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Public science and environmental sustainability: a national culture framework for innovation ecosystems en route to net zero

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Abstract

Despite the proliferation of national environmental science worldwide, the erosion of environmental sustainability presents a problem for advanced economies with a substantial volume of scientific output. The worsening state of the natural environment presents a profound conundrum at the intersection of science and sustainability, characterised by conflicting pathways for the world's nations. In this study, I confront this predicament by examining whether the influence of national culture moderates the transition of domestic scientific research into tangible CO_2 emissions reduction. Drawing on a dataset spanning 30 nations renowned for their high scientific productivity over a 24-year period, I use a panel data model that incorporates lag time to analyse the nuanced impact of national cultures on sustainability. My findings reveal distinctive outcomes: those cultures characterised by high Power Distance (e.g., Eastern European) contribute to increased CO_2 emissions via an industrial innovation pathway that prioritises economic growth, while those with high Individualism and high Uncertainty Avoidance (e.g., Western European) facilitate a reduction in CO_2 emissions through the translation of scientific knowledge into public science that stimulates a societal innovation pathway and sustainability. In addition to these moderating effects, my investigation exposes that Gross Domestic Product (GDP) per capita exerts a direct positive influence on CO_2 emissions, while an increase of GDP allocated to military expenditure (e.g., USA, China, Israel, South Korea) has detrimental effects on CO_2 emissions, potentially hampering Net Zero aspirations. These findings hold significant implications for both theory and policymaking in the environmental arena.

Keywords Environmental sustainability, Net zero, National culture, Climate change, Carbon emissions, Innovation system, Science and technology policy

1 Introduction

Over the past few decades, there has been a significant surge in scientific publications in innovative economies such as those in the Advanced Industrialised Countries, while paradoxically, environmental sustainability has been on a decline in these regions. Figure 3 in Appendix 1 illustrates a steep upward trajectory in scientific publications within OECD economies and China, juxtaposed with persistently high CO_2 emissions over the past two decades. Likewise, Hickel (2020) in his study quantifying national responsibility for climate breakdown, shows that the USA, the EU-28, the Rest of Europe, and the Global North are responsible for 92% of the world's excess emissions, often due to the intensity of meat production (Revoredo-Giha et al. 2011) and the waste generated by the fashion industry (Periyasamy and Periyasami 2023). The escalating environmental hazard stemming from CO_2 emissions reached a critical point in 2017, when WMO Secretary-General Petteri Taalas stated that 'the window of opportunity to stop climate change is almost closed' (WMO 2018),

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sparking intense debate about the interplay between science and sustainability.

Policy research suggests that science can serve as a mitigating force against environmental hazards, offering solutions to the impending degradation of our environment (York and Venkataraman 2010), like in the case of increased robotisation being associated with a decrease of CO2 emissions (Lu et al. 2023). Conversely, evidence indicates that the pursuit of rapid economic growth through industrialisation has contributed to a deterioration in environmental sustainability. Consequently, the worsening state of the natural environment presents a profound conundrum at the intersection of science and sustainability, characterised by conflicting pathways (Malik 2023b) (Fig. 1).

One pathway shows that increased science production drives innovation, ultimately leading to environmental sustainability, but only when the policy of scientific and technological development focuses on supporting blue sky research and solutions that benefit society at large. Scientific discoveries, for example, when coupled with upskilling in supply chains (Cacciolatti and Molinero 2013) can enhance technological efficiencies or reduce reliance on polluting energy sources. Aligned with this perspective, scientific policy complements structural mechanisms aimed at constraining pollution, particularly CO_2 emissions but only, as shown by Lera-López et al. (2014). Simultaneously, the dissemination of scientific knowledge among the public influences the behaviour of industrial firms, as demand is driven by societal needs and businesses adapt to satisfy such demand (Cacciolatti and Lee 2015a, b).

Conversely, the alternative pathway, i.e., an industrial pathway, involves the vertical transformation of science and suggests that scientific discoveries primarily serve the economic interests of industrial firms, reducing costs and increasing economic benefits. Such a pathway is deeply dependent upon the economic policy of the nation and the influence businesses have on it (Nelson 1959; Khan et al. 2021). This development of scientific knowledge into commercial products can inadvertently harm environmental sustainability (Malik 2023b). High-growth economies, driven by an aggressive pursuit of their economic goals and cost efficiencies, are more prone to such negative environmental impacts. Notably, both the USA and China are leaders in scientific output and CO_2 emissions, reinforcing this perspective whereby national science might benefit environmental sustainability accidentally.

The competition between these two pathways and their conflicting consequences raises broader questions about the institutional context underpinning these structures and processes that lead to divergent paths (Zhao et al. 2015). The institutional theory relies on the interplay of formal and informal mechanisms that define goals, means, and behaviours.

Formal mechanisms encompass regulations and policies that induce both stability and change in the innovation ecosystem. They influence the transformation of scientific discoveries into practical usage and facilitate transactions between organisations, defining the national goals for a country's scientific and technological development. In essence, formal institutional mechanisms shape the vision and decision-making of the actors within a national economy and its national innovation system (Anand et al. 2021). On the other hand, informal institutional mechanisms extend further across space and time. These informal mechanisms encompass national culture, which directly influences scientific discovery and the adaptation of such discoveries for societal and industrial use. Cultural factors also indirectly impact the choice between following a societal path versus an

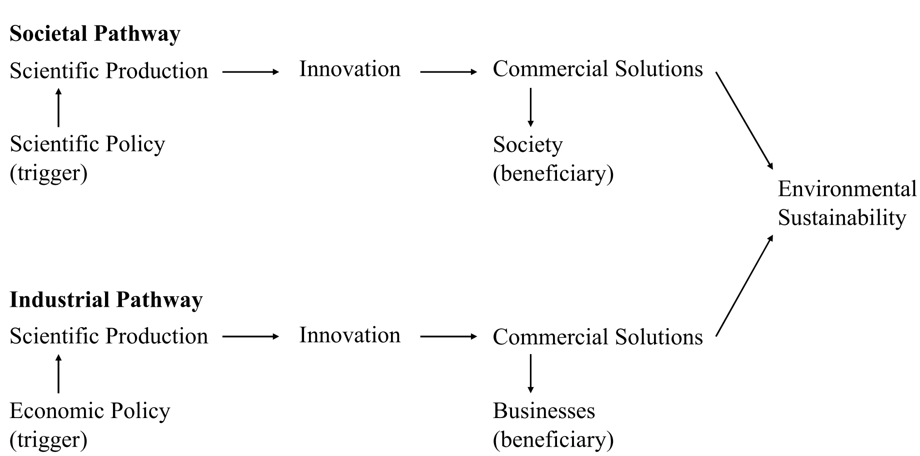

Fig. 1 Societal and industrial innovation pathways leading to environmental sustainability. Source: Author's own

industrial path, which may either mitigate or propitiate environmental sustainability through the transformation of scientific discoveries, as they define national policies and practices. At a higher analytical level, national culture provides insights into why some economies excel in one path or the other regarding their scientific discoveries' advancement and their impact on environmental sustainability, particularly regarding CO_2 emissions. Thus, national culture may explain why some countries harness their national science to mitigate environmental sustainability challenges, while others inadvertently exacerbate them.

2 A national culture framework for the support of public science and environmental sustainability in innovation ecosystems

2.1 Net zero as an environmental sustainability priority in the fight against climate change and its relationship with national culture

Environmental sustainability has become a fundamental component within the broader framework of sustainability, a concept that assumes diverse connotations contingent upon the vantage point of individual authors. Renowned Nobel Laureate economist Amartya Sen (Sen 1985) directed the focus of his studies towards the sustainability of social development and resources, while Nobel Laureate Angus Deaton extends the concept to encompass improvements in healthcare (Deaton 2013), showing the inextricable link among environmental, social, and economic sustainability. Furthermore, the World Bank incorporates environmental sustainability into its lexicon of socio-economic development considerations (World Bank 2018). It is undeniable that environmental sustainability occupies a central position within these sustainability paradigms, given its pervasive influence on the socio-economic concerns of the world's nations.

In essence, without addressing environmental sustainability, economic growth can inadvertently undermine environmental quality due to the potential hazards emanating from industrial activities. Such hazards pose significant threats to all countries' socio-economic development. Consequently, environmental sustainability not only precedes but also follows in the wake of the socio-economic progress of the nations, as a relationship between financial development and carbon emissions is established in the extant literature (*see* Shahbaz et al. 2020).

This study directs its focus on the quantifiable metric of CO_2 emissions as a proxy for environmental sustainability. This emphasis stems from the fact that greenhouse gases, of which CO_2 is a primary contributor, represent the sole human-induced cause of environmental degradation (Fankhauser et al. 2022). In straightforward terms, elevated CO_2 emissions elevate environmental hazards while diminishing sustainability, whereas reduced CO_2 emissions enhance sustainability while mitigating environmental risks.

My focus on CO_2 emissions is substantiated for several reasons. First, CO_2 emissions, directly and indirectly, harm environmental sustainability, contributing to air pollution, increased health risks in urban populations, disruptions in the food chain, global warming-related agricultural damage, and an array of other detrimental effects on the health of people and economies. Second, CO_2 emissions exhibit a direct and positive correlation with human intervention in the environment. Activities such as industrial processes that disregard national ecological concerns (e.g., water pollution), competition for resource exploitation (e.g., soil impoverishment), and prioritising self-interest over societal welfare, collectively contribute to environmental degradation. Unsurprisingly, the awareness and response to environmental sustainability-related concerns in different nations vary across institutions, encompassing formal policies and informal values, such as national culture.

Environmental sustainability has gained prominence across diverse national cultures, albeit to varying degrees, marking a progression since its inception in the 1970s (*see* Meadows et al. 2018). In recent decades, it has gained substantial traction in prominent literature spanning the social sciences (Sen et al. 2010). Various scholars have adopted differing perspectives in their exploration of the science-sustainability relationship, with some focusing on singular facets while others adopt a more comprehensive approach. On the level of innovation through knowledge transformation, certain perspectives concentrate on specific scientific disciplines, such as environmental science, while others broaden their perspective to encompass the national level. Inter-institutional perspectives delve into national institutions (Vallas and Kleinman 2008), whereas others draw upon comparative institutional analysis. Expanding the scope, comparative studies have been scrutinising institutional hierarchies, some focusing on specific levels within the hierarchy, while others explore vertical and horizontal linkages (Hollingsworth 2003). At the broadest level, the global discourse on environmental sustainability bifurcates into those acknowledging the sustainability crisis and those who refute it. While some, including the then-US President in 2017, as well as certain scientists and citizens, have been dismissing the role of human intervention and industrial activity in driving CO_2 emissions and environmental degradation, others, adhering to the Kyoto Protocols, attribute CO_2 emissions to human intervention and acknowledge the harm they do to environmental sustainability. Nonetheless, a consensus prevails that the environment has reached a critical juncture, prompting a diverse array of cultures to craft varied policies and practices in response to this issue.

To evaluate environmental sustainability, this study employs an exploratory framework with three key components rooted in the concept of national culture, established in the organisational behaviour literature. This study establishes some connections between public science and CO_2 emissions, between national culture and CO_2 emissions, and between the interplay of public science, national culture, and CO_2 emissions. Public science encompasses the practices within the national economy that impact environmental quality, thus influencing sustainable socio-economic development. National culture encapsulates the social attitudes and collective mental structures within society. The interaction between these two domains implies that national culture exerts a moderating influence on the policies and practices of public science, subsequently shaping CO_2 management strategies within leading innovative economies. Consequently, this investigation starts by examining public science and its alignment with policies and practices aimed at achieving environmental sustainability.

2.2 The relationship between public science and national culture: scientific paths and types of knowledge

The seminal definition of public science is found in the sociological literature as the boundary-work used by scientists to control the market of knowledge, or 'the attribution of selected characteristics to the institution of science (i.e., to its practitioners, methods, stock of knowledge, values and work organization) for purposes of constructing a social boundary that distinguishes some intellectual activities as non-science' (Gyerin et al. 1985:394). Therefore, public science defines the 'specialist knowledge providers *[other than]* consultancies, private research organisations' (Tether and Tajar 2008). Public science plays a critical role in the innovation ecosystem of a nation: 'universities specialise in upstream research and corporations specialise in downstream development.' (Arora et al. 2023).

The productivity of public science and its transition from various scientific domains, including environmental science and CO_2 emissions reduction, hinges significantly on the national institutional capabilities. This process unfolds through two distinct paths within the science-sustainability paradigm. One path, i.e., the industrial path, leads to socioeconomic growth, often without an emphasis on sustainability. In this context, science engages national institutions and knowledge systems to drive technological development aimed at enhancing market efficiency. Actors and structures within this sphere adhere to specific goals, coordination mechanisms, and incentive structures. Conversely, the environmental science-based path, i.e., the societal path, prioritises sustainability and engages a broader spectrum of actors, systems, and coordination structures dispersed across the national economy (Rosli and Cacciolatti 2022). The industrial path embodies a distributive perspective, while the societal path fosters an integrative outlook (Garud and Karnøe 2003).

The performance of public science for environmental sustainability is not solely contingent on the chosen path but also on the type of knowledge involved in the transformation process, spanning from discovery to utilisation. Two fundamental types of knowledge come into play: the explicit and tacit dimensions (Polanyi 1967). Explicit knowledge comprises declarative and codified knowledge applicable to the market, whereas tacit knowledge pertains to context-specific procedural knowledge. Explicit knowledge is encapsulated in codified objects and repertoires, while tacit knowledge resides within routines and experience. Codified knowledge readily flows within and between organisations, while tacit knowledge demands time, incurs significant costs, and takes different routes during its transformation due to interactive processes and diverse interpretations. Despite their interdependence, codified knowledge, as found in scientific publications, underpins the argument for interdisciplinary and inter-institutional comparative cultures. The interdisciplinarity needed to address the world's grand challenges is paradoxically juxtaposed with publication practices in universities, which are driven by journal rankings, and the aggregation of research journals that hamper interdisciplinary research (Rafols et al. 2012).

The transformation of national knowledge into tangible outcomes relies on the national bricolage — a concept rooted in the work of French anthropologist Claude Levi-Strauss (Levi-Strauss 1966), denoting the practice of 'tinkering' with existing resources. National economies employ this concept to harness existing knowledge and socio-economic resources, fostering innovation (Douglas 1986; Stinchfield et al. 2013; Turner 2014).

National bricolage transmutes codified public science into practical applications through contextual interpretations within policies and practices, occurring at both organisational and national levels. In essence, national bricolage materialises when the distributive components of widespread knowledge interact to create a novel path within the industrial sector. The emergence of this new path, resulting from the amalgamation of the two preceding paths, governs the behavioural patterns of the sector and associated national institutions. Consequently, organisations, national agencies, and networks provide an interactive context influenced by culture and comparative culture, extending across temporal and spatial dimensions that encompass both social and technical elements.

The perspective of national culture offers insights into the vertical transformation of public science into sustainability, showcasing variations attributable to the moderating influence of national cultural differences. Existing literature highlights that national culture exerts influence on public science and its transformation into environmental sustainability, primarily via three pathways aimed at reducing CO_2 emissions. First, national culture stimulates national knowledge production, codified within published scientific works (Steensma et al. 2000). Second, national culture impacts CO_2 emissions by fostering general awareness. Third, national culture links public science with national technology, thereby reducing CO_2 emissions and enhancing environmental sustainability. Consequently, the moderating role of national culture on national practices within the science and technology domain significantly influences environmental sustainability.

The literature on institutional development offers a lens through which to view national institutions and emphasises the integration of knowledge producers with knowledge users within the vertical value chain. Institutional development implies a transition from distributive perspectives characterised by isolated institutions to integrative institutions, and multiple institutional interactions transpire vertically and horizontally. These institutional developments revolve around the central theme of interactive resource exchange across various levels of the innovation ecosystem (Hollingsworth 2003). The national innovation system serves as a critical component of public science and socio-economic performance (Freeman 2002). For instance, the university-industry relationships facilitating the transformation of public science into socio-economic products have evolved in developed economies (Fagerberg et al. 2005), enabling knowledge transfer in both directions in the value chain, i.e., suppliers and consumers of public science, contributing to socio-economic development (Etzkowitz 2003). These institutional developments exert moderating influences on the vertical transformation of public science for socio-economic development.

Within the realm of institutional development, one group of scholars expounds upon the structural view of national institutions, elucidating how institutional structures constrain the actors' behaviour. Notably, Nobel Laureate institutional economist Douglas North has made significant contributions along this structural line, characterising institutions as the 'rules of the game' (North 1990). This overarching definition of institutions as such has permeated literature spanning the social sciences and economics. Conversely, another group of institutional theorists adopted a behavioural approach, explicating how actors operate within the context of national institutions (Schotter 1981). The structural view adopts a macro perspective for institutional analysis, while the behavioural perspective adopts a micro viewpoint. Either perspective in isolation offers only a partial understanding of public science or socio-economic development. However, when combined, the structural and behavioural institutional arguments merge policy and processes, offering insights into the dynamics of stability and change within socio-economic development (Hollingsworth 2003). Consequently, structure moderates the processes, while practice mediates institutional structure within the transformation of public science for socio-economic development.

National culture fulfils a dual role, acting as a moderator of structure at the macro level and as a moderator of practice at the micro level. At the macro level, national culture shapes formal institutions, including regulations (Casson et al. 2010), policies, and programmes (Campbell 2004). Cultural studies provide ample evidence that national culture moulds mental models, future assessments, and decisions regarding appropriate institutional structures (Hofstede 2001). For instance, certain national cultures favour formal legal systems, while others prefer informal relational network structures. At the micro-level of practice, institutions establish interpretative decision rules. Depending on the institutional context at the practice level, structural mechanisms and procedural information processing, different situations translate into context-specific decisions, deviating from the established and dominant structures and situations. National culture influences an individual's interactions within a network system, resulting in diverse mechanisms and situations, leading to various trajectories of human behaviour. Consequently, the juxtaposition of established structures with new situations yields a multitude of paths, processes, and rates of public science transformation.

2.3 National culture as a moderator of public science

Numerous scholars have recognised the pivotal role of culture in shaping human behaviour, both directly and indirectly through the impact on public policy and formal regulations. In the realm of business and management decision-making processes, national culture emerges as a key factor in explaining inter-country differences, operating at both macro and micro levels (Hofstede 2001). Furthermore, national culture has the potential to elucidate environmental sustainability by addressing the critical issue of CO_2 emissions (Disli et al. 2016; Husted 2005). Despite the acknowledged significance of national culture across a wide spectrum of socio-economic activities within national settings, empirical research has been scarce in exploring whether and how national culture moderates socioeconomic activities pertaining to CO_2 emissions. With a few exceptions (Disli et al. 2016; Wang et al. 2021; Chan et al. 2022), previous literature predominantly utilised the lens of economic development to explain environmental sustainability by estimating the bell-shaped Kuznets Curve (Grossman and Krueger 1995). This analysis of cultural moderation in the context of national science for vertical transformation into economic activity has been notably absent from the analysis of CO_2 emissions, until recently (Ullah et al. 2022).

Public science plays a dual role by promoting economic growth on one hand and sustainability on the other through the spillover effects of knowledge generated within the national system (Frank 1997; Gallopín, 1992; Nichols 2008). It is imperative to consider that public science must develop within a national cultural framework that supports public policy. The national culture-based framework warrants particular attention, as the Kuznet curve weakens when national cultural dimensions are introduced into the sustainability argument (Park et al. 2007). In essence, national cultural variations give rise to differences in the production of national science, the vertical transformation of national science, and the management of sustainability through CO_2 emissions reduction. Environmental science, on the other hand, is concerned with the consequences, policies, and management of environmental impacts (Merrill and Sintov 2016; Schweizer-Ries 2008).

Environmental science differs from other sciences in several key aspects. First, environmental science primarily develops through field experiments on the demand side, bringing it closer to the real-world context of sustainability. In contrast, science experiments typically initiate at the inception of the idea-value chain, on the supply side, distant from environmental concerns. Second, environmental science relies on both scientific and social structures, whereas science is primarily driven by knowledge content. In principle, environmental science serves as a bridge between the need for environmental quality enhancement and the scientific knowledge required to address this need. Third, environmental science encompasses a broader spectrum of knowledge types, stakeholders, resources, and conditions compared to science. Finally, environmental science incorporates distal disciplines (it is more interdisciplinary in nature), while science predominantly focuses on proximal disciplines in exploration. Given its temporal, spatial, intellectual, and structural positioning as a facilitator between science and sustainability, environmental science bridges science and sustainability.

The study of national culture has been a prominent research theme within the social sciences and socioeconomic development across various national, sectoral, and cross-national contexts. The dimensional approach to the study of national culture has gained dominance, supported by several factors. Over the past three decades, the dimensional approach to national culture has transcended into nearly all social sciences. Furthermore, recent research has reaffirmed the validity of the five cultural dimensions (Malik 2023a; Malik et al. 2021). Finally, national culture has provided valuable insights into empirical literature in the context of comparative studies, international business alliances, and inter-organisational relationships between countries. The dimensional approach has garnered legitimacy as there is little evidence challenging its validity and reliability. Thus, the dimensional perspective of national culture should serve as a moderating context for the vertical transformation of public science into socioeconomic development.

While socioeconomic development encompasses multiple elements, this discussion primarily centres on environmental sustainability. As previously noted, environmental sustainability has emerged as a central focus in socio-economic development. A critical measure of environmental sustainability hinges on CO_2 levels, where a high concentration poses environmental hazards, while a low concentration signifies a move towards sustainability, therefore prompting firms and governments towards net zero solutions. The question at hand is whether national culture moderates public science for CO_2 management, thereby explaining differences in CO_2 emissions across countries. To address this, the following analysis employs five dimensions of national culture and their associated indices to evaluate their moderating roles in the transformation of public science for environmental sustainability.

Environmental science contributes to environmental sustainability in two distinct ways (Malik 2023b; Malik et al. 2021). First, it provides input for transformation, such as discoveries leading to knowledge applicable to industrial applications through new products and processes. Second, it offers alternative technologies that present radical solutions to imminent environmental challenges. In other words, input-oriented science enhances the efficiency of existing processes and pathways, while output-oriented science introduces entirely new structures and solutions to socio-economic issues, opening the way to new pathways. Both input and output-oriented environmental sciences are influenced by the cultural context that defines the meaning, goals, and processes of the situation. For instance, cultural variations on the scale can either positively or negatively moderate the transformation of national science into novel solutions.

At a policy level, national culture exerts influence on R&D management across various cultures (Hoppe 1993). At the managerial level, national culture impacts the development of new products (Malik 2023b; Malik et al. 2021) and the adoption of innovative products favouring environmental sustainability (van Everdingen and Waarts 2003). National cultural differences play a substantial role in shaping attitudes towards supporting a sustainable environment within business enterprises. In what follows I present the dimensions of national culture that moderate public science.

2.3.1 Power distance as a moderator of the relationship between public science and carbon emissions

High Power Distance cultures play a crucial moderating role in the context of national science, favouring sustainability and challenging the direct impact of economic growth on environmental sustainability, as suggested by the Kuznets curve. The Kuznets curve posits an inverted U-shaped relationship, proposing that less developed economies tend to increase CO_2 emissions, while more developed ones reduce them (Grossman and Krueger 1995). I argue that national culture acts as a moderator in the process of CO_2 emissions, with high power distance cultures having the potential to exert both positive and negative influences on CO_2 emissions through their moderating effects.

In the case of high-power distance cultures with high CO_2 emissions, the argument suggests that these economies prioritise economic growth over social responsibility and ethical considerations, thus emphasising growth at the expense of environmental quality. On the other hand, in high power distance cultures with low CO_2 emissions, the argument is that State institutions exert regulatory power over CO_2 emissions, steering the process away from greenhouse gas-intensive technologies towards environmentally friendly alternatives.

Taking the stance that high power distance negatively moderates the relationship between national science and CO_2 emissions, I propose that high power distance cultures possess the capability to impose constraints on CO_2 emissions by redirecting national science away from pathways leading to CO_2 increase and towards those that result in CO_2 reduction. In contrast, low power distance cultures face challenges in achieving consensus through the democratic process, impacting the intensity and speed of their environmental policy decisions. Evidence suggests that high power distance countries exhibit a greater ability to influence environmental policies at a more rapid pace compared to low power distance countries at similar levels of economic development (Malik et al. 2023; Xiang et al. 2022).

By applying the concept of power distance to the realm of public science, which is inherently intertwined with national policies and economic development, I propose that high power distance cultures naturally moderate the effects of public science on CO_2 emissions. In essence, high power distance cultures, in conjunction with public science, shift the focus from hazardous paths to sustainable pathways. If this assumption holds at the level of public science, the following propositions can be made.

> H1: A high power distance culture negatively moderates the relationship between public science transformation and CO_2 emissions.

2.3.2 Individualism-collectivism as a moderator of the relationship between public science and carbon emissions

Highly individualistic cultures promote public science and its transformation through entrepreneurial activities, ultimately driving economic growth. The argument posits that highly individualistic cultures encourage economic growth through private initiative and lobbying, which, in turn, has adverse effects on environmental sustainability. The absence of cohesive groups supporting environmental sustainability in highly individualistic societies, in contrast to self-interest-driven corporations, implies a direct link between high individualism cultures and high CO_2 emissions (Roy and Pal 2009). In other words, high levels of economic growth and high individualistic cultures pose environmental hazards.

While this argument offers a valid explanation when not considering the role of national science in highly individualistic cultures (Grossman and Krueger 1995), the introduction of public science production introduces an alternative argument that paradoxically favours highly individualistic cultures in terms of environmental sustainability compared to highly collectivist cultures (Malik 2023b; Malik and Huo 2022).

Highly individualistic cultures are instrumental in the production of national science, particularly in the context of radical innovation, which leads to alternative solutions for economic and social challenges. Environmental issues often arise from economic activities and societal demands (Hofstede 2001). Highly individualistic cultures meet two conditions that support the negative moderation of public science for environmental sustainability. First, high individualism tends to produce more science in both quantity and quality. For example, highly developed economies generate both incremental and radical technological advancements through discoveries. Beneath these formal national institutional structures, the influence of national cultures, such as liberal economies and non-liberal economies, plays a significant role in producing a high quantity of high-quality public science (Malik 2017b). Second, highly individualistic cultures actively engage in entrepreneurial activities in the vertical transformation of public science. They promote openness in the disclosure of information for external observation, including by the media and social organisations.

Even though managers in highly individualistic cultures may exhibit weaker signs of commitment to sustainability compared to those in collectivist cultures, the interaction with public science alters this proposition. Building on the foundation of an individualistic culture, which encourages information disclosure, openness, and scrutiny of enterprises in economic production activities, it is not unreasonable to argue that highly individualistic cultures have the potential to negatively moderate the impact of public science on CO_2 emissions, thus supporting environmental sustainability. This shift redirects the path from pollution towards sustainability.

> H2: A highly individualistic culture negatively moderates the relationship between public science transformation and CO_2 emissions.

2.3.3 Masculinity-femininity as a moderator of the relationship between public science and carbon emissions

A highly masculine culture refers to societies in which individuals and organisations tend to exhibit assertive attitudes and behaviour, thus embodying masculine characteristics. Conversely, a culture with low masculinity stands at the opposite end of the spectrum and is associated with femininity. Feminine cultures are characterised by nurturing, caring attitudes and behaviours towards others, society, and the environment. Between these two extremes, highly masculine cultures typically prioritise material success, while predominantly feminine cultures emphasise quality of life, care for others, and social well-being (Hofstede 2001).

In the context of economic growth, masculine cultures strive for material success even at the expense of social development and care for the environment. In other words, highly masculine cultures have a negative impact on environmental sustainability by steering public science away from the path of socio-economic development and towards a singular focus on economic growth. The latter approach encompasses not only economic growth and material success but also has implications for environmental sustainability (Anand and Sen 2000). Evidence supports the notion that highly masculine cultures can adversely affect the environment due to their pursuit of material success and competitiveness (Husted 2005). Similarly, highly masculine cultures often exhibit weaker support for sustainability (Parboteeah et al. 2012). Therefore, I propose the following.

> H3: A highly masculine culture positively moderates the relationship between public science transformation and CO_2 emissions.

2.3.4 Uncertainty avoidance as a moderator of the relationship between public science and carbon emissions

National cultures exhibit variations in the way they shape the attitudes and behaviours of individuals and organisations towards uncertainty. Cultures characterised by high uncertainty avoidance tend to prevent uncertainty, by engaging in forward-looking activities that codify routines and tasks, display emotional responses to uncertainty, limit risk and resist change (Hofstede 2001). On the contrary, a low uncertainty avoidance culture, characterised by its tolerance for uncertainty, can facilitate the generation of discoveries and their subsequent transformation into commercial activities. In this context, high uncertainty avoidance cultures slow down both pathways of vertical technology transfer: the economic growth trajectory for an industrial path and the socio-economic development trajectory of a societal path. Although clashing with socio-economic growth, this deceleration in economic activities reduces energy consumption, consequently leading to reduced CO_2 emissions.

Additionally, high uncertainty avoidance cultures tend to establish institutional barriers and regulations aimed at managing environmental uncertainty. For instance, they often employ formal policy procedures, rules, and norms to address environmental sustainability. While one study suggests that individuals from high uncertainty avoidance cultures may exhibit insignificant support aptitude for sustainability (Parboteeah et al. 2012), empirical evidence points to a different outcome, indicating a negative correlation between high uncertainty avoidance and CO_2 emissions (Disli et al. 2016). Therefore, I propose a negative moderation effect of high uncertainty avoidance on the transformation of public science and its impact on CO_2 emissions, suggesting a positive role in promoting environmental sustainability.

> H4: A culture of high uncertainty avoidance negatively moderates the relationship between public science transformation and CO_2 emissions.

2.3.5 Long-term orientation as a moderator of the relationship between public science and carbon emissions

The concept of Long-term Orientation (LTO) relates to the extent of temporal orientation towards thinking about the distant future (Hofstede 2001). High LTO cultures, characterised by their belief in control over their destiny, tend to focus on long-term thinking and planning (Bourdieu 2005). Long-term orientation indicates the degree to which the members of society direct their thoughts and actions towards the more distant future. Moreover, LTO cultures prioritise future outcomes even if it comes at the expense of short-term gains. In the context of environmental sustainability, high LTO cultures implement policies and procedures that favour sustainability over short-term orientation cultures.

Regarding science, high LTO cultures allocate investments in science and technology with a long-term perspective, prioritising long-term benefits over short-term gains. Likewise, entrepreneurs in LTO cultures leverage technology to create value for the future. Finally, high LTO cultures invest in the development of technologies leading to sustainability, striking a balance between future preferences and present economic growth (Hofstede 2001). Taking this perspective into consideration, I propose the following (Fig. 2).

> H5: The high LTO culture negatively moderates the relationship between public science transformation and CO_2 emissions.

3 Methods

3.1 Measures

The variables used in the study were adopted from well-established measures used by the World Bank. The Hofstede dimensions were used to measure the effects of national culture. Table 3 in Appendix 2 shows a summary of the variables and some descriptive statistics.

3.1.1 Dependent variable

National CO_2 emissions (expressed in thousands of tonnes, kt) are based on the World Bank's data (World Bank 2023). I transformed the dependent variable by computing its logarithm.

3.1.2 Independent variables

Public science is measured as the total number of publications in science and technology with a focus on sustainability (keywords: sustainability, environment, carbon emissions, net zero). This measure was compiled using papers published in science and technology in general, and environmental science in specific. The source of the journals is the SRJ database (Scimago 2023). On the other hand, the dimensions of national culture were taken from the dataset of Hofstede's dimension data matrix available online at geerthofstede.com and presented as an index. They comprise a measure of power distance (var. name *power*), individualism vs. collectivism (var. name *individualism*), masculinity vs. femininity (var. name *masculinity*), uncertainty avoidance (var. name *uncertainty*), and long-term vs. short-term orientation (var. name *long-term*). The sixth and last measure, i.e., indulgence, was not used due to the instability of the index (Taras et al. 2023).

3.1.3 Moderators

The interaction between culture and public science is computed by multiplying the number of publications in science and environmental science by the cultural dimensions' indices. Thus, I obtained a set of moderators for science and environmental science as follows: *science-PDI* for power distance, *science-IDV* for individualism, *science-MAS* for masculinity, *science-UAI* for uncertainty avoidance, and *science-LTO* for long-term orientation.

3.1.4 Controls

Finally, GDP, military expenditure, and exports have been adopted as controls and were taken from the World Bank Database. *logGDP* is measured as the official log of the GDP of the country, *military expenditure* as a percentage of the national GDP, *military personnel* as the total number of active military staff operating in the country, and finally, *high-tech exports* as a percentage of manufactured exports.

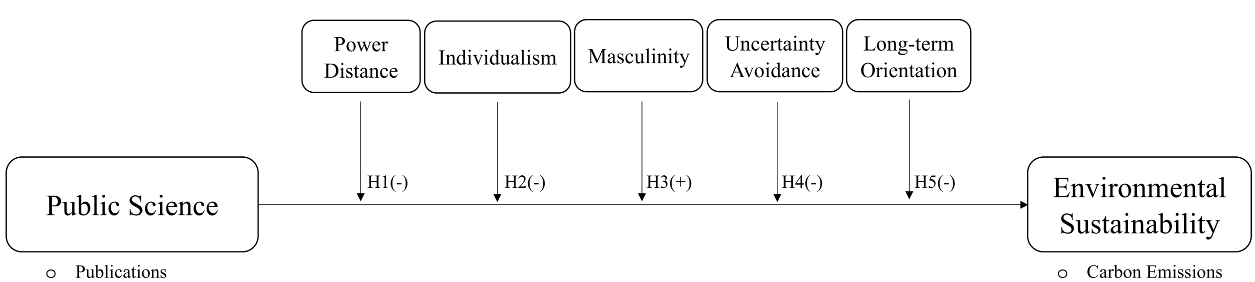

Fig. 2 A national culture framework for the support of public science and environmental sustainability in innovation ecosystems. Source: Author's own

3.2 Data description

For the analysis, I employed data involving OECD and non-OECD economies to assess sustainability. This analysis encompassed a sample of 30 economies (Table 5 in Appendix 4). Within these economies, public science exhibited integrated productivity in two primary disciplines: science and environmental science. Further breakdown at the sub-discipline level revealed that science comprised 6 disciplines (i.e., mathematics, physics, chemistry, biology, medicine, and engineering), while environmental science comprised 14 constituents (see Appendix 5). Consequently, environmental science drew upon a wide spectrum of diversity, complexity, and an intricate network of actors and structures.

The data I utilised encompassed scientific and technological academic publications (excluding patents) within the sample of the countries, spanning from 1996 to 2020, following a yearly time series pattern.

Scientific publications played a pivotal role in this analysis for several reasons. First, they offered comparable attributes of quantity and quality across nations. Scientific knowledge transcended borders through interactions among research organisations, scientists, and the enabling reach of information and communication technologies. Second, scientific publications served as reliable indicators for scrutinising national innovation systems. Third, most publications directly or indirectly linked various scientific domains to sustainability. Fourth, the aggregated weight of published science at the macro level facilitated the time series analysis, spanning 24 years from 1996 to 2020. Finally, with China being the second-largest economy outside the OECD, its inclusion in the list of scientific nations rendered published science a meaningful and comparable metric across countries.

Two primary sources provided consistent, reliable, and comparable data for this analysis. For the two disciplines of public science, I relied on the SJR (Science Journal Ranking) database. The SJR maintained comprehensive data on every discipline within all economies featured in the sample, covering the period from 1996 to 2020. After securing data for the independent variables, I obtained information on CO_2 emissions from the World Bank database. The World Bank meticulously curated national CO_2 emission data for all economies within the sample, over the same period as the panel data. Figure 3 in Appendix 1 provides insights into the composition and construction of the five primary components of CO_2 emissions in the World Bank database.

In this study, there is an inherent complexity of the relationship between public science and carbon emissions, which can involve collaborations among researchers from different countries and diverse research topics. To address this complexity, I have taken a country-specific approach in the analysis rather than focusing on the nationality of the authors of the studies. I use the country context as a basis for examining the relationship between public science production and carbon emissions. For example, if a USA-based author collaborates on a paper focused on China's environmental issues, I consider this contribution within the context of China's public science production. My study looks at the collective impact of public science within a specific country, considering the research conducted within its borders or in collaboration with other nations. By doing so, I aim to capture the influence of a country's science production on its own carbon emissions.

4 Analysis and results

4.1 Analysis

The analysis employed a robust panel data approach, incorporating both random and fixed effects models, to investigate the intricate relationship between national culture, public science productivity, and CO_2 emissions across a diverse sample of 30 economies, including both OECD and non-OECD nations. The use of panel data analysis allowed for the examination of trends spanning 24 years, from 1996 to 2020, providing a rich temporal perspective. I used an OLS estimation and checked it against a robust estimation, which did not bear differences in the results. This reassured me that there was no substantial influence from the outliers. The random effects model accounted for unobserved heterogeneity and allowed for the assessment of time-invariant factors, such as cultural attributes unique to each nation. On the other hand, the fixed effects model enabled the scrutiny of time-varying factors within each economy, capturing the nuances of change over time. This analytical approach (Zyphur et al. 2020) facilitated the disentanglement of the intricate interplay between high and low PDI, IDV, MAS, UAI, and LTO cultural dimensions, their impact on public science production, and ultimately, their influence on CO_2 emissions. Through this rigorous panel data analysis, the study aimed to discern how national culture moderates the transformation of public science into pathways either propitiating or mitigating environmental sustainability, offering valuable insights into the complex dynamics of science, culture, and sustainability on a global scale.

The general form of the equation adopted is:

$$Y_{it} = \beta_0 + \beta_1 X_{it} + \beta_2 Z_{it} + \beta_3 (X_{it} \cdot W_{it}) + u_{it} \qquad (1)$$

where Y_{it} is the dependent variable for the individual i at time t; X_{it} are the independent variables for the individual i at time t; Z_{it} are the control variables for the individual i at time t; β_0 is the constant; β_1 is the coefficient for the independent variables; β_2 the coefficient for the controls;

$X_{it} \cdot W_{it}$ is the interaction term; β_3 the coefficient for the interaction term; u_{it} is the error term.

The data show that only 19% of the variables are highly correlated (Table 4 in Appendix 3) thus indicating that multicollinearity is not a concern. The goodness-of-fit shows that for the random effects models, the highest R-square is 0.768, with an F statistic of 52.08 significant at $p < 0.001$, indicating that the model is better than the mean model. The modified Wald test for heteroskedasticity shows that $p > \chi^2 = 0.001$ showing the panel is not affected by heteroskedasticity and thus residuals are drawn from a population with constant variance. These models include time-invariant variables, i.e., cultural dimensions.

In the fixed effects model, I assess within-group and between-group variation, with a good fit indicated by reduced within-group variability relative to between-group variability. The goodness-of-fit shows that for the fixed effects model, the R-square is 0.789, with an F statistic of 45.12 significant at $p < 0.001$. The modified Wald test for heteroskedasticity shows that $p > \chi^2 = 0.001$, thus ruling out heteroskedasticity. These models include time-variant variables only, therefore the national cultural dimensions are excluded.

4.2 Results

The results support all hypotheses except for H1, which is only partially supported. In what follows I report the findings of the analysis.

4.2.1 Time-invariant effects of national culture and public science on carbon emissions

The results for the random effects (Table 1) estimation, comprise model 1 (intercept and controls only), model 2 (independent variables ex high-tech exports), model 3 (independent variables including high-tech exports), and model 4 (interaction effects). The time-invariant random effects model shows that the constant has a significant initial effect and CO_2 emissions are rising between 29.5 k tonnes (RE_3: Beta = 29.503, $p < 0.001$) and 49.6 k (RE_2: Beta = 46.032, $p < 0.001$) tonnes for each unit of variation in the intercept.

When looking at the direct effects of national culture, CO_2 emissions increase by almost 8% for each increase in power distance (RE_3: Beta = 0.078, $p < 0.05$), between 5 and 30% with each increase in individualism (RE_3: Beta = 0.051, $p < 0.05$ and RE_4: Beta = 0.301, $p < 0.001$), and between 5 and 31% for every increase in the long-term orientation (RE_2: Beta = 0.050, $p < 0.001$ and RE_4: Beta = 0.301, $p < 0.001$). However, I also observe a

Table 1 Random effects (RE) models

DV: CO2 emissions (kt)	RE_1			RE_2			RE_3			RE_4		
	β	sig.	ε	β	sig.	ε	β	sig.	ε	β	sig.	ε
Constant	46.032	***	-3.565	49.612	***	-5.078	29.503	***	-6.438	-5.509		-7.940
Independent												
power				-.020		-.030	.078	**	-.035	.056		-.146
individualism				.083	***	-.022	.051	**	-.024	.301	***	-.088
masculinity				-.021		-.018	.028		-.020	-.298	**	-.116
uncertainty				-.015		-.025	-.093	***	-.029	.163		-.116
long-term				.050	***	-.017	.050	***	-.018	.311	***	-.098
Moderators												
science_PDI										.018		-.018
science_IDV										-.033	***	-.011
science_MAS										.047	***	-.015
science_UAI										-.040	***	-.014
science_LTO										-.032	**	-.012
Controls												
high-tech exports	.061	*	-.034				.005		-.040	-.026		-.041
military expenditure	.310		-.400	-.133		-.413	1.603	***	-.571	2.715	***	-.610
military personnel	.085		-.461	.670		-.558	-.223		-.666	-1.405	**	-.679
logGDP	-3.170	***	-.346	-3.918	***	-.436	-1.968	***	-.574	1.089		-.702
R-square	.230			.218			.761			.768		
N	714			714			621			621		

*** *p* < 0.01

** *p* < 0.05

* *p* < 0.1

decrease of almost 30% in CO_2 emissions when masculinity increases (RE_4: Beta = -0.298, $p < 0.001$).

National culture also moderates the effects of public science on CO_2 emissions, as I observe a cumulative decrease of 9% in carbon emissions when individualism (RE_4: Beta = -0.033, $p < 0.001$), uncertainty avoidance (RE_4: Beta = -0.040, $p < 0.05$), and long-term orientation (RE_4: Beta = -0.032, $p < 0.001$) are high. On the contrary, when public science is prosperous, I observe an increase of almost 5% in CO_2 emissions in countries where masculinity scores high (RE_4: Beta = -0.047, $p < 0.001$).

Finally, the controls show that CO_2 emissions increase by 6% when high-tech exports increase (RE_1: Beta = 0.061, $p < 0.01$), although this relationship is weak with a p-value significant at the 10% level, and by a staggering 160% to 271% when military expenditure increases (RE_3: Beta = 1.603, $p < 0.001$ and RE_4: Beta = 2.715, $p < 0.001$). However, CO_2 emissions decrease between 109 and 392% when a country's GDP increases.

4.2.2 Time-varying effects of national culture and public science on carbon emissions

The results for the fixed effects (Table 2) estimation, comprise model 1 (intercept and controls only ex high-tech exports and military personnel), model 2 (independent variables ex high-tech exports), model 3 (independent variables incl. high-tech exports), and model 4 (interaction effects). The time-variant fixed effects model shows that the constant has a significant initial effect and CO_2 emissions are rising by almost 51 k tonnes (FE_1 and FE_2: Beta = 50.980, $p < 0.001$) for each unit of variation in the intercept.

National culture moderates the effects of public science on CO_2 emissions, as I observe a cumulative decrease of 12% in carbon emissions when individualism (FE_4: Beta = -0.083, $p < 0.001$), and uncertainty avoidance (FE_4: Beta = -0.054, $p < 0.001$) are high.

Finally, the controls show that CO_2 emissions increase by up to 290% when military expenditure increases (FE_3: Beta = 2.906, $p < 0.001$), and up to 279% when military personnel are large in number (FE_3: Beta = 2.791, $p < 0.001$). However, CO_2 emissions decrease by 12% when high-tech exports increase (FE_4: Beta = -0.123, $p < 0.05$) and up to a massive 389% when a country's GDP increases. Notwithstanding the importance of this last finding, it should be noted that when the moderation effect of culture on public science is taken into consideration, economic prosperity, i.e., higher GDP, increases carbon emissions six-fold (FE_4: Beta = 6.351, $p < 0.001$).

5 Discussion and conclusion

In recent decades, developed economies have exhibited a significant surge in environmental science production, with the aim of mitigating CO_2 emissions and fostering environmental sustainability. Paradoxically, this upswing in carbon emissions has prompted concerns among researchers and policymakers, revealing a counteractive relationship between national science endeavours and environmental preservation.

Table 2 Fixed effects (FE) models

DV: CO2 emissions (kt)	FE_1			FE_2			FE_3			FE_4		
	β	sig.	ε	β	sig.	ε	β	sig.	ε	β	sig.	ε
Constant	50.980	***	6.164	50.980	***	6.153	5.695		9.031	2.023		8.454
Moderators												
science_PDI										.028		.024
science_IDV										-.083	***	.013
science_MAS										.012		.017
science_UAI										-.054	***	.012
science_LTO										.001		.013
Controls												
high-tech exports							.033		.053	-.123	**	.052
military expenditure				.129		.582	2.906	***	.825	2.840	***	.739
military personnel	2.086	***	.767	2.128	***	.258	2.791	***	.917	.148		.865
logGDP	-3.889	***	.559	-3.791	***	.523	.247		.817	6.351	***	.672
R-square	.176			.183			.756			.789		
N	714			714			621			621		

*** $p < .01$

** $p < .05$

* $p < .1$

This article addressed this conundrum by introducing the moderating influence of national culture, employing the well-established framework of cultural dimensions proposed by Hofstede (2001). The utilisation of national cultural moderation effects in examining the vertical transformation of national science is underpinned by several key rationales. First, national cultures exert a profound influence on policy formulation and practical implementation, shaping both macrostructural and biobehavioural aspects within societies and organisations. Second, the dimensional approach to cultural analysis has gained widespread acceptance and credibility in scholarly discourse. As anticipated, the findings provide support for the role of these cultural dimensions in shaping outcomes.

The study reveals that high Power Distance (PDI) cultures tend to contribute to higher CO_2 emissions in comparison to low PDI cultures. In the context of the vertical transformation of national environmental science, high power distance cultures exhibit limited effects on socioeconomic development. Instead, they tend to prioritise the economic growth trajectory, favouring an industrial innovation pathway (Fig. 1), often at the expense of increased CO_2 emissions. Conversely, highly Individualistic (IDV) and high Uncertainty Avoidance (UAI) cultures exhibit a negative correlation between public sciences and CO_2 emissions. Elevated national public science levels in conjunction with high individualism or uncertainty avoidance values suggest that such cultures gravitate towards pathways that reduce CO_2 emissions, paradoxically focusing on a societal innovation pathway (Fig. 1), and ultimately benefitting environmental sustainability. This observation highlights the notion that environmental science plays a pivotal role in bolstering sustainability by fostering incremental and radical innovations.

The study findings indicate that Nordic countries such as Finland (FIN), Norway (NOR), Sweden (SWE), and Denmark (DEN) characterised by High Individualism Avoidance and Low Power Distance exhibit a propensity for prioritising societal innovation pathways with lower CO2 emissions (Disli et al. 2016; Miska et al. 2018; Ullah et al. 2022). Similarly, Anglophone nations like the United States (USA), Australia (AUL), Canada (CAN), New Zealand (NZL), and the United Kingdom (GBR), which share traits of High Individualism and Low Power Distance, tend to follow an environmentally sustainable trajectory (Nichols 2008; Polanyi 1967).

These findings align with the extant literature on innovation and sustainability. Previous research has indicated that, at parity of GDP per capita, high-Power Distance and high Masculinity (MAS) tend to increase CO_2 emissions, whereas high Individualism (IDV) and high Uncertainty Avoidance (UAI) decrease them (Disli et al. 2016). This study extends this insight by controlling for GDP as a measure of wealth (i.e., increased GDP often corresponds to increased consumption) and ascertaining a positive correlation with CO_2 emissions in the absence of cultural influences on national environmental science.

Moreover, the study distinguishes itself by focusing on OECD and non-OECD economies, including China, based on their scientific publications, thereby elucidating the impact of GDP per capita on CO_2 emissions — primarily driven by economic growth corroborating its theoretical foundations (Anand and Sen 2000). While the results reaffirm high Uncertainty Avoidance's inducement of sustainability practices for industrial firms, they diverge by identifying a positive association between high Power Distance and sustainability practices (Miska et al. 2018), which does not support sustainability. Additionally, the study uncovers a noteworthy link between military expenditures and CO_2 emissions (Erdogan et al. 2022), as indicated by both models.

Despite the valuable insights offered, this study raises several avenues for future research. First, the sample primarily comprises developed nations, chosen for their advanced scientific capabilities, potentially overlooking the diverse approaches adopted by underdeveloped countries in managing environmental challenges. Second, the OECD economies featured in the study encompass a wide array of policy and practical contexts, potentially yielding nuanced implications for environmental sustainability. Third, the quality of codified science in publications may exhibit variations that merit exploration. Fourth, the study's focus on the transformation of national public science into environmental sustainability may overlook the role of international science, warranting further investigation. Finally, I must acknowledge a limitation: international collaboration in scientific research can sometimes transcend nationalist boundaries and contribute positively to a country's progress, even when the researchers do not reside in the country that benefits from that research. My approach assumes that international collaboration is antithetical to nationalist stands on knowledge contribution, yet, collaborations can often enhance the quality and impact of research, which may not be fully captured by my analysis. Furthermore, this study relied on the existing data, so not all countries report data for all years and for those countries that do report them, reporting standards often differ. Future research could explore the nuanced dynamics of international collaborations in the context of public science and environmental sustainability to provide a more comprehensive understanding of this relationship.

Appendix 1

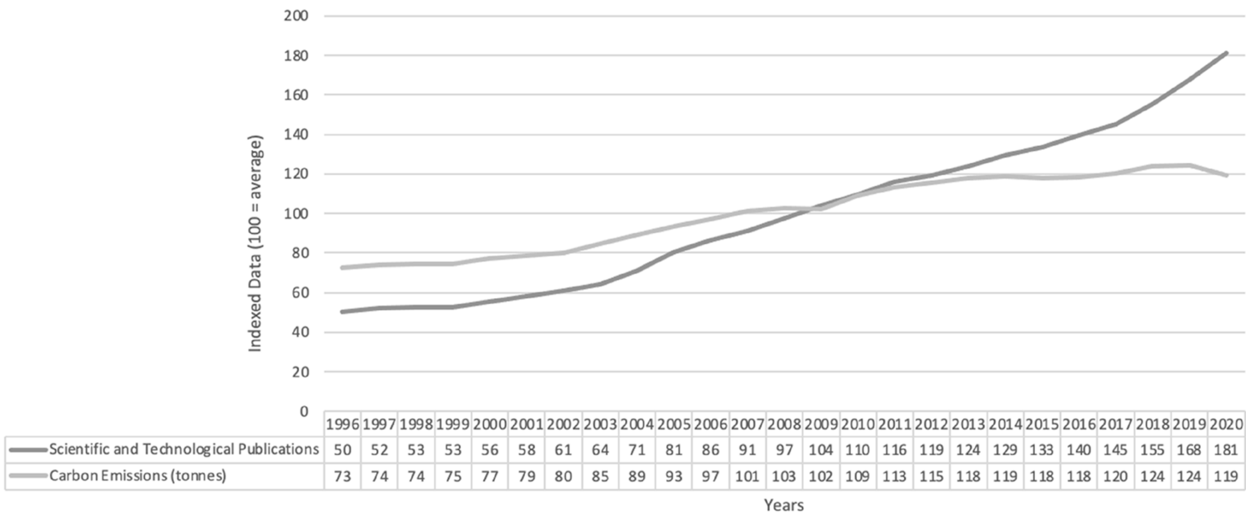

Fig. 3 Scientific and Technological Publications versus CO_2 emissions, World Bank data (1996–2020). Source: Author's own

Appendix 2

Table 3 Summary statistics

Variable	N	Mean	Std. Dev	Min	Max
country_ID	30			1	30
year	720	2005	7	1996	2020
CO_2 emissions (kt)	720	16	6	0	28
military personnel	624	4949	9206	116	74485
log GDP	720	10	1	6	12
high-tech exports	714	16	9	1	48
military expenditure (% GDP)	720	1.9	1.3	0.3	13.3
science_PDI	624	361	159	66	898
science_IDV	624	469	199	109	997
science_MAS	624	398	192	35	877
science_UAI	624	507	171	151	849
science_LTO	624	401	197	127	976
power	720	47	19	11	81
individualism	720	60	21	18	91
masculinity	720	51	22	5	95
uncertainty	720	67	23	23	100
long-term	720	51	22	21	100

Appendix 3

Table 4 Pearson correlation

	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	CO2	-													
2	military personnel	-.121	-												
3	science_PDI	.033	.401 *	-											
4	science_IDV	-.110	.347	-.227	-										
5	science_MAS	-.009	.443 *	.359	.221	-									
6	science_UAI	-.130	.000	.527 *	-.240	.312	-								
7	science_LTO	.044	.294	.461	.000	.392 *	.290	-							
8	power	.115	.119	.921 *	-.430 *	.192	.554 *	.278	-						
9	individualism	-.042	.087	-.456 *	.923 *	.100	-.372	-.181	-.566 *	-					
10	masculinity	.048	.175	.196	.100	.923 *	.285	.231	.150	.039	-				
11	uncertainty	-.037	-.291	.341	-.474 *	.111	.898 *	.065	.527 *	-.477 *	.231	-			
12	long-term	.133	.100	.334	-.151	.277	.290	.948 *	.252	-.204	.217	.180	-		
13	high-tech exports	-.026	.245	.000	.200	.150	-.338	.277	-.189	.215	.107	-.428	.221	-	
14	military expenditure	.060	.160	-.094	-.100	-.101	.103	-.136	-.135	-.104	-.138	.156	-.133	-.069	-
15	log GDP	-.326	.000	-.457	.600 *	-.087	-.087	-.012	-.589 *	.563 *	-.184	-.245	-.063	.264	-.144

* $p < .05$

Appendix 4

Table 5 List of countries included in the study

Country	Group	Main Characteristic	Power Distance Index (PDI)	Individualism vs Collectivism (IDV)	Masculinity vs Femininity (MAS)	Uncertainty avoidance (UAI)	Long-term Orientation (LTO)
FIN	Nordic	High Individualism Avoidance and Low Power Distance	18	74	16	23	35
NOR	Nordic	High Individualism Avoidance and Low Power Distance	33	63	26	59	38
SWE	Nordic	High Individualism Avoidance and Low Power Distance	31	69	8	50	35
DEN	Nordic	High Individualism Avoidance and Low Power Distance	31	71	5	29	53
USA	Anglophone	High Individualism and Low Power Distance	38	90	61	51	21
AUL	Anglophone	High Individualism and Low Power Distance	39	80	52	48	36
CAN	Anglophone	High Individualism and Low Power Distance	22	79	58	49	33
NZL	Anglophone	High Individualism and Low Power Distance	40	91	62	46	26

Country	Group	Main Characteristic	Power Distance Index (PDI)	Individualism vs Collectivism (IDV)	Masculinity vs Femininity (MAS)	Uncertainty avoidance (UAI)	Long-term Orientation (LTO)
GBR	Anglophone	High Individualism and Low Power Distance	35	89	66	35	51
KOR	Confucian	High Collectivism, High Power Distance and High Long-term Orientation	58	17	45	69	93
TAI	Confucian	High Collectivism, High Power Distance and High Long-term Orientation	60	18	39	85	100
CHI	Confucian	High Collectivism, High Power Distance and High Long-term Orientation	80	20	66	30	87
ISR	Israel	Egalitarian and Low Power Distance	13	54	47	81	38
JPN	Japan	High Masculinity and High Uncertainty Avoidance	54	46	95	92	88
GER	Germanic	High Individualism and Low Uncertainty Avoidance	35	67	66	65	83
SWI	Germanic	High Individualism and Low Uncertainty Avoidance	34	68	47	58	74
FRA	Western European	High Individualism and High Uncertainty Avoidance	68	71	43	86	63
BEL	Western European	High Individualism and High Uncertainty Avoidance	65	75	54	94	82
CZE	Western European	High Individualism and High Uncertainty Avoidance	57	58	57	74	70
LUX	Western European	High Individualism and High Uncertainty Avoidance	40	60	50	70	64
ITA	Western European	High Individualism and High Uncertainty Avoidance	50	76	70	75	61
ROM	Eastern European	High Collectivism and High Uncertainty Avoidance	90	30	42	90	52
SER	Eastern European	High Collectivism and High Uncertainty Avoidance	86	25	43	92	52
SPA	Eastern European	High Collectivism and High Uncertainty Avoidance	57	51	42	86	48
MLT	Eastern European	High Collectivism and High Uncertainty Avoidance	56	59	47	96	47
BRA	Eastern European	High Collectivism and High Uncertainty Avoidance	69	38	49	76	44
TUR	Eastern European	High Collectivism and High Uncertainty Avoidance	66	37	45	85	48
CRO	Eastern European	High Collectivism and High Uncertainty Avoidance	73	33	40	80	58

Country	Group	Main Characteristic	Power Distance Index (PDI)	Individualism vs Collectivism (IDV)	Masculinity vs Femininity (MAS)	Uncertainty avoidance (UAI)	Long-term Orientation (LTO)
BUL	Eastern European	High Collectivism and High Uncertainty Avoidance	70	30	40	85	69
POL	Eastern European	High Collectivism and High Uncertainty Avoidance	68	60	64	93	38

Data retrieved from Hofstede's cultural dimensions index [Retried from https://www.hofstede-insights.com]

Source: Author's own

Appendix 5

Sub-disciplines of the environmental sciences

1. Energy miscellaneous
2. Energy engineering
3. Energy fuel technology
4. Nuclear energy
5. Renewable energy
6. Environment miscellaneous
7. Ecology modelling
8. Ecology
9. Environmental chemistry
10. Environmental engineering
11. Global planet
12. Environmental policy
13. Nature conservation
14. Heath technology

Authors' contributions

LC collected and analysed the data for the study, wrote the manuscript, and reviewed the final manuscript.

Declarations

Competing interests

I hereby declare that the disclosed information is correct to the best of my knowledge and that no other situation of real, potential, or apparent conflict of interest is known to me. I undertake to inform you of any change in these circumstances, including if an issue arises during the course of the review process.

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References

Anand, S., and A.K. Sen. 2000. Human development and economic sustainability. *World Development* 28 (12): 2029–49.

Anand, J., G. McDermott, R. Mudambi, and R. Narula. 2021. Innovation in and from emerging economies: New insights and lessons for international business research. *Journal of International Business Studies* 52: 545–59.

Arora, A., S. Belenzon, and B. Dionisi. 2023. First-mover advantage and the private value of public science. *Research Policy* 52 (9): 104867.

Bourdieu, P. 2005. *The social structures of the economy*. Cambridge: Polity Press.

Cacciolatti L., and C. Molinero. 2013. Analysis the demand for supply chain jobs through job advertisements. Working Paper No. 264. Kent Business School Repository. KAR URL: https://kar.kent.ac.uk/33775/1cacciolatti%20mar%20molinero%20(2012)_versioneintegrale2%20Web.pdf.

Cacciolatti, L., and S.H. Lee. 2015a. Revisiting the relationship between marketing capabilities and firm performance: The moderating role of market orientation, marketing strategy and organisational power. *Journal of Business Research* 69 (12): 5597–610.

Cacciolatti, L., and S.H. Lee. 2015b. Entrepreneurial cognition and learning. In *Entrepreneurial marketing for SMEs*, ed. Cacciolatti and Lee, 46–56. London: Palgrave.

Campbell, J. 2004. *Institutional change and globalization*. Princeton: Princeton University Press.

Casson, M.C., M.D. Giusta, and U.S. Kambhampati. 2010. Formal and informal institutions and development. *World Development* 38 (2): 137–41.

Chan, H.W., A.M. Udall, and K.P. Tam. 2022. Effects of perceived social norms on support for renewable energy transition: Moderation by national culture and environmental risks. *Journal of Environmental Psychology* 79: 101750.

Deaton, A. 2013. *The great escape: health, wealth, and the origins of inequality*. Princeton: Princeton University Press.

Disli, M., A. Ng, and H. Askari. 2016. Culture, income, and CO2 emission. *Renewable and Sustainable Energy Reviews* 62: 418–28.

Douglas, M. 1986. *How institutions think*. Syracuse: Syracuse University Press.

Erdogan, S., A. Gedikli, E.İ Çevik, and M.A. Öncü. 2022. Does military expenditure impact environmental sustainability in developed Mediterranean countries? *Environmental Science and Pollution Research* 29 (21): 31612–30.

Etzkowitz, H. 2003. Research groups as 'quasi-firms': The invention of the entrepreneurial university. *Research Policy* 32 (1): 109–21.

Fagerberg, J., D.C. Mowery, and R.R. Nelson. 2005. *The Oxford handbook of innovation*. Oxford; New York: Oxford University Press.
Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., ... and Wetzer, T. 2022. The meaning of net zero and how to get it right. *Nature Climate Change* 12(1):15–21.
Frank, J.D. 1997. Science, nature, and the globalization of the environment, 1870–1990. *Social Forces* 76: 409–35.
Freeman, C. 2002. The learning economy and international inequality. In *The globalizing learning economy*, ed. D. Archibugi and B.-A. Lundvall, 147–62. Oxford: Oxford University of London.
Gallopín, G. 1992. Science, technology and the ecological future of Latin America. *World Development* 20 (10): 1391–400.
Garud, R., and P. Karnøe. 2003. Bricolage versus breakthrough: Distributed and embedded agency in technology entrepreneurship. *Research Policy* 32 (2): 277–30.
Gieryn, T. F., Bevins, G. M., and Zehr, S. C. 1985. Professionalization of American scientists: Public science in the creation/evolution trials. *American Sociological Review* 392–409.
Grossman, G.M., and A.B. Krueger. 1995. Economic growth and the environment. *The Quarterly Journal of Economics* 110 (2): 353–77.
Hickel, J. 2020. Quantifying national responsibility for climate breakdown: An equality-based attribution approach for carbon dioxide emissions in excess of the planetary boundary. *The Lancet Planetary Health* 4 (9): e399-404.
Hofstede, G. 2001. *Culture's consequences: comparing values, behaviors, institutions and organizations across nations*. Thousand Oaks: Sage.
Hollingsworth, J.R. 2003. Advancing the socio-economic paradigm with institutional analysis. *Socio-Economic Review* 1 (1): 130–4.
Hoppe, M.H. 1993. The effects of national culture on the theory and practice of managing R&D professionals abroad. *R&D Management* 23 (4): 313–25.
Husted, B.W. 2005. Culture and ecology: A cross-national study of the determinants of environmental sustainability. *Management International Review* 45 (2): 349–71.
Khan, I.S., M.O. Ahmad, and J. Majava. 2021. Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, circular economy and sustainable business models perspectives. *Journal of Cleaner Production* 297: 126655.
Lera-López, F., M. Sánchez, J. Faulin, and L. Cacciolatti. 2014. Rural environment stakeholders and policy making: Willingness to pay to reduce road transportation pollution impact in the Western Pyrenees. *Transportation Research Part d: Transport and Environment* 32: 129–42.
Levi-Strauss, C. 1966. *The savage mind*. Chicago: University of Chicago Press.
Lu, Y., J. Tian, and M. Ma. 2023. The effect of automation on firms' carbon dioxide emissions of China. *Digital Economy and Sustainable Development* 1 (1): 8.
Malik, T.H. 2017b. Varieties of capitalism, innovation performance and the transformation of science into exported products: A panel analysis. *Technological Forecasting & Social Change* 118: 324–33.
Malik, T.H. 2023a. Institutionally manifested mortalities religiosity mitigates suicides; uncertainty intolerance eclipses. In *The Palgrave handbook of global social change*, ed. S.S.M. RajendraBaikady, Varoshini Nadesan, Jaroslaw Przeperski, M. Rezaul Islam, and Gao Jianguo. London: Palgrave.
Malik, T.H. 2023b. Science and sequestration for sustainability: More green space; more carbon free earth. *Digital Economy and Sustainable Development* 1 (1): 4.
Malik, T.H., and C. Huo. 2022. National culture moderates the link between work stress and depression: An analysis of clinical trial projects across countries. *Cross Cultural Research* 57 (1): 23–55.
Malik, T.H., T. Xiang, and C. Huo. 2021. The transformation of national patents for high-technology exports: Moderating effects of national cultures. *International Business Review* 30 (1): 101771.
Malik, T.H., C. Huo, and K. Nielsen. 2023. Legal distance moderation in the inter-partner distance on cross-country equity investments: A multilevel analysis of the ICT sector. *Journal of General Management*. https://doi.org/10.1177/03063070221123052.
Meadows, D. H., Meadows, D. L., Randers, J., and Behrens, W. W. 2018. The limits to growth. In Green planet blues (pp. 25–29). Routledge.
Merrill, R., and N. Sintov. 2016. An affinity-to-commons model of public support for environmental energy policy. *Energy Policy* 99: 88–99.
Miska, C., I. Szőcs, and M. Schiffinger. 2018. Culture's effects on corporate sustainability practices: a multi-domain and multi-level view. *Journal of World Business* 53 (2): 263–79.
Nelson, R.R. 1959. The simple economics of basic scientific research. *Journal of Political Economy* 67 (3): 297–306.
Nichols, R.W. 2008. Innovation, change, and order: Reflections on science and technology in India, China, and the United States. *Technology in Society* 30 (3–4): 437–50.
North, D. 1990. *Institutions, institutional change and economic performance*. Cambridge: Cambridge University Press.
Parboteeah, K.P., H. Addae, and M.J.B. Cullen. 2012. Propensity to support sustainability initiatives: A cross-national model. *Journal of Business Ethics* 105 (3): 403–13.
Park, H., C. Russell, and J. Lee. 2007. National culture and environmental sustainability: A cross-national analysis. *Journal of Economics and Finance* 31 (1): 104–21.
Periyasamy, A.P., and S. Periyasami. 2023. Rise of digital fashion and metaverse: Influence on sustainability. *Digital Economy and Sustainable Development* 1 (1): 16.
Polanyi, M. 1967. *The tacit dimension*. London: Routledge & Kegan Paul.
Rafols, I., L. Leydesdorff, A. O'Hare, P. Nightingale, and A. Stirling. 2012. How journal rankings can suppress interdisciplinary research: A comparison between innovation studies and business & management. *Research Policy* 41 (7): 1262–82.
Revoredo-Giha, Cesar, Chrysa Lamprinopoulou, Philip Leat, Beata Kupiec-Teahan, Luiza Toma, and Luca Cacciolatti. 2011. How differentiated is Scottish beef? An analysis of supermarket data. *Journal of Food Products Marketing* 17 (2–3): 183–210.
Rosli, A., and L. Cacciolatti. 2022. The role of universities in the development of the local knowledge base: Supporting innovation ecosystems through skills development and entrepreneurship. *International Journal of Intellectual Property Management* 12 (1): 64–87.
Roy, J., and S. Pal. 2009. Lifestyles and climate change: Link awaiting activation. *Current Opinion in Environmental Sustainability* 1 (2): 192–200.
Schotter, A. 1981. *The economic theory of social institutions*. Cambridge: Cambridge University Press.
Schweizer-Ries, P. 2008. Energy sustainable communities: Environmental psychological investigations. *Energy Policy* 36 (11): 4126–35.
Scimago. 2023. *Journals Ranking*. Scimago, https://www.scimagojr.com/journalrank.php. Accessed 12 Aug 2023.
Sen, A.K. 1985. *Commodities and capabilities*. Oxford: Oxford University Press.
Sen, A.K., J.E. Stiglitz, and J.-P. Fitoussi. 2010. *Mismeasuring our lives: why GDP doesn't add up: the report*. New York: New Press.
Shahbaz, M., M.A. Nasir, E. Hille, and M.K. Mahalik. 2020. UK's net-zero carbon emissions target: Investigating the potential role of economic growth, financial development, and R&D expenditures based on historical data (1870–2017). *Technological Forecasting and Social Change* 161: 120255.
Steensma, H.K., L. Marino, and P.H. Dickson. 2000. The influence of national culture on the formation of technology alliances by entrepreneurial firms. *Academy of Management Journal* 45 (2): 951–73.
Stinchfield, B.T., R.E. Nelson, and M.S. Wood. 2013. Learning from Levi-Strauss' legacy: art, craft, engineering, bricolage, and brokerage in entrepreneurship. *Entrepreneurship Theory & Practice* 37 (4): 889–921.
Taras, V., P. Steel, and M. Stackhouse. 2023. A comparative evaluation of seven instruments for measuring values comprising Hofstede's model of culture. *Journal of World Business* 58 (1): 101386.
Tether, B.S., and A. Tajar. 2008. Beyond industry–university links: Sourcing knowledge for innovation from consultants, private research organisations and the public science-base. *Research Policy* 37 (6–7): 1079–95.
Turner, S.D. 2014. Mundane theorizing, bricolage, and bildung. In *Theorizing in social science: The context of discovery*, ed. R. Swedberg. Princeton University Press: Princeton.
Ullah, S., H. Agyei-Boapeah, J.R. Kim, and A. Nasim. 2022. Does national culture matter for environmental innovation? A study of emerging economies. *Technological Forecasting and Social Change* 181: 121755.
Vallas, S.P., and D.L. Kleinman. 2008. Contradiction, convergence and the knowledge economy: The confluence of academic and commercial biotechnology. *Socio-Economic Review* 6 (2): 283–311.
van Everdingen, Y., and E. Waarts. 2003. The effect of national culture on the adoption of innovations. *Marketing Letters* 14 (3): 217–32.

Wang, H., T. Guo, and Q. Tang. 2021. The effect of national culture on corporate green proactivity. *Journal of Business Research* 131: 140–50.
WMO. 2018. *Greenhouse gas levels in atmosphere reach new record*. Press release no. 22112018. https://public.wmo.int/en/media/press-release/greenhouse-gas-levels-atmosphere-reach-new-record.
World Bank. 2018. *Countries and Economies*. The World Bank: IBRD-IDA, http://data.worldbank.org/country. Accessed 15 Oct 2018.
World Bank. 2023. *Countries and Economies*. The World Bank: IBRD-IDA, http://data.worldbank.org/country. Accessed 26 Oct 2023.
Xiang, T., T.H. Malik, J.W. Hou, and J. Ma. 2022. The impact of climate change on agricultural total factor productivity: A cross-country panel data analysis, 1961–2013. *Agriculture* 12 (12): 2123.
York, J.G., and S. Venkataraman. 2010. The entrepreneur–environment nexus: Uncertainty, innovation, and allocation. *Journal of Business Venturing* 25 (5): 449–63.
Zyphur, M. J., Voelkle, M. C., Tay, L., Allison, P. D., Preacher, K. J., Zhang, Z., ... and Diener, E. 2020. From data to causes II: Comparing approaches to panel data analysis. *Organizational Research Methods* 23(4):688–716.
Zhao, S. L., Cacciolatti, L., Lee, S. H., and Song, W. 2015. Regional collaborations and indigenous innovation capabilities in China: A multivariate method for the analysis of regional innovation systems. *Technological Forecasting and Social Change* 94: 202–220.

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