitat at a regional level (van den Heiligenberg et al., 2017). Reference is also made to innovative measures to enhance ecosystem vitality in some domains such as creating an artificial reef to reduce fishing pressure (Su et al., 2021).

Environmental health, namely protecting the population from environmental health risks, can be evaluated by four dimensions: air quality, sanitation and drinking water, lead exposure, and waste management (Wolf et al., 2022). It is known that air quality can be measured by a heterogeneous mix of gases and several studies have noted that low air quality (also known as air pollution) negatively affects human health and is linked to several diseases (Al-Kindi et al., 2020; Roberts et al., 2019; Schraufnagel et al., 2019). People without sustainable access to safe drinking water and basic sanitation are also more exposed to diseases (and deaths) worldwide (Ferreira et al., 2021), notably in low-and middle-income countries and among young children (Prüss-Ustün et al., 2019). In addition, "disorders of various body systems and the role of inflammation due to lead exposure has been proven by various studies" (Boskabady et al., 2018), particularly in neurologic, cardiovascular, and hepatic systems (Obeng-Gyasi, 2018). Finally, the waste management in some domains (controlled solid waste, recycling, ocean plastics) by municipalities, regions and countries impacts human health (Wolf et al., 2022). Therefore, improving the management of solid waste can improve environment and health outcomes, particularly in developing countries (Ziraba et al., 2016), as can recycling waste (Cook et al., 2023; Huysveld et al., 2019) or preventing ocean pollution (Landrigan et al., 2020); the presence of microplastics whether on land or at sea indicates potential particle, chemical and microbial hazards that can lead to human health toxicity by inducing or aggravating an immune response (Wright and Kelly, 2017).

In this vein, some literature shows that NIS contribute to improving air quality (Hao et al., 2020), and water and sanitation (van Welie et al., 2019), or minimising exposure to the health threats of heavy metals (Zou et al., 2017) and reducing waste in several sectors (Baron et al., 2017; Baggio et al., 2008).

Regarding the influence of climate change policy on environmental sustainability, some authors claim that climate change is posing a range of threats to environmental sustainability (Phour and Sindhu, 2022; Arora et al., 2018; Arora, 2019). Climate change can be assessed through a set of emission indicators (Wolf et al., 2022), namely: greenhouse gases (GHG) (carbon dioxide, methane, nitrous oxide), fluorinated gases (F-Gases), and black carbon. GHG emissions are known to be the major cause of climate change; although carbon dioxide is the primary cause (Zheng et al., 2019), F-Gases (Sovacool et al., 2021) and black carbon (Ramanathan and Carmichael, 2008) also play a role.

Given that climate change is now unquestionable (Phour and Sindhu, 2022), NIS can contribute (positively) to tackling and stabilising climate change in the long-term. NIS could have a positive impact on climate change policy through the stakeholders' engagement (Hao et al., 2020), building sectorial networks (Boyer and Touzard, 2021), or by technology transfer mechanisms (Ockwell and Byrne, 2016). Underlining this key idea, Su and Moaniba (2017, p.49) argue that "technological innovation is responding strongly to climate change".

Based on the review of the literature and theorising about the relationship between environmental domains and NIS, we hypothesise the following:

H1: The environmental health of countries is positively influenced by NIS
H2: The ecosystem vitality of countries is positively influenced by NIS
H3: The climate change policy of countries is positively influenced by NIS

Methods

Variables and sample

The dependent variables are in accordance with the main factors identified in the EPI in 2022, namely: environmental health (EH), ecosystem vitality (EV), and climate change (CC). These three factors together formed the main indicator of EPI and are weighted 20 %, 42 %, and 38 %, respectively. Several studies used the reported factors as proxies of the environmental domains, primarily the EPI (Morse, 2018; Shittu et al., 2021; Folayan et al., 2020). The values for these three factors were obtained from the 2022 edition of the Environmental Performance Index Report (EPIR) (see Wolf et al., 2022). The composition of each factor is detailed in Fig. 1.

In brief, EH captures the level of population protection from environmental health risks and is made up of four subfactors: air quality, sanitation and drinking water, heavy metals, and waste management. EV is comprised of six subfactors, namely biodiversity and habitat, ecosystem services, fisheries, acidification, agriculture, and water resources; these capture the extent to which ecosystems are preserved, protected, and the services they provide. CC captures the progress towards climate change mitigation, which exacerbates all other environmental threats and imperils human health and safety. CC is a unidimensional factor formed by nine observable indicators: i) 'adjusted emissions growth rate for carbon dioxide', ii) 'adjusted emissions growth rate for methane', iii) 'adjusted emissions growth rate for F-gases', iv) 'adjusted emissions growth rate for nitrous oxide', v) 'adjusted emissions growth rate for black carbon', vi) 'projected GHG Emissions in 2050, vii) 'growth rate in carbon dioxide emissions from land cover', viii) 'greenhouse gas intensity growth rate', and ix)'greenhouse gas emissions per capita'.

We chose the seven pillars of the Global Innovation Index (GII) from 2021 as our explanatory variables, namely: Institutions, Human Capital and Research, Infrastructures, Market Sophistication, Business Sophistication, Knowledge and Technology Outputs, and Creative Outputs. The GII pillars are widely used as a benchmark in the innovation ecosystem performance at national level and various studies have used them as proxies of NIS performance (Fernandes et al., 2022; Gogodze, 2016; Menna et al., 2019).

This cross-sectional study is focused on data from 130 countries common to the two databases – Table 1

Procedures

As heteroscedasticity is common in cross-sectional data (Agunbiade and Adeboye, 2012) and due to the heterogeneity of economies in our sample, there is likely to be greater variance in the innovation expenditures of high-income economies than that of lower-income economies (Brás, 2023). The variance of the residuals would therefore be unequal across the innovation variables within the economies studied, confirming the presence of heteroscedasticity through the White test. Hence we estimate a heteroscedasticity-corrected least squares regression using the weighted least squares (WLS) estimator, as suggested by Wooldridge (2015).

Assuming the exogeneity of variables, the confirmation of the correct specification of models by the RESET Test, and the absence of collinearity within explanatory variables (VIF<5), we run a WLS estimation

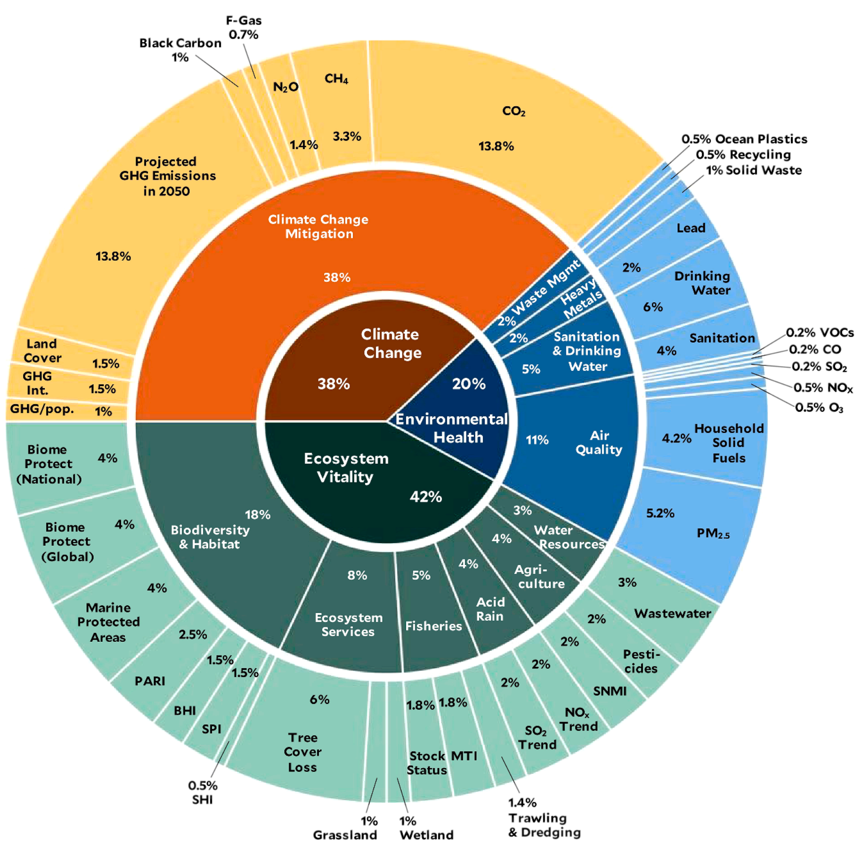

Fig. 1. The 2022 EPIR framework; weights show the percentage of the total EPI score
Source: Wolf et al. (2022, p.XI).

Table 1
Countries in the sample.

Countries				
Angola	Colombia	India	Mali	Russian Federation
Albania	Cape Verde	Ireland	Malta	Rwanda
United Arab Emirates	Costa Rica	Iran (Islamic Republic of)	Myanmar	Saudi Arabia
Argentina	Cyprus	Iceland	Montenegro	Senegal
Armenia	Czech Republic	Israel	Mongolia	Singapore
Australia	Germany	Italy	Mozambique	El Salvador
Austria	Denmark	Jamaica	Mauritius	Serbia
Azerbaijan	Dominican Rep.	Jordan	Malawi	Slovakia
Belgium	Algeria	Japan	Malaysia	Slovenia
Benin	Ecuador	Kazakhstan	Namibia	Sweden
Burkina Faso	Egypt	Kenya	Niger	Togo
Bangladesh	Spain	Kyrgyzstan	Nigeria	Thailand
Bulgaria	Estonia	Cambodia	Netherlands	Tajikistan
Bahrain	Ethiopia	Republic of Korea (the)	Norway	Trinidad and Tobago
Bosnia and Herzegovina	Finland	Kuwait	Nepal	Tunisia
Belarus	France	Lao People's Democratic Republic	New Zealand	Turkey
Bolivia (Plurinational State of)	United Kingdom	Lebanon	Oman	United Republic of Tanzania (the)
Brazil	Georgia	Sri Lanka	Pakistan	Uganda
Brunei Darussalam	Ghana	Lithuania	Panama	Ukraine
Botswana	Guinea	Luxembourg	Peru	Uruguay
Canada	Greece	Latvia	Philippines	United States of America
Switzerland	Guatemala	Morocco	Poland	Uzbekistan
Chile	Honduras	Republic of Moldova (the)	Portugal	Vietnam
China	Croatia	Madagascar	Paraguay	South Africa
Cote d'Ivoire	Hungary	Mexico	Qatar	Zambia
Cameroon	Indonesia	North Macedonia	Romania	Zimbabwe

(HSK command in GRETL Software, version 3[1]) to address the problem of heteroscedasticity, as this "typically provides the most accurate results" (Steel and Kammeyer-Mueller, 2002, p.96).

Dealing with nonconstant diagonal elements of the covariance matrix,[2] Long and Ervin (2000) suggested Heteroskedasticity-Consistent Covariance Matrix Estimators (HCCME) in which various attempts to estimate $\Omega = diag(\omega_1, \ldots, \omega_n)$ result in several versions of HCCME, such as HC0, HC1, HC2, HC3:

$HC0 : \omega_i = \widehat{\mu}_i^2$ (see White, 1980)

$HC1 : \omega_i = \frac{n}{n-k}\widehat{\mu}_i^2$ (see Hinkley, 1977; MacKinnon & White, 1985)

$HC2 : \ \omega_i = \frac{\widehat{\mu}_i^2}{1-h_i}$ (see Horn et al., 1975; MacKinnon & White, 1985)

$HC3 : \ \omega_i = \frac{\widehat{\mu}_i^2}{(1-h_i)^2}$ (see Davidsson & MacKinnon, 1993)

where $\widehat{\mu}$ are the estimated residuals, n is equal to the number of independent scores, k corresponds to the number of parameters estimated, $h_i = H_{ii}$ are the diagonal elements of the hat matrix $H = x(x'x)^{-1}x$, and $\overline{h}$ is their mean.

More recently, other versions of HCCME have appeared:

$HC4 : \ \omega_i = \frac{\widehat{\mu}_i^2}{(1-h_i)^{\delta_i}}$ (see Cribari-Neto, 2004)

$HC5 : \ \omega_i = \frac{\widehat{\mu}_i^2}{(1-h_i)^{\alpha_i}}$ (see Cribari-Neto et al., 2007)

where $\delta_i = min\left\{4, \frac{h_i}{\overline{h}}\right\}$, and $\alpha_i = min\left\{\frac{h_i}{\overline{h}}, max\left\{4, \frac{kh_{max}}{\overline{h}}\right\}\right\}$ with k as a predefined constant, $0 < k < 1$.

The focus lies on weighted regressions as suggested by Cribari-Neto and Zarkos (2001), although equations through HCCME are also provided to test the robustness of our results for HC1, HC2, and HC3, as these variants outperform the others (Şimşek and Orhan, 2016).

Finally, in the knowledge that there is a delay between an innovation and its effectiveness (Gerken et al., 2015), we assume that NIS in 2021 might impact environmental variables in 2022. Therefore, we use lagged independent GII variables with a lag of one period (data from 2021) as opposed to dependent environmental variables (data from 2022) as we assume that the causal effect of NIS occurs gradually and manifests itself in changes to the environmental domains at a later date.

Econometric models

Considering the dependent and explanatory variables, the three models take the following lin-lin specification:

$$EH_i = \beta_0 + \beta_1 I_{i-1} + \beta_2 HC\&R_{i-1} + \beta_3 Inf_{i-1} + \beta_4 MS_{i-1} + \beta_5 BS_{i-1} + \beta_6 K\&TO_{i-1} + \beta_7 CO_{i-1} + \mu_{i-1} \quad (1)$$

$$EV_i = \beta_0 + \beta_1 I_{i-1} + \beta_2 HC\&R_{i-1} + \beta_3 Inf_{i-1} + \beta_4 MS_{i-1} + \beta_5 BS_{i-1} + \beta_6 K\&TO_{i-1} + \beta_7 CO_{i-1} + \mu_{i-1} \quad (2)$$

$$CC_i = \beta_0 + \beta_1 I_{i-1} + \beta_2 HC\&R_{i-1} + \beta_3 Inf_{i-1} + \beta_4 MS_{i-1} + \beta_5 BS_{i-1} + \beta_6 K\&TO_{i-1} + \beta_7 CO_{i-1} + \mu_{i-1} \quad (3)$$

where i represents the country, and μ corresponds to the error term; dependent variables are environmental health (EH), ecosystem vitality (EV), and climate change (CC), while explanatory variables are institutions (I), human capital and research (HC&R), infrastructures (Inf), market sophistication (MS), business sophistication (BS), knowledge and technology outputs (K&TO), and creative outputs (CO).

Descriptives

For the observable variables, the descriptive statistics aim to present measures of central tendency (e.g. mean), measures of dispersion (e.g.

[1] The procedure involves OLS estimation followed by an auxiliary regression to generate an estimate of the error variance ($\widehat{\sigma}_i^2$), and finally weighted least squares, using the reciprocal of the estimated variance ($\frac{1}{\widehat{\sigma}_i^2}$) as weight. This is based on the procedure described in Ramanathan (1992), Introductory econometrics with applications, Dryden Press, California: USA, 1992., where the weighted linear regression takes the following specification: $Depvariable_i/\widehat{\sigma}_i^2 = \beta_0/\widehat{\sigma}_i^2 + \beta_1 Indvariable_i/\widehat{\sigma}_i^2 + \ldots + \beta_n Indvariable_i/\widehat{\sigma}_i^2 + \mu_i/\widehat{\sigma}_i^2$

[2] $\Psi = (x'x)^{-1}x'\Omega x(x'x)^{-1}$

Table 2
Summary statistics.

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness	Kurtosis
EH	130	11.4	94.7	46.833	22.8209	0.51	−0.871
EV	130	19.3	73.9	47.138	12.5888	−0.057	−0.629
CC	130	10.1	92.4	39.271	15.5106	0.969	1.437
I	130	37.8	95.1	65.049	14.0771	0.251	−0.84
HC&R	130	7	67.4	32.756	15.3081	0.353	−0.794
Inf	130	17.6	64.8	41.51	12.2569	−0.056	−1.083
MS	130	23.7	84.7	47.504	11.3044	0.639	0.978
BS	130	8.7	68.1	29.737	14.1307	1.012	0.005
K&TO	130	2.5	63.9	24.213	14.4676	0.894	0.02
CO	130	4.5	60.2	26.328	12.984	0.559	−0.546

standard deviation), the minimum and maximum values recorded, and indicators that can show some violations of the normal distribution (skewness and kurtosis) – Table 2.

In short, regarding the reference values defined by George and Mallery (2010) | Sk | > 2 (marked asymmetry) or | Ku | values > 2 (marked kurtosis), we note that none of the variables seriously violated the univariate normal distribution.

Results

Table 3 and Table 4 provide the estimation results.

Briefly describing the results of WLS and HCCME regressions through Table 3 and Table 4 we can say that there is no structural difference between estimations. Multicollinearity is not a serious concern as all explanatory variables showed a variance inflation factor (VIF) lower than 5. WLS estimations presented lower standard errors of regressions compared to HCCME and, therefore, the distances between the data points and the fitted values are smaller, which means the predictions are more precise. Moreover, as WLS regressions presented higher values for R-squared, the regression models explain higher percentages of the variance when compared to HCCME.

Accordingly. and in line with WLS estimations, Table 3 shows that institutional framework (I), human capital (HC&R), infrastructural conditions (Inf), business sophistication (BS) and creative outputs (CO) have a positive impact on environmental health. Additionally, only infrastructural conditions (Inf) and business sophistication (BS) show a positive impact on ecosystem vitality, and only institutional framework (I) has a positive impact on climate change policy. However, and unlike in HCCME regressions, some (unexpected) results in the WLS regressions should be noted, namely the negative effect of knowledge and

Table 3
WLS estimation results.

	Model 1		Model 2		Model 3		
	EH (coeff.)	t-ratio	EV (coeff.)	t-ratio	CC (coeff.)	*t*-ratio	VIF
Constant	−12.38***	−2.98	34.19***	5.23	−1.86	−0.24	
I	0.36***	4.09	0.05	0.43	0.57***	4.25	3.252
HC&R	0.47***	4.49	- 0.26*	−1.81	−0.12	−0.71	4.254
Inf	0.57***	5.33	0.30*	1.91	0.23	1.39	4.520
MS	−0.34***	−3.55	- 0.22*	−1.88	−0.18	−1.14	2.511
BS	0.35***	3.13	0.47***	3.11	0.18	0.98	4.369
K&TO	−0.26**	−2.18	- 0.02	−0.14	−0.20	−1.21	3.457
CO	0.36***	3.87	0.07	0.54	0.24	1.49	3.831
F-Statistic	F (7, 122) = 173.16***		F (7, 122) = 9.82***		F (7, 122) = 13.26***		
R-squared	0.91		0.36		0.43		
Std. error of the regression	1.85		2.09		1.97		

Significance levels: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

Table 4
HCCME results (HC1, HC2, HC3).

	Model 1				Model 2				Model 3			
	EH (coeff.)	t_{hc1}	t_{hc2}	t_{hc3}	EV (coeff.)	t_{hc1}	t_{hc2}	t_{hc3}	CC (coeff.)	t_{hc1}	t_{hc2}	t_{hc3}
Constant	−16.87***	−3.23	−3.18	−3.03	21.36***	3.27	3.23	3.09	4.39	0.51	0.50	0.48
I	0.41***	2.96	2.92	2.78	0.21	1.29	1.28	1.22	0.54***	3.70	3.65	3.49
HC&R	0.51***	4.75	4.70	4.51	−0.09	−0.61	−0.61	−0.58	−0.01	−0.06	−0.06	−0.05
Inf	0.54***	3.93	3.90	3.76	0.31*	1.83	1.82	1.75	0.09	0.46	0.45	0.43
MS	−0.29**	−2.46	−2.42	−2.31	−0.09	−0.74	−0.73	−0.70	−0.25	−1.22	−1.20	−1.14
BS	0.30*(*)	2.03	2.00	1.91	0.35*(*)	2.07	2.05	1.97	0.10	0.46	0.45	0.43
K&TO	−0.29	−1.59	−1.56	−1.49	−0.16	−0.94	−0.92	−0.88	−0.10	−0.55	−0.54	−0.51
CO	0.37***	3.06	3.02	2.89	−0.01	−0.01	−0.01	−0.01	0.30	1.53	1.50	1.42
F-Statistic (7122)		128.55***	127.03***	117.74***		8.59***	8.44***	7.78***		11.30***	11.12***	10.27***
R-squared	0.86				0.32				0.41			
Std. error of the regression	8.90				10.70				12.29			

Significance levels: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

technology outputs on environmental health, as well as the negative effect of human capital and research on ecosystem vitality; the negative effect of market sophistication on both environmental variables was partially documented in the literature.

Regardless of the typology of estimation (WLS or HCCME), the results partially support the first hypothesis (H1), i.e., the environmental health of countries is positively influenced by the NIS.

However, there is no evidence to support H2 and H3 due to the lack of statistical significance of most of the NIS variables to explain ecosystem vitality and climate change. Overall, we can conclude that NIS do not have a have a significant impact on either enhancing ecosystem vitality or mitigating climate change.

Discussion

Given the results, it is pertinent to discuss some unexpected behaviours of the GII pillars in each environmental domain and take a broad approach to shed light on the relationship between NIS and environmental performance.

Regarding the negative impact of knowledge and technology outputs (K&TO) on environmental health (EH), it is important to recognise that inventions and/or innovations can be complex and can jeopardise the population's protection from environmental health risks. Despite being unexpected, this inverse relationship between K&TO and EH is to some extent supported by sporadic literature that emphasises specific features, either by explicitly highlighting some innovation/invention harmful for environmental health (Taormina et al., 2018; Lin and Zhu, 2019), by tacitly recognising the limitations of innovation/invention processes for better environmental health (Sumrin et al., 2021; Ilyas et al., 2018), or even by claiming new innovation/invention processes with that aim (Wang et al., 2020).

Decoding the unexpected negative impact of human capital and research (HC&R) on ecosystem vitality (EV) is aimed at understanding how/why education/tertiary education and research and development can undermine the preservation, protection and enhancement of ecosystems. Piaggio et al. (2017, p.97) claimed "that there has been insufficient engagement by the conservation community [of biodiversity] with practitioners of synthetic biology". Also Roux et al. (2017) identified failures in learning and research domains and proposed new forms of group learning and the sharing of knowledge on advancing sustainability themes, particularly on the topic of freshwater ecosystems for conservation. Considering the current biodiversity crisis (Lees et al., 2020) together with the recent attempts to teach sustainable development through business simulation games (Gatti et al., 2019), we can conclude that there is still a long path ahead if we are to avoid education and research having a negative impact on ecosystem vitality. "Consumer culture and neoliberalism have significantly influenced contemporary globalised, Western(ised) and highly visual societies" and there is a teaching challenge "to resist dominant discourses promoted by the media" (Varea et al., 2018, p.949). A country may achieve high scores in HC&R, but if environmental sustainability issues are absent from secondary and tertiary curricula and are not included in the research agenda, this could negatively impact ecosystem vitality. Recently, Null and Asirvatham (2023) advocated for the increased inclusion of sustainability topics in university curricula to improve students' behaviour towards environmental issues. Unless education and research are up to date with the issues of ecosystems vitality and biodiversity, education/tertiary education/research will be unable to fulfil their task of knowledge transfer and therefore of having a positive impact on these domains.

Moreover, market sophistication (MS) has a negative impact on both environmental health and ecosystem vitality. Despite being negative, MS had already been found to have this impact on countries' environmental performance (Fernandes et al., 2022). As MS reflects market conditions and the total level of an economy's transactions, this inverse relationship with environmental domains may be due to the market's failure to deliver sound innovation outcomes focusing on sustainable development (Schomberg, 2019; van den Hove et al., 2012). Nevertheless, this inverse relationship underpins the argument that innovation/invention processes mediated and valued only by the market are "an inducer of production and consumption real or virtual, but both resource consumers" (Nunes et al., 2021) and are therefore potentially harmful for both environmental health and ecosystem vitality. From a micro perspective, desirable shifts towards sustainable consumption in consumer and producer behaviours and their alignment with circular economy principles (Durán-Romero et al., 2020) should help address this inverse relationship.

To sum up, although the environmental health of countries is positively influenced by NIS, neither ecosystem vitality nor climate change policy is benefiting significantly from NIS. As a number of authors argue that NIS is a means of enhancing ecosystem vitality and mitigating climate change, these results are quite alarming given that, according to Wolf et al. (2022), both variables have a weight of 80 % in the total environmental performance.

Practical implications and recommendations

While some authors have sought to define measures to limit the irreversible damage to the environment (Rapf and Kranert, 2021), others openly argue that it is time to implement sustainable environmental policies (Pe'er et al., 2020; Gills and Morgan, 2020) if we are to avoid jeopardising the well-being of future generations. Even though some claim we are close to tipping points in several environmental domains (Liu et al., 2018; Albrich et al., 2020), we should not give up building a meaningful society guided by the principles of environmental sustainability. Therefore, we should ask whether the innovation systems being built foster environmental sustainability and promote the 2030 and post-2030 Agendas for sustainable development? According to our updated results, they are not. Academics have already claimed that policy makers are aware of the critical role NIS play in this pursuit (Altenburg and Pegels, 2012; Green, 2005), so it is time to press for the urgent alignment of NIS with environmentally sustainable goals as opposed to those driven purely by the market. Given the updated diagnosis, "there is no time for complacency" (van den Hove et al., 2012, p.79). There must be an environmental and sustainable transition in NIS to strengthen the path towards the 2030 and post-2030 sustainability Agenda. Specifically, special attention should be given to addressing the negative impact of market sophistication on both environmental health and ecosystem vitality. This finding is not totally new (see Fernandes et al., 2022) and NIS should move away from a market-only orientation towards environmentally sustainable objectives by fostering sustainable consumption behaviour and ecological business practices. Accordingly, public policy supporting innovation through funds for both public and private institutions is valuable if it strives to benefit society as a whole and not just business and commerce. The critical role played by public policy could be underpinned by new voices from civil society collectively engaged in the search for integrated solutions in innovation systems with the aim of achieving environmental sustainability. If supranational institutions had more power to monitor environmental sustainability, it would create synergy between national public policies to promote innovation efficiently in our planet. Hence, "international governance is needed not simply to help provide global public goods that would otherwise be under-supplied, but to guard against self-serving behaviour by states that, in providing a global public good, given short shrift to the negative externalities that may result" (Bodansky, 2012, p.668).

Theoretical implications

Institutions is the only NIS variable that shows a (positive) impact on climate change mitigation. This theoretical contribution deserves an in-depth analysis in an attempt to contribute to this relevant and urgent issue; moreover, a theoretical framework should be built to explain the institutional domain's unique and positive contribution to climate change mitigation. Although alarming, it is important to understand from a theoretical point of view which institutional variables have an effective and positive impact on climate change policy: regulatory environment, political environment, or business environment?

On the other hand, unlike other studies reflecting the positive role of innovative initiatives in preserving, protecting, and enhancing ecosystems (Borremans et al., 2018; van den Heiligenberg et al., 2017), another theoretical contribution of our work reveals the insignificant impact of NIS (as a whole) on enhancing ecosystem vitality.

Finally, a major contribution of this study is that it speculates on market procedures within NIS that are harmful to environmental health and ecosystem vitality. It discloses the negative externalities of education and research embedded in NIS on enhancing ecosystem vitality and exposes the negative impact from the outcomes of innovations/inventions on environmental health. This theoretical evidence on NIS should act as a starting point to further research developments in the field of environmental sustainability.

Concluding remarks

NIS are viewed as a dynamic instrument, with systemic changes, that can foster environmental sustainability and bring about environmental sustainable outputs (Fernandes et al., 2022). However, the major findings of this research show that NIS play an insignificant role in contributing to meaningful environmental goals, such as enhancing ecosystem vitality or mitigating climate change. Although their extremely positive contribution to protecting the population from environmental health risks cannot be neglected, some aspects of NIS exert negative pressure on environmental sustainability. We note in particular: their trade-market guidance combined with harmful behaviours by consumer and producer (consumerism), their unalignment of education and research policies to preserve ecosystem vitality, and the inadequacy of their innovations/inventions to prevent and mitigate environmental health risks. In short, NIS urgently need to make a paradigm shift towards environmental sustainability.

The limitations of the study include its cross-sectional nature and its solely quantitative approach. Addressing these limitations can be the starting point for fruitful avenues of further research such as: i) the inclusion of longitudinal data for panel data modelling and ii) an in-depth understanding of the influence of NIS on environmental sustainability by including sub-factors of NIS, and therefore using a quantitative and qualitative approach.

CRediT authorship contribution statement

Gonçalo Rodrigues Brás: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Margarita Robaina:** Writing – review & editing, Validation, Supervision, Project administration.

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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References

Agunbiade, D., Adeboye, N., 2012. Estimation of heteroscedasticity effects in a classical linear regression model of a cross-sectional data. Prog. Appl. Math. 4 (2), 18–28. https://doi.org/10.3968/j.pam.1925252820120402.1677.

Al-Kindi, S.G., Brook, R.D., Biswal, S., Rajagopalan, S., 2020. Environmental determinants of cardiovascular disease: lessons learned from air pollution. Nature Rev. Cardiol. 17 (10), 656–672. https://doi.org/10.1038/s41569-020-0371-2.

Albrich, K., Rammer, W., Seidl, R., 2020. Climate change causes critical transitions and irreversible alterations of mountain forests. Glob. Chang. Biol. 26 (7), 4013–4027. https://doi.org/10.1111/gcb.15118.

Altenburg, T., Pegels, A., 2012. Sustainability-oriented innovation systems – managing the green transformation. Innov. Develop. 2 (1), 5–22. https://doi.org/10.1080/2157930X.2012.664037.

Alvey, A.A., 2006. Promoting and preserving biodiversity in the urban forest. Urban. For. Urban. Green. 5 (4), 195–201. https://doi.org/10.1016/j.ufug.2006.09.003.

Arora, N.K., Fatima, T., Mishra, I., Verma, M., Mishra, J., Mishra, V., 2018. Environmental sustainability: challenges and viable solutions. Environ. Sustainability 1 (4), 309–340. https://doi.org/10.1007/s42398-018-00038-w.

Arora, N.K., 2019. Impact of climate change on agriculture production and its sustainable solutions. Environ. Sustainability 2 (2), 95–96. https://doi.org/10.1007/s42398-019-00078-w.

Baggio, P., Baratieri, M., Gasparella, A., Longo, G.A., 2008. Energy and environmental analysis of an innovative system based on municipal solid waste (MSW) pyrolysis and combined cycle. Appl. Therm. Eng. 28 (2), 136–144. https://doi.org/10.1016/j.applthermaleng.2007.03.028.

Baron, S., Patterson, A., Maull, R., Warnaby, G., 2017. Feed people first: a service ecosystem perspective on innovative food waste reduction. J. Serv. Res. 21 (1), 135–150. https://doi.org/10.1177/1094670517738372.

Bodansky, D., 2012. What's in a concept? Global public goods, international law, and legitimacy. Eur. J. Int. Law 23 (3), 651–668. https://doi.org/10.1093/ejil/chs035.

Borremans, L., Marchand, F., Visser, M., Wauters, E., 2018. Nurturing agroforestry systems in Flanders: analysis from an agricultural innovation systems perspective. Agric. Syst. 162, 205–219. https://doi.org/10.1016/j.agsy.2018.01.004.

Boskabady, M., Marefati, N., Farkhondeh, T., Shakeri, F., Farshbaf, A., Boskabady, M.H., 2018. The effect of environmental lead exposure on human health and the contribution of inflammatory mechanisms, a review. Environ. Int. 120, 404–420. https://doi.org/10.1016/j.envint.2018.08.013.

Boyer, J., Touzard, J.-M., 2021. To what extent do an innovation system and cleaner technological regime affect the decision-making process of climate change adaptation? Evidence from wine producers in three wine clusters in France. J. Clean. Prod. 315, 1–13. https://doi.org/10.1016/j.jclepro.2021.128218.

Brás, G.R., Moniz, A.B., 2021. EU's 7-year budget and pandemic recovery package: last call for a new entrepreneurship paradigm? World Futures. 77 (8), 591–612. https://doi.org/10.1080/02604027.2021.1984156.

Brás, G.R., 2023. Pillars of the Global Innovation Index by income level of economies: longitudinal data (2011-2022) for researchers' use. Data Brief. 46, 1–11. https://doi.org/10.1016/j.dib.2022.108818.

Chen, S., Gong, B., 2021. Response and adaptation of agriculture to climate change: evidence from China. J. Dev. Econ. 148, 1–17. https://doi.org/10.1016/j.jdeveco.2020.102557.

Cook, E., Derks, M., Velis, C.A., 2023. Plastic waste reprocessing for circular economy: a systematic scoping review of risks to occupational and public health from legacy substances and extrusion. Sci. Total Environ. 859, 1–17. https://doi.org/10.1016/j.scitotenv.2022.160385.

Cribari-Neto, F., Zarkos, S.G., 2001. Heteroskedasticity-consistent covariance matrix estimation:white's estimator and the bootstrap. J. Stat. Comput. Simul. 68 (4), 391–411. https://doi.org/10.1080/00949650108812077.

Cribari-Neto, F., Souza, T.C., Vasconcellos, K.L.P., 2007. Inference under heteroskedasticity and leveraged data. Commun. Stat. Theory and Methods 36 (10), 1877–1888. https://doi.org/10.1080/03610920601126589.

Cribari-Neto, F., 2004. Asymptotic inference under heteroskedasticity of unknown form. Comput. Stat. Data Anal. 45 (2), 215–233. https://doi.org/10.1016/S0167-9473(02)00366-3.

Curtis, P.G., Slay, C.M., Harris, N.L., Tyukavina, A., Hansen, M.C., 2018. Classifying drivers of global forest loss. Science 361 (6407), 1108–1111. https://doi.org/10.1126/science.aau3445.

Daily, G.C., Matson, P.A., 2008. Ecosystem services: from theory to implementation. Proc. Natl. Acad. Sci. 105 (28), 9455–9456. https://doi.org/10.1073/pnas.0804960105.

Davidson, R., MacKinnon, J.G., 1993. Estimation and Inference in Econometrics. Oxford New York, New York.

Durán-Romero, G., López, A.M., Beliaeva, T., Ferasso, M., Garonne, C., Jones, P., 2020. Bridging the gap between circular economy and climate change mitigation policies through eco-innovations and Quintuple Helix Model. Technol. Forecast. Soc. Change 160, 1–13. https://doi.org/10.1016/j.techfore.2020.120246.

Edrisi, S.A., Abhilash, P.C., 2021. Need of transdisciplinary research for accelerating land restoration during the UN decade on ecosystem restoration. Restor. Ecol. 29 (8), 1–7. https://doi.org/10.1111/rec.13531.

Fernandes, A.J.C., Rodrigues, R.G., Ferreira, J.J., 2022. National innovation systems and sustainability: what is the role of the environmental dimension? J. Clean. Prod. 347, 1–10. https://doi.org/10.1016/j.jclepro.2022.131164.
Ferreira, D.C., Graziele, I., Marques, R.C., Gonçalves, J., 2021. Investment in drinking water and sanitation infrastructure and its impact on waterborne diseases dissemination: the Brazilian case. Sci. Total Environ. 779, 1–16. https://doi.org/10.1016/j.scitotenv.2021.146279.
Folayan, M.O., El Tantawi, M., Schroth, R.J., Kemoli, A.M., Gaffar, B., Amalia, R., Feldens, C.A., 2020. Association between environmental health, ecosystem vitality, and early childhood caries. Front. Pediatr. 8 (196), 1–7. https://doi.org/10.3389/fped.2020.00196.
França, C.L., Broman, G., Robèrt, K.-H., Basile, G., Trygg, L., 2017. An approach to business model innovation and design for strategic sustainable development. J. Clean. Prod. 140 (1), 155–166. https://doi.org/10.1016/j.jclepro.2016.06.124.
Gatti, L., Ulrich, M., Seele, P., 2019. Education for sustainable development through business simulation games: an exploratory study of sustainability gamification and its effects on students' learning outcomes. J. Clean. Prod. 207, 667–678. https://doi.org/10.1016/j.jclepro.2018.09.130.
George, D., Mallery, P., 2010. SPSS For Windows Step By Step: A Simple Guide and Reference, 17.0 Update. Pearson, Boston.
Gerken, J.M., Moehrle, M.G., Walter, L., 2015. One year ahead! Investigating the time lag between patent publication and market launch: insights from a longitudinal study in the automotive industry. R&D Manage. 45 (3), 287–303. https://doi.org/10.1111/radm.12085.
Ghazinoory, S., Nasri, S., Ameri, F., Montazer, G.A., Shayan, A., 2020. Why do we need 'Problem-oriented Innovation System (PIS)' for solving macro-level societal problems? Technol. Forecast. Soc. Change 150, 1–18. https://doi.org/10.1016/j.techfore.2019.119749.
Gills, B., Morgan, J., 2020. Global Climate Emergency: after COP24, climate science, urgency, and the threat to humanity. Globalizations. 17 (6), 885–902. https://doi.org/10.1080/14747731.2019.1669915.
Gogodze, J., 2016. Mechanisms and functions within a national innovation system. J. Technol. Manage. Innov. 11 (4), 12–21. https://doi.org/10.4067/S0718-27242016000400003.
Green, K., 2005. Towards environmental innovation — a policy synthesis. In: Weber, M., Hemmelskamp, J. (Eds.), Towards Environmental Innovation Systems. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 319–323.
Groombridge, B., Jenkins, M.D., Jenkins, M., 2002. World Atlas of biodiversity: Earth's Living Resources in the 21st Century. Cambridge University Press, Cambridge UK.
Hao, Y., Wu, Y., Wu, H., Ren, S., 2020. How do FDI and technical innovation affect environmental quality? Evidence from China. Environ. Sci. Pollut. Res. 27 (8), 7835–7850. https://doi.org/10.1007/s11356-019-07411-0.
Hinkley, D.V., 1977. Jacks. Technometrics. 19 (3), 285–292. https://doi.org/10.1080/00401706.1977.10489550.
Horn, S.D., Horn, R.A., Duncan, D.B., 1975. Estimating heteroscedastic variances in linear models. J. Am. Stat. Assoc. 70 (350), 380–385. https://doi.org/10.1080/01621459.1975.10479877.
Huysveld, S., Hubo, S., Ragaert, K., Dewulf, J., 2019. Advancing circular economy benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions. J. Clean. Prod. 211, 1–13. https://doi.org/10.1016/j.jclepro.2018.11.110.
Ilyas, M., Ahmad, W., Khan, H., Yousaf, S., Khan, K., Nazir, S., 2018. Plastic waste as a significant threat to environment – a systematic literature review. Rev. Environ. Health 33 (4), 383–406. https://doi.org/10.1515/reveh-2017-0035.
Jiang, L., He, S., Cui, Y., Zhou, H., Kong, H., 2020. Effects of the socio-economic influencing factors on SO2 pollution in Chinese cities: a spatial econometric analysis based on satellite observed data. J. Environ. Manage. 268, 1–10. https://doi.org/10.1016/j.jenvman.2020.110667.
Johnson, B., Lundvall, B.-Å., 2013. National Innovation Systems (NIS). In: Carayannis, E. G. (Ed.), Encyclopedia of Creativity, Invention, Innovation and Entrepreneurship. Springer New York, New York, NY, pp. 1341–1347.
Kennelly, S.J., Broadhurst, M.K., 2021. A review of bycatch reduction in demersal fish trawls. Rev. Fish. Biol. Fish. 31 (2), 289–318. https://doi.org/10.1007/s11160-021-09644-0.
Klaus, V.H., Kiehl, K., 2021. A conceptual framework for urban ecological restoration and rehabilitation. Basic Appl. Ecol. 52, 82–94. https://doi.org/10.1016/j.baae.2021.02.010.
Kowarik, I., Fischer, L.K., Kendal, D., 2020. Biodiversity conservation and sustainable urban development. Sustainability 12 (12), 1–8. https://doi.org/10.3390/su12124964.
Landrigan, P.J., Stegeman, J.J., Fleming, L.E., Allemand, D., Anderson, D.M., Backer, L. C., Brucker-Davis, F., Chevalier, N., Corra, L., Czerucka, D., Bottein, M.D., Demeneix, B., Depledge, M., Deheyn, D.D., Dorman, C.J., Fénichel, P., Fisher, S., Gaill, F., Galgani, F., Gaze, W.H., Giuliano, L., Grandjean, P., Hahn, M.E., Hamdoun, A., Hess, P., Judson, B., Laborde, A., McGlade, J., Mu, J., Mustapha, A., Neira, M., Noble, R.T., Pedrotti, M.L., Reddy, C., Rocklöv, J., Scharler, U.M., Shanmugam, H., Taghian, G., van de Water, J., Vezzulli, L., Weihe, P., Zeka, A., Raps, H., Rampal, P., 2020. Human health and ocean pollution. Ann. Glob. Health 86 (1), 1–64. https://doi.org/10.5334/aogh.2831.
Lees, A.C., Attwood, S., Barlow, J., Phalan, B., 2020. Biodiversity scientists must fight the creeping rise of extinction denial. Nat. Ecol. Evol. 4 (11), 1440–1443. https://doi.org/10.1038/s41559-020-01285-z.
Li, E., Parker, S.S., Pauly, G.B., Randall, J.M., Brown, B.V., Cohen, B.S., 2019. An urban biodiversity assessment framework that combines an urban habitat classification scheme and citizen science data. Front. Ecol. Evol. 7, 1–15. https://doi.org/10.3389/fevo.2019.00277.
Lin, B., Zhu, J., 2019. Determinants of renewable energy technological innovation in China under CO2 emissions constraint. J. Environ. Manage. 247, 662–671. https://doi.org/10.1016/j.jenvman.2019.06.121.
Liu, J., Ma, Y., Zhu, D., Xia, T., Qi, Y., Yao, Y., Guo, X., Ji, R., Chen, W., 2018. Polystyrene nanoplastics-enhanced contaminant transport: role of irreversible adsorption in glassy polymeric domain. Environ. Sci. Technol. 52 (5), 2677–2685. https://doi.org/10.1021/acs.est.7b05211.
Long, J.S., Ervin, L.H., 2000. Using heteroscedasticity consistent standard errors in the linear regression model. Am. Stat. 54 (3), 217–224. https://doi.org/10.2307/2685594.
MacKinnon, J.G., White, H., 1985. Some heteroskedasticity-consistent covariance matrix estimators with improved finite sample properties. J. Econom. 29 (3), 305–325. https://doi.org/10.1016/0304-4076(85)90158-7.
Mebratu, D., 1998. Sustainability and sustainable development: historical and conceptual review. Environ. Impact. Assess. Rev. 18 (6), 493–520. https://doi.org/10.1016/S0195-9255(98)00019-5.
Menna, A., Walsh, P.R., Ekhtari, H., 2019. Identifying enablers of innovation in developed economies: a national innovation systems approach. J. Innov. Manage. 7 (1), 108–128. https://doi.org/10.24840/2183-0606_007.001_0007.
Miqueleiz, I., Miranda, R., Ariño, A.H., Ojea, E., 2022. Conservation-Status gaps for marine top-fished commercial species. Fishes 7 (1), 1–11. https://doi.org/10.3390/fishes7010002.
Morse, S., 2018. Relating environmental performance of nation states to income and income inequality. Sustainable Develop 26 (1), 99–115. https://doi.org/10.1002/sd.1693.
Murphy, D., 1988. Challenges to biological diversity in urban areas. In: Wilson, E.O. (Ed.), Biodiversity. National Academies Press, Washington (DC), pp. 71–76.
Null, D.C., Asirvatham, J., 2023. College students are pro-environment but lack sustainability knowledge: a study at a mid-size Midwestern US university. Int. J. Sustainability Higher Educ. 24 (3), 660–677. https://doi.org/10.1108/IJSHE-02-2022-0046.
Nunes, S., Cooke, P., Grilo, H., 2021. Green-Sphere circular experiences and well-being along the road: Portugal from North to South. In: Ratten, V., Leitão, J., Braga, V. (Eds.), Tourism Innovation in Spain and Portugal. Springer, Cham, pp. 89–111.
Obeng-Gyasi, E., 2018. Lead exposure and oxidative stress—a life course approach in U. S. adults. Toxics 6 (3), 1–10. https://doi.org/10.3390/toxics6030042.
Ockwell, D., Byrne, R., 2016. Improving technology transfer through national systems of innovation: climate relevant innovation-system builders (CRIBs). Clim. Policy 16 (7), 836–854. https://doi.org/10.1080/14693062.2015.1052958.
Pe'er, G., Bonn, A., Bruelheide, H., Dieker, P., Eisenhauer, N., Feindt, P.H., Hagedorn, G., Hansjürgens, B., Herzon, I., Lomba, Â., Marquard, E., Moreira, F., Nitsch, H., Oppermann, R., Perino, A., Röder, N., Schleyer, C., Schindler, S., Wolf, C., Zinngrebe, Y., Lakner, S., 2020. Action needed for the EU Common Agricultural Policy to address sustainability challenges. People Nature 2 (2), 305–316. https://doi.org/10.1002/pan3.10080.
Phour, M., Sindhu, S.S., 2022. Mitigating abiotic stress: microbiome engineering for improving agricultural production and environmental sustainability. Planta 256 (85), 1–34. https://doi.org/10.1007/s00425-022-03997-x.
Piaggio, A.J., Segelbacher, G., Seddon, P.J., Alphey, L., Bennett, E.L., Carlson, R.H., Friedman, R.M., Kanavy, D., Phelan, R., Redford, K.H., Rosales, M., Slobodian, L., Wheeler, K., 2017. Is it time for synthetic biodiversity conservation? Trends Ecol. Evol. 32 (2), 97–107. https://doi.org/10.1016/j.tree.2016.10.016.
Prüss-Ustün, A., Wolf, J., Bartram, J., Clasen, T., Cumming, O., Freeman, M.C., Gordon, B., Hunter, P.R., Medlicott, K., Johnston, R., 2019. Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: an updated analysis with a focus on low- and middle-income countries. Int. J. Hyg. Environ. Health 222 (5), 765–777. https://doi.org/10.1016/j.ijheh.2019.05.004.
Purvis, B., Mao, Y., Robinson, D., 2019. Three pillars of sustainability: in search of conceptual origins. Sustain. Sci. 14 (3), 681–695. https://doi.org/10.1007/s11625-018-0627-5.
Ramanathan, V., Carmichael, G., 2008. Global and regional climate changes due to black carbon. Nat. Geosci. 1 (4), 221–227. https://doi.org/10.1038/ngeo156.
Ramanathan, R., 1992. Introductory Econometrics With Applications. Dryden Press, California USA.
Rapf, M., Kranert, M., 2021. Irreversible entropy to account for environmental impacts and sustainability. Procedia CIRP 98, 601–606. https://doi.org/10.1016/j.procir.2021.01.161.
Roberts, S., Arseneault, L., Barratt, B., Beevers, S., Danese, A., Odgers, C.L., Moffitt, T.E., Reuben, A., Kelly, F.J., Fisher, H.L., 2019. Exploration of NO2 and PM2.5 air pollution and mental health problems using high-resolution data in London-based children from a UK longitudinal cohort study. Psychiatry Res. 272, 8–17. https://doi.org/10.1016/j.psychres.2018.12.050.
Roux, D.J., Nel, J.L., Cundill, G., O'Farrell, P., Fabricius, C., 2017. Transdisciplinary research for systemic change: who to learn with, what to learn about and how to learn. Sustain. Sci. 12 (5), 711–726. https://doi.org/10.1007/s11625-017-0446-0.
Schomberg, R.v., 2019. International Handbook on Responsible Innovation. In: Schomberg, R.v., Hankins, J. (Eds.), Why Responsible Innovation? Edward Elgar Publishing, Cheltenham, UK, pp. 12–32.
Schraufnagel, D.E., Balmes, J.R., Cowl, C.T., De Matteis, S., Jung, S.-H., Mortimer, K., Perez-Padilla, R., Rice, M.B., Riojas-Rodriguez, H., Sood, A., Thurston, G.D., To, T., Vanker, A., Wuebbles, D.J., 2019. Air pollution and noncommunicable diseases: a review by the forum of international respiratory societies' environmental committee, part 2: air pollution and organ systems. Chest 155 (2), 417–426. https://doi.org/10.1016/j.chest.2018.10.041.
Shittu, W., Adedoyin, F.F., Shah, M.I., Musibau, H.O., 2021. An investigation of the nexus between natural resources, environmental performance, energy security and

environmental degradation: evidence from Asia. Resour. Policy. 73, 1–9. https://doi.org/10.1016/j.resourpol.2021.102227.

Şimşek, E., Orhan, M., 2016. Heteroskedasticity-consistent covariance matrix estimators in small samples with high leverage points. Theor. Econ. Lett. 6 (4), 658–677. https://doi.org/10.4236/tel.2016.64071.

Sovacool, B.K., Griffiths, S., Kim, J., Bazilian, M., 2021. Climate change and industrial F-gases: a critical and systematic review of developments, sociotechnical systems and policy options for reducing synthetic greenhouse gas emissions. Renew. Sustainable Energy Rev. 141, 1–55. https://doi.org/10.1016/j.rser.2021.110759.

Steel, P.D., Kammeyer-Mueller, J.D., 2002. Comparing meta-analytic moderator estimation techniques under realistic conditions. J. Appl. Psychol. 87 (1), 96–111. https://doi.org/10.1037/0021-9010.87.1.96.

Stephen, C., Wittrock, J., Wade, J., 2018. Using a harm reduction approach in an environmental case study of fish and wildlife health. EcoHealth 15 (1), 4–7. https://doi.org/10.1007/s10393-017-1311-4.

Su, H.-N., Moaniba, I.M., 2017. Does innovation respond to climate change? Empirical evidence from patents and greenhouse gas emissions. Technol. Forecast. Soc. Change 122, 49–62. https://doi.org/10.1016/j.techfore.2017.04.017.

Su, L., Chen, Z., Zhang, K., Xu, Y., Xu, S., Wang, K., 2021. Decadal-Scale variation in mean trophic level in beibu gulf based on bottom-trawl survey data. Marine Coastal Fish. 13 (3), 174–182. https://doi.org/10.1002/mcf2.10144.

Sumrin, S., Gupta, S., Asaad, Y., Wang, Y., Bhattacharya, S., Foroudi, P., 2021. Eco-innovation for environment and waste prevention. J. Bus. Res. 122, 627–639. https://doi.org/10.1016/j.jbusres.2020.08.001.

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., Carlier, A., 2018. A review of potential impacts of submarine power cables on the marine environment: knowledge gaps, recommendations and future directions. Renew. Sustain. Energy Rev. 96, 380–391. https://doi.org/10.1016/j.rser.2018.07.026.

Taylor, L., Hochuli, D.F., 2015. Creating better cities: how biodiversity and ecosystem functioning enhance urban residents' wellbeing. Urban. Ecosyst. 18 (3), 747–762. https://doi.org/10.1007/s11252-014-0427-3.

Tian, H., Chen, G., Lu, C., Xu, X., Ren, W., Zhang, B., Banger, K., Tao, B., Pan, S., Liu, M., Zhang, C., Bruhwiler, L., Wofsy, S., 2015. Global methane and nitrous oxide emissions from terrestrial ecosystems due to multiple environmental changes. Ecosyst. Health Sustainability 1 (1), 1–20. https://doi.org/10.1890/EHS14-0015.1.

van den Heiligenberg, H.A.R.M., Heimeriks, G.J., Hekkert, M.P., van Oort, F.G., 2017. A habitat for sustainability experiments: success factors for innovations in their local and regional contexts. J. Clean. Prod. 169, 204–215. https://doi.org/10.1016/j.jclepro.2017.06.177.

van den Hove, S., McGlade, J., Mottet, P., Depledge, M.H., 2012. The Innovation Union: a perfect means to confused ends? Environ. Sci. Policy. 16, 73–80. https://doi.org/10.1016/j.envsci.2011.11.006.

van Welie, M.J., Truffer, B., Yap, X.-S., 2019. Towards sustainable urban basic services in low-income countries: a technological innovation system analysis of sanitation value chains in Nairobi. Environ. Innov. Soc. Transit. 33, 196–214. https://doi.org/10.1016/j.eist.2019.06.002.

Varea, V., González-Calvo, G., Alcalá, D.H., 2018. The influence of consumerism on Spanish physical education teachers. Eur. Phy. Educ. Rev. 25 (4), 949–963. https://doi.org/10.1177/1356336X18789196.

Vatananan-Thesenvitz, R., Schaller, A.-A., Shannon, R., 2019. A bibliometric review of the knowledge base for innovation in sustainable development. Sustainability. 11 (20), 1–22. https://doi.org/10.3390/su11205783.

Wang, L., Su, C.-W., Ali, S., Chang, H.-L., 2020. How China is fostering sustainable growth: the interplay of green investment and production-based emission. Environ. Sci. Pollut. Res. 27 (31), 39607–39618. https://doi.org/10.1007/s11356-020-09933-4.

White, H., 1980. A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. Econometrica 48 (4), 817–838. https://doi.org/10.2307/1912934.

Wolf, M.J., Emerson, J.W., Esty, D.C., de Sherbinin, A., Wendling, Z.A., 2022. 2022 Environmental Performance Index. Yale Center for Environmental Law & Policy, New Haven, CT.

Wooldridge, J.M., 2015. Introductory Econometrics: A Modern Approach. Cengage Learning, Boston.

Wright, S.L., Kelly, F.J., 2017. Plastic and human health: a micro issue? Environ. Sci. Technol. 51 (12), 6634–6647. https://doi.org/10.1021/acs.est.7b00423.

Zheng, X., Streimikiene, D., Balezentis, T., Mardani, A., Cavallaro, F., Liao, H., 2019. A review of greenhouse gas emission profiles, dynamics, and climate change mitigation efforts across the key climate change players. J. Clean. Prod. 234, 1113–1133. https://doi.org/10.1016/j.jclepro.2019.06.140.

Ziraba, A.K., Haregu, T.N., Mberu, B., 2016. A review and framework for understanding the potential impact of poor solid waste management on health in developing countries. Arch. Public Health 74 (1), 1–11. https://doi.org/10.1186/s13690-016-0166-4.

Zou, B., Jiang, X., Duan, X., Zhao, X., Zhang, J., Tang, J., Sun, G., 2017. An integrated H-G scheme identifying areas for soil remediation and primary heavy metal contributors: a risk perspective. Sci. Rep. 7 (1), 1–11. https://doi.org/10.1038/s41598-017-00468-2.