



Endangering just sustainabilities: An IPD meta-analysis on the social stratification of youth environmental attitudes in 65 countries

Marcus Pietsch^{a,b,*}, Nurullah Eryilmaz^{a,c}, Rolf Strietholt^c, Ronny Scherer^d,
Matheus Monteiro Nascimento^{a,e}, Simone Abels^{a,e}, Daniel Fischer^{a,e}

^a School of Education, Leuphana University, Germany

^b School of Management & Technology, Leuphana University, Germany

^c Research and Analysis Unit, International Association for the Evaluation of Educational Achievement, Germany

^d Centre for Educational Measurement (CEMO), University of Oslo, Norway

^e School of Sustainability, Leuphana University, Germany

ABSTRACT

This study examines global socioeconomic inequality in environmental attitudes among young people. Using novel data from an international study of nearly 700,000 individuals across 65 countries, we combine a two-stage individual participant data (IPD) meta-analysis with a machine learning (Meta-CART) approach to examine cross-national variation in inequality in environmental attitudes and its associations with the macrostructural dimensions of capacity, distribution, and institutional openness. Higher socioeconomic status (SES) is consistently associated with stronger environmental preservation attitudes in both primary and secondary school. However, the strength of this relationship varies across countries. Revealing a structural paradox, press freedom and gross domestic product (GDP) interact to moderate SES disparities: the largest gaps appear in nations with both high institutional openness and affluence. Contrary to expectations, human development (HDI) and academic freedom do not exert consistent effects. The results suggest that national conditions shape the social distribution of environmental attitudes and that institutional enablers of knowledge may reinforce environmental engagement among advantaged youth, challenging the equity aspirations of sustainability education.

1. Introduction

Environmental attitudes are widely recognized as foundational to the development and maintenance of environmentally responsible behaviour, serving as key predictors of pro-environmental action across age groups and cultural contexts (Hines et al., 1987; Morren & Grinstein, 2016). These attitudes begin to form in childhood and adolescence, shaped by multiple socializing agents such as family, school, and broader cultural norms (Wray-Lake et al., 2010). In particular, the bio-centric dimension of environmental values—often referred to as environmental preservation—reflects an individual's commitment (or lack thereof) to protecting nature and mitigating climate change (Wiseman & Bogner, 2003). It represents a psychological disposition that directly affects individuals' behaviour, particularly in the actions people take—or avoid—in relation to preserving the Earth's climate and natural environment (Baierl et al., 2022).

In this regard, scholars frequently use the term environmental concern as an umbrella construct. Environmental concern can be conceptualized as comprising three dimensions: the cognitive

recognition that the environment is endangered by human activities, the affective reaction that finds environmental destruction threatening, and the conative willingness to contribute to environmental protection (Dunlap & Jones, 2002; Franzen & Bahr, 2024). While environmental concern is sometimes defined narrowly as worry about, or perceived seriousness of, environmental problems, it has also been used to denote broader evaluative orientations and value-based attitudes toward the environment (Fransson & Gärling, 1999). Environmental attitudes, in turn, can be defined both as the intensity of positive or negative affect about a particular environmental topic and as a hierarchical attitude system that connects and organizes more specific attitudes about a range of environmental topics (Cruz & Manata, 2020; Milfont & Duckitt, 2010). Environmental attitudes are multidimensional and can be organized hierarchically. One major higher-order dimension is 'preservation', reflecting endorsement of protecting nature for its own sake (Milfont & Duckitt, 2010; Wiseman & Bogner, 2003).

The complex interplay between individual environmental attitudes and broader socioeconomic conditions contributes to persistent cross-national disparities in climate concern—a manifestation of

* Corresponding author. School of Education, Leuphana University, Germany.
E-mail address: marcus.pietsch@leuphana.de (M. Pietsch).

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environmental inequality, challenging the notion of just sustainabilities (Agyeman, 2013). At the individual level, pro-environmental attitudes are often shaped by socioeconomic status (SES), yet this association is not consistent across contexts (Aral & López-Sintas, 2022). The affluence hypothesis posits that wealthier individuals and nations exhibit stronger environmental concern (Diekmann & Franzen, 1999), but empirical findings remain mixed: while several studies report positive associations, particularly for general climate concern (Kim & Wolinsky-Nahmias, 2014; Lo & Chow, 2015), others find inverse (Knight & Messer, 2012) or nonsignificant (Kvaløy et al., 2012) relationships, especially when concern is framed around climate impacts.

These inconsistencies may stem from heterogeneity in research design, nonrepresentative samples, outcome measures, and sociocultural heterogeneous national contexts, including variations in how environmental concern is conceptualized. For instance, economic resources may enhance perceived responsibility to act (Drews & Van den Bergh, 2016), but residents in wealthier countries may face fewer visible climate threats in daily life (Kim & Wolinsky-Nahmias, 2014).

While much of the cross-national literature on environmental attitudes has focused on adult populations, research on children and adolescents suggests that the formation of environmental attitudes follows a distinct developmental trajectory with important implications for the present study. In a longitudinal study, Otto et al. (2019) showed that reliable measures of both environmental attitudes and behaviour emerge by the age of seven, rise until about an age of ten, stabilise through early adolescence, and decline thereafter into late adolescence. Wang et al. (2022) established causal evidence that educational attainment increases both pro-environmental attitudes and behaviours, with environmental knowledge acquisition serving as the primary mediating channel. Liu and Green (2024), in a systematic review of children's pro-environmental behaviour, confirmed that environmental education is the most frequently identified external factor shaping children's environmental engagement, while attitudes and values constitute the most investigated internal factors.

Although environmental attitudes are often associated with pro-environmental behaviour, prior research suggests that this relationship is shaped by family, peer, and educational contexts. Family socialization, particularly parental modelling of pro-environmental behaviour rather than verbal instruction, plays a strong influence on adolescents' environmental orientations (Grønhøj & Thøgersen, 2017; Evans et al., 2018), and socioeconomic background has been shown to produce larger effect sizes on secondary students' environmental attitudes than school-level environmental education policies (Mónus, 2022). Among adolescents, environmental concern is also shaped by interpersonal influences, such as family and peers (Stevenson et al., 2019). Together, these patterns highlight the need for nuanced, large-scale analyses that can detect nonlinearities, account for multilevel interactions, and clarify when and where environmental attitudes toward preservation become stratified. However, large-scale international studies simultaneously investigating both between- and within-country differences alongside moderating factors are lacking, and it remains unclear whether schools can effectively help close the environmental preservation gap in student attitudes.

Given the fragmented nature of existing findings, meta-analyses offer a powerful tool for synthesizing results across diverse contexts and uncovering consistent patterns in environmental attitudes and behaviors (Hurst et al., 2013; Maki et al., 2019). In particular, individual participant data (IPD) meta-analyses are increasingly recognized as the gold standard for evidence synthesis, enabling greater precision, flexibility, and comparability across heterogeneous samples (Stewart et al., 2015).

A two-stage IPD meta-analysis based on complex sample designs offers a robust and flexible framework for assessing the consistency of findings across diverse educational and national settings (Brunner et al., 2023; Campos et al., 2023). When combined with meta-analytical machine learning (ML) methods (Li et al., 2020), this approach enables the detection of interaction and nonlinear effects, supports data-driven

theory validation (Leavitt et al., 2021), and extends the explanatory power of existing models and assumptions (Pietsch et al., 2025).

Addressing these gaps, this study systematically investigates global inequalities in student environmental attitudes using Trends in International Mathematics and Science Study (TIMSS) 2023 data from nearly 700,000 students across 65 countries. We focus on students' environmental attitudes toward preservation as assessed by the TIMSS "Value Environmental Preservation" scale. We draw on prior cross-national work on "environmental concern" and affluence because much of that evidence is based on closely related evaluative measures, but we use the more specific and theoretically grounded concept of preservation attitudes. In this study, students' socioeconomic status (SES) is operationalized using the number of books at home, a widely used proxy for family cultural and educational resources in international large-scale assessments (Hept et al., 2022). Employing a two-stage individual participant data (IPD) meta-analysis, we first test the association between SES and pro-environmental attitudes. We then use meta-regression and machine learning techniques to examine how national and cultural factors moderate this relationship and interact to shape the social stratification of environmental attitudes among youth.

2. Theoretical framework

Understanding why socioeconomic status relates to environmental attitudes, and why this relationship varies across national contexts, requires an integrative framework connecting individual-level stratification to macro-structural conditions. The literature is organized around two competing hypotheses: the affluence hypothesis, which posits that material security enables environmental concern, and the environmental degradation hypothesis, which holds that exposure to ecological harm drives concern regardless of wealth (Brechin & Kempton, 1994; Inglehart, 1995). These perspectives have generated inconsistent findings, partly because they address different dimensions of environmental concern, partly because they neglect the institutional conditions under which wealth translates into attitudes, and partly because the boundaries among environmental attitudes, concern, and behaviour are frequently blurred (Dunlap & York, 2008; Givens & Jorgenson, 2011; Pohjolainen et al., 2024).

The most influential account linking prosperity to environmental attitudes is Inglehart's (1990, 1995, 2015) postmaterialist values theory, which argues that cohorts raised in material security shift toward postmaterialist concerns including environmental protection. Diekmann and Franzen (1999) advanced a complementary prosperity hypothesis grounded in economic reasoning, conceptualizing environmental quality as a normal good for which demand rises with income. Using ISSP data, Franzen and Meyer (2010) and Franzen and Vogl (2013) demonstrated strong positive correlations between GDP per capita and environmental concern across 33 countries. However, Brechin and Kempton (1994) documented widespread concern in developing nations, and Dunlap and York (2008) found that affluence correlated inconsistently with concern when appropriate measures were used, concluding that environmentalism has become a globalized phenomenon. Inglehart's objective problems–subjective values framework, which attributed concern in poorer nations to degradation exposure, was criticized by Brechin (1999) as unfalsifiable. Givens and Jorgenson (2011), employing multilevel regression across 38 nations, found that higher GDP was associated with lower pro-environmental concern, while economic growth and CO₂ increases predicted greater concern, directly contradicting the affluence hypothesis and suggesting that the SES–attitude link operates differently depending on national structural conditions.

A third perspective proposes nonlinear relationships. The Environmental Kuznets Curve (Grossman & Krueger, 1991), originally describing an inverted U-shape between growth and pollution, has been extended to attitudinal outcomes. Duroy (2008) found a U-shaped relationship between GDP and environmental behaviour across 35 nations, with income inequality, education, and subjective well-being also

playing significant roles. Shobande and Ogbeifun (2023), using the STIRPAT framework, similarly demonstrated that affluence–environment relationships are not monotonic but depend on technological and structural characteristics. These curvilinear findings inform our decision to test quadratic moderating effects.

A further source of inconsistency stems from conceptual differences across studies. Dunlap and Jones (2002) noted that environmental concern encompasses awareness, attitudes, intentions, and behaviour, yet these are frequently conflated. Environmental attitudes represent evaluative dispositions toward the natural environment (Milfont & Duckitt, 2010), of which the Two Major Environmental Values model (Bogner & Wiseman, 1999, 2006) employed in TIMSS distinguishes preservation from utilization. Environmental concern refers more broadly to perceived seriousness of problems and motivation to address them (Schultz, 2001), while environmental behaviour involves actual actions (Stern, 2000), with meta-analyses reporting only moderate attitude–behaviour correlations (Hines et al., 1987), positioning the present study explicitly within the attitudinal rather than behavioral dimension of environmental orientation.

To reconcile the conflicting predictions of the affluence and environmental degradation hypotheses, we must recognize that national wealth alone is an insufficient mechanism for translating individual socioeconomic status into environmental attitudes (Givens & Jorgenson, 2011). We selected three theoretically distinct dimensions, namely capacity, distribution, and institutional openness in the form of freedom of information and inquiry, because they capture the crucial macrostructural pathways through which individual socioeconomic status is either activated or constrained (Pampel, 2014; Wang, 2025).

First, economic development and human capabilities provide the foundational material and educational infrastructure required for post-materialist values to emerge (Inglehart, 1995). National affluence and structural development furnish the cognitive resources and security that allow individuals with high socioeconomic status to prioritize ecological concerns over immediate material needs, explaining why wealth can amplify the individual status effect (Pampel, 2014; Pohjolainen et al., 2024).

Second, social stratification determines whether this wealth is broadly shared. We focus on income inequality because high stratification fosters status competition and economic insecurity, which effectively dampens the postmaterialist shift even in wealthy nations and suppresses the protective effect of individual privilege on environmental concern (Wang, 2025).

Finally, the environmental degradation hypothesis inherently assumes that citizens are aware of ecological harm (Brechtin, 1999). However, objective degradation more strongly translates into subjective concern if information flows freely (Martínez-Zarzoso & Phillips, 2020). Thus, institutional openness, which guarantees the free flow of ideas and reliable information, acts as a critical boundary condition (Carayannis et al., 2021; Uzar, 2024). Specifically, the environmental democracy literature posits that civil liberties and unrestricted information flows provide the necessary civic space for citizens to become accurately informed about ecological threats, mobilize collectively, and hold governments accountable (Bättig & Bernauer, 2009; Neumayer, 2002). Consequently, without press and academic freedom, even privileged individuals lack the reliable information and civic space necessary to formulate preservation attitudes and hold institutions accountable (Barrett & Graddy, 2000).

Regarding economic development, GDP provides a narrow measure of national output, while HDI incorporates education and health, capturing broader capabilities enabling cognitive and political engagement with environmental issues (UNDP, 2022). Pampel (2014) showed that the SES–concern relationship is stronger in higher-HDI nations, and Pohjolainen et al. (2024) confirmed that national affluence strengthens the link between perceived climate responsibility and both policy support and personal action. Including both GDP and HDI allows us to disentangle economic output from broader developmental conditions.

Income inequality may fundamentally alter how SES relates to environmental attitudes. The postmaterialist framework implicitly assumes broadly shared growth; when growth accrues disproportionately to elites, the predicted values shift may not materialize. Boyce (1994) theorized that inequality increases degradation by concentrating political power among beneficiaries of harmful activities. Duroy (2008) found negative associations between the Gini coefficient and environmental action, and Wilkinson and Pickett (2024) showed that more equal societies exhibit 10–20 percentage points greater support for environmental protection. We conceptualize inequality as a contextual moderator of the individual-level SES–attitude association: the country-level Gini coefficient conditions the within-country SES slope. Our IPD meta-analytic design captures precisely this cross-level interaction, consistent with the analytical logic applied to all moderators.

Press freedom and academic freedom constitute institutional enablers shaping how effectively environmental knowledge reaches the public. Barrett and Graddy (2000) provided foundational evidence that civil freedoms improve environmental quality through media accountability. Uzar (2022) shows that press freedom significantly reduces CO₂ emissions in emerging economies, and Martínez-Zarzoso and Phillips (2020) confirm that open media increase transparency and governmental responsiveness to environmental challenges. Pohjolainen et al. (2024) found that democracy strengthens the link between climate concern and perceived responsibility. For higher-SES students with greater capacity to access and process environmental information, a free press may amplify the translation of socioeconomic advantage into awareness, while restricted media may suppress this pathway.

Academic freedom operates through a complementary but distinct mechanism affecting the production, validation, and diffusion of environmental knowledge within educational institutions. Research in science communication shows that science and media function as separate subsystems with different levels of source credibility and public trust (Brewer & Ley, 2013). The V-Dem Academic Freedom Index (Spannagel & Kinzelbach, 2023) now enables systematic cross-national examination of this channel. Drawing on the Triple-Helix model (Etzkowitz & Leydesdorff, 2000), we view universities as key nodes linking science, government, and industry; their capacity to contribute to public deliberation depends on protections for free inquiry. When academic freedom erodes, politically sensitive research is curtailed and curricular pluralism narrows (Altbach, 2001). In countries with strong academic freedom, universities may equalize access to environmental knowledge across socioeconomic strata through curricula, outreach, and teacher training, thereby attenuating the SES gradient in attitudes.

In summary, the theoretical framework underlying this study moves beyond the binary affluence-versus-degradation debate by positioning the SES–environmental attitude link within a multilayered structural context. Individual socioeconomic advantage may facilitate pro-environmental attitudes, consistent with both the postmaterialist and the prosperity hypotheses, but the strength of this association is shaped by national economic conditions (GDP, HDI), social stratification patterns (GINI), and institutional enablers of information and knowledge (press freedom, academic freedom). The Environmental Concern Kuznets Curve further suggests that some of these moderating effects may be nonlinear. This integrated framework motivates the specific hypotheses tested in the present study.

3. Hypotheses

In the present study, we used a novel database that includes survey data on pro-environmental attitudes along with detailed information on students' SES. Specifically, we used data from the Trends in International Mathematics and Science Study (TIMSS) from 2023. While TIMSS has been administered every four years since 1995, the latest cycle in 2023 included a new sustainability module, featuring a scale measuring pro-environmental attitudes (Reynolds & Komakhidze, 2022). TIMSS draws nationally representative random samples of students in Grade 4

($N = 389,097$) and Grade 8 ($N = 309,251$) across a total of 65 countries. This uniquely large and diverse sample provides a robust foundation for examining the global landscape of socio-environmental inequalities (von Davier et al., 2024). To test ten theoretically grounded hypotheses, we applied a two-stage individual participant data (IPD) meta-analysis to replicate the analyses across countries. We used both linear and nonlinear meta-regressions, as well as meta-analytical ML techniques, to investigate how individual-level SES interacts with national-level contextual factors in shaping students' environmental attitudes.

H1. Higher SES predicts stronger pro-environmental attitudes.

According to the affluence hypothesis, individuals with greater socioeconomic resources are more likely to express pro-environmental attitudes, as material security allows them to prioritize long-term and collective concerns, such as environmental protection (Diekmann & Franzen, 1999; Franzen & Meyer, 2010). In the educational context, SES has been shown to correlate positively with both environmental concern and behavioral engagement, particularly among adolescents (Bucht et al., 2024). Students from higher SES backgrounds often benefit from more supportive learning environments, greater access to environmental education, and stronger affective-motivational orientations toward sustainability (Mónus, 2022). Accordingly, we hypothesize that students' socioeconomic status will be positively associated with their attitudes toward environmental preservation.

H2. The SES–environmental attitude link is stronger in primary than in secondary education.

Educational effectiveness research suggests that schools play a dual role: enhancing learning outcomes and mitigating the impact of socioeconomic disadvantage (Kyriakides et al., 2018). While the family serves as the primary developmental environment for children, especially in their early years, its influence tends to decrease over time, as school increasingly becomes the central context for learning and development. From a developmental perspective, this implies that younger students' environmental attitudes are more strongly shaped by parental SES, whereas older students are more influenced by formal education and peer environments (Coertjens et al., 2010). Studies in environmental education further suggest that age moderates how students internalize ecological values, with younger children being more susceptible to SES-driven differences in opportunity and exposure (Liefänder & Bogner, 2014). Accordingly, we hypothesize that the SES–environmental attitude association will be stronger in Grade 4 than in Grade 8.

H3. Nonlinear moderator effects explain SES–environmental attitude differences better than linear models alone.

The relationship between SES and environmental concern may be shaped by national-level moderators, such as wealth, press freedom, or inequality. However, these moderating effects may be nonlinear. The environmental Kuznets curve suggests that environmental concern initially rises with affluence, then plateaus or declines beyond a certain threshold (Grossman & Krueger, 1991; Panayotou, 1993). Similarly, the influence of institutional and cultural factors may exhibit diminishing or threshold effects rather than linear change. As such, relying solely on linear assumptions may obscure important variation in how structural conditions shape SES-based attitudinal gaps (Martínez-Zarzoso & Phillips, 2020). We also acknowledge that some of the cross-national evidence for nonlinear relationships between development and environmental orientations derives from behavioral measures (Duroy, 2008) and individual-level concern indicators (Franzen & Meyer, 2010) rather than from the preservation attitudes examined in the present study. While these constructs are conceptually distinct, the convergence of curvilinear findings across different operationalizations and levels of analysis suggests that the nonlinear pattern is not an artifact of a single measurement approach. We therefore hypothesize that meta-regression models incorporating nonlinear moderator effects will better explain

variation in the SES–environmental attitude relationship than models restricted to linear terms.

H4. The SES–environmental attitude association varies across countries.

While SES is often associated with pro-environmental concern, the strength and direction of this relationship are not universal. Theories of ecological modernization and postmaterialism suggest that national context—such as economic development, institutional capacity, or cultural values—can moderate how individual SES translates into environmental concern (Buttel, 1992; Inglehart, 2015). For instance, while postmaterialist theories suggest increasing affluence fosters pro-environmental values, recent research indicates that contextual inequality substantially attenuates the positive effects of both higher SES and postmaterialist values on environmental concern (Wang, 2025). This holds true even in affluent or democratic societies, as inequality can diminish the prioritization of environmental conservation, raise the costs of pro-environmental behaviour for low-SES groups, and foster values of self-enhancement and status competition. Drawing on a contextualist perspective, we hypothesize that the relationship between student SES and environmental attitudes will vary significantly across countries.

H5. National gross domestic product (GDP) strengthens the SES–environmental attitude association.

According to the environmental degradation hypothesis, individuals in lower-income countries—particularly those from disadvantaged backgrounds—are more likely to experience environmental harms directly (Brechtin & Kempton, 1994). Yet paradoxically, this does not always translate into greater environmental concern. In contrast, residents of wealthier countries often exhibit higher environmental concern, despite experiencing fewer tangible risks. Prior research suggests that national affluence can amplify the influence of individual-level SES by enabling access to environmental education, civic infrastructure, and green consumption opportunities (Franzen & Vogl, 2013; Mohai et al., 2009). In this view, pro-environmental attitudes are more likely to reflect postmaterialist values in high-GDP settings, where personal security allows individuals—particularly those with higher SES—to prioritize long-term environmental outcomes. We therefore hypothesize that national GDP strengthens the relationship between student SES and environmental attitudes.

H6. National Human Development Index (HDI) strengthens the SES–environmental attitude association.

The Human Development Index (HDI) captures broader dimensions of societal well-being beyond economic wealth, including education and health. According to the environmental degradation hypothesis, residents of more developed countries are more willing to make personal sacrifices for environmental protection (Ambasz et al., 2023; Haller & Hadler, 2008). However, this willingness varies within countries, with individuals of higher SES more likely to hold strong pro-environmental attitudes and behaviors (Pampel, 2014). This pattern is often attributed to unequal access to high-quality education, which shapes environmental awareness and engagement (Ambasz et al., 2023). In contexts with higher HDI, the educational system may amplify the advantages of SES, strengthening the attitudinal divide between more and less privileged students. We therefore hypothesize that national HDI moderates the SES environmental attitude relationship, such that the association becomes stronger in countries with higher levels of human development.

H7. National income inequality (GINI) weakens the SES–environmental attitude association.

The postmaterialist hypothesis suggests that in societies marked by high inequality, status competition and economic insecurity may reduce individuals' capacity—and willingness—to prioritize environmental concerns. Under such conditions, materialist priorities often override

collective environmental values, dampening the attitudinal influence of socioeconomic status (Qiao & Dowell, 2022). Empirical studies have shown that income inequality is negatively associated with pro-environmental concern and behaviour at the national level (Aral & López-Sintas, 2022). In these contexts, high-SES individuals may be less inclined to express environmental concern if their social advantage is perceived as fragile or contested. We therefore hypothesize that national income inequality, as measured by the GINI index, attenuates the relationship between student SES and pro-environmental attitudes.

H8. Press freedom (WPFI) strengthens the SES–environmental attitude association.

According to the extended degradation hypothesis, the extent to which rising income and social status translate into environmental concern depends on individuals' access to information and capacity to express their preferences (Martínez-Zarzoso & Phillips, 2020). Press freedom enhances both: it increases public awareness of environmental issues through media coverage and strengthens civic channels for environmental discourse. In societies with limited press freedom, even high-SES individuals may lack sufficient exposure to environmental reporting or the means to advocate for ecological policies (Barrett & Graddy, 2000; Martínez-Zarzoso & Phillips, 2020). We therefore hypothesize that greater press freedom strengthens the relationship between student SES and pro-environmental attitudes.

H9. Academic freedom (AFI) weakens the SES–environmental attitude association.

The triple helix model posits that academic institutions play a central role in advancing societal innovation by fostering collaboration across universities, industry, and governments (Posso & Zhang, 2023). When academic freedom is strong, universities are better positioned to conduct socially responsive research, develop inclusive curricula, and cultivate critical thinking—particularly in domains such as sustainability and environmental justice (Posso & Zhang, 2023; Rao et al., 2023). Such environments may reduce the reproduction of social privilege in environmental attitudes, enabling lower-SES students to engage meaningfully with sustainability issues. We therefore hypothesize that greater academic freedom attenuates the relationship between student SES and environmental attitudes.

H10. GDP, HDI, GINI, WPFI, and AFI interact to jointly moderate the SES–environmental attitude association.

The preceding hypotheses examine each macro-level indicator as an individual moderator of the SES–environmental attitude link. However, these structural conditions rarely operate in isolation. Prior research suggests that contextual factors such as wealth, human development, inequality, and institutional openness interact in complex, often nonlinear ways to shape civic engagement and environmental concern (Barrett & Graddy, 2000; Franzen & Meyer, 2010; Kim & Wolinsky-Nahmias, 2014; Martínez-Zarzoso & Phillips, 2020). For example, the influence of national wealth may depend on the level of press or academic freedom, and the impact of inequality may vary with access to education or democratic institutions. Traditional regression frameworks often struggle to detect such high-order interactions. To address this, we apply an ML-based meta-analytical approach capable of identifying combinatorial patterns across macro-level moderators. We hypothesize that interactions among GDP, HDI, GINI, press freedom (WPFI), and academic freedom (AFI) jointly moderate the association between student SES and environmental attitudes.

4. Methods

4.1. Data sources and sample

This study utilized student questionnaire data from the 2023 cycle of the IEA's Trends in International Mathematics and Science Study

(TIMSS), that can be found at <https://timss2023.org/data/>. TIMSS 2023 was conducted under national and international ethical review process. We analyzed data from both Grade 4 and Grade 8, in TIMSS, Grade 4 students are typically around 9–10 years old and Grade 8 students around 13–14 years old, although exact ages may vary slightly across countries depending on national school entry regulations, covering environmental attitudes and socioeconomic status (SES) from a total of 698,348 students in 21,916 schools across 65 countries. The dataset provides representative cross-national coverage of education systems and social conditions.

4.2. Measures

Dependent variable: Students' environmental attitudes were measured using the Students Value Environmental Preservation scale (ASBGVEP for Grade 4; BSBGVEP for Grade 8), which captures agreement with six items in grade 8 and five items in grade 4 reflecting concern for nature and the importance of protecting the environment.

The TIMSS 2023 assessment of environmental attitudes utilizes the two-dimensional Model of Ecological Values, which is grounded in the Theory of Ecological Attitude (Bogner & Wiseman, 1999, 2006; Wiseman & Bogner, 2003). Within this framework, our study examines students' attitudes toward environmental preservation: "an individual's endorsement of the conservation and protection of nature" (Reynolds & Komakhidze, 2022, p. 3). An example item is: „I care about the protection of plants and animals“. Items could be answered on a 4-point Likert-type scale ranging from „disagree a lot“ to „agree a lot“.

Socioeconomic status (SES): The number of books at home (ASBG04/BSBG04) served as a proxy for SES. The variable was dichotomized into low (<100 books) and high (≥100 books) SES categories, following established thresholds in international large-scale assessments (Evans et al., 2010; OECD, 2019).

4.3. Country-level moderators

The following national-level indicators were included:

The Human Development Index (HDI) measures a country's development based on life expectancy and access to education, indicated by the expected years of schooling of children at school-entry age and mean years of schooling of the adult population, as well as gross national income per capita adjusted for the price level of the country. The data are provided by the United Nations Development Program (<https://hdr.undp.org/en/data/>); we used values for 2023.

Gross domestic product (GDP) is the total monetary value of all the finished goods and services produced within a country's borders in a single year in US\$. The data are provided by the World Bank (<https://databank.worldbank.org/>); we used values for 2023.

The GINI index measures income or economic inequality within a country. The data are provided by the World Bank (<https://databank.worldbank.org/>); we used the values from 2023.

The World Press Freedom Index (WPFI) assesses the degree of freedom available to journalists in a given country, based on a range of indicators such as media independence, transparency, legal environment, and the safety of journalists. It is published annually by Reporters Without Borders (RSF). The index is scaled from 0 to 100, with higher values indicating greater press freedom. We used country scores from the 2023 edition of the index, available at <https://rsf.org/en/index>.

The Academic Freedom Index (AFI) measures the freedom of academic institutions and scholars to conduct research, teach, and disseminate knowledge without undue interference. It includes indicators related to institutional autonomy, freedom of academic and cultural expression, and campus integrity. The data are compiled and published by the Varieties of Democracy (V-Dem) project. We used national scores for 2023, accessible via <https://www.v-dem.net>.

4.4. Analytical strategy

4.4.1. IPD meta-analysis

We employed a two-stage individual participant data (IPD) meta-analysis approach to estimate and synthesize country-specific effects of SES on students' environmental attitudes. This method is increasingly recognized as the gold standard for evidence synthesis in education and social science research, particularly when analyzing data from complex survey designs across multiple contexts (Brunner et al., 2023; Campos et al., 2023; Viechtbauer, 2010).

Stage 1. (Within-Country Estimation): Linear regression models were fitted separately for each country and grade level to estimate the association between SES and environmental attitudes. These models accounted for the complex sampling design of TIMSS 2023 by applying student sampling weights and adjusting standard errors accordingly. This within-country estimation ensures that effect sizes are not confounded by between-country differences in sample design or measurement (von Davier et al., 2024). The within-country regression models account for the complex sampling design of TIMSS by applying student sampling weights and design-based variance estimation, which adjusts standard errors for clustering of students within schools.

Stage 2. (Between-Country Synthesis): The resulting country-level regression coefficients were pooled using random-effects and mixed-effects meta-regression models via restricted maximum likelihood (REML) estimation. The five institutional features were standardized to ease the interpretation of linear and quadratic terms. To examine contextual heterogeneity, we tested the moderating effects of national-level indicators using both linear and quadratic specifications. Between-study heterogeneity was assessed using τ , I^2 statistics, and Q-tests for heterogeneity (Borenstein et al., 2009; Higgins & Thompson, 2002). Model comparisons were performed using standard information criteria—the Akaike information criterion (AIC) and the Bayesian information criterion (BIC)—as well as likelihood ratio tests to evaluate the relative fit of competing models and identify the most parsimonious specification.

4.4.2. Meta-CART analysis

To explore complex, nonlinear, and higher-order interactions among national-level moderators, we applied Meta-CART (classification and regression trees for meta-analysis). Meta-CART is a machine learning-based approach that extends conventional meta-regression by recursively partitioning studies (or countries, in our case) into subgroups with relatively homogeneous effect sizes based on combinations of moderator variables (Dusseldorp et al., 2014; Li et al., 2020). This technique enables the detection of hierarchical interaction patterns and nonlinear thresholds that would be difficult to identify using standard parametric models. The analysis was implemented using the metaCART R package, which conducts model-based recursive partitioning and uses permutation testing to determine optimal split points. Final tree structures were pruned based on cross-validation to minimize overfitting and ensure robustness of subgroup findings (Li et al., 2020).

In the present study, Meta-CART was used to identify interactions among GDP, HDI, GINI, press freedom (WPIF), and academic freedom (AFI) in moderating the association between student SES and environmental attitudes. These moderators correspond to the same set of country-level indicators examined in the meta-regression models and were selected because they capture key structural characteristics of national contexts, economic development, inequality, and institutional openness that may explain between-country heterogeneity in the SES–environmental attitude association. Moreover, complete data for these indicators was available across participating countries, which is required for recursive partitioning procedures such as Meta-CART.

Meta-CART analysis was performed under a random-effects framework, with the pruning parameter fixed at $c = 1$. All other parameters were set to their default specifications: the maximum number of

allowable splits was five; a minimum of six studies was required in a parent node before a split; the stopping criterion for the reduction in between-group heterogeneity (Q) was set to 0.00001; terminal nodes were required to contain at least three studies; and model selection was based on 10-fold cross-validation. This method is especially valuable in the context of international large-scale assessments, where complex contextual conditions may exert conditional or combinatorial influences on attitudinal outcomes (Leavitt et al., 2021; Pietsch et al., 2025).

5. Confirmatory hypothesis testing

The two main variables in the analysis are pro-environmental attitudes and SES. Pro-environmental attitudes were measured using the Students Value Environmental Preservation scale, which includes six items rated on a four-point Likert scale (Reynolds & Komakhidze, 2022). The scale captures values such as caring for nature, concern about environmental destruction, and prioritizing climate action. As a proxy for SES, we used the number of books at home, dichotomized into fewer than 100 books versus 100 books or more (Heppt et al., 2022). We tested whether students from higher-SES backgrounds report stronger environmental values and whether this association varies by grade and national context.

We tested ten hypotheses in three steps. Different analytical approaches were used because the hypotheses addressed distinct methodological questions. First, **hypotheses 1 and 2** were examined using a two-stage individual participant data (IPD) meta-analysis, which allows for estimating country-specific SES effects and assessing cross-national heterogeneity in the relationship between socioeconomic status and environmental attitudes. Second, **hypotheses 3 to 9** were examined using a joint meta-regression, in which the SES–environmental attitude association was regressed on grade level and five institutional variables (GDP, HDI, GINI, press freedom, and academic freedom), testing for both linear and nonlinear moderation effects. Including grade level as a control variable ensured that potential differences between primary and secondary education were accounted for in the moderation analyses. Third, we applied meta-analytical machine-learning techniques (Meta-CART) to explore complex interaction structures and nonlinear combinations among country-level predictors and their joint influence on the SES–environmental attitude relationship that may not be detectable using conventional parametric meta-regression models.

H1. In the first step of the IPD meta-analysis, we tested the association between students' SES—measured by the number of books at home—and their attitudes toward environmental preservation. The results showed a positive and statistically significant mean effect of SES on environmental values for both fourth-grade ($\beta = 0.08$, 95% CI [0.07, 0.10]) and eighth-grade students ($\beta = 0.07$, 95% CI [0.06, 0.09]). These findings confirm the affluence hypothesis: students from higher-SES backgrounds report stronger commitments to environmental preservation across both educational stages. The hypothesis is therefore supported.

H2. In a mixed-effects meta-regression model, we tested whether the average effect size differed between Grades 4 and 8. The analysis suggests a slightly stronger association in Grade 4; however, the difference is not statistically significant ($\beta = -0.0104$, $p = .3493$), indicating no meaningful difference between the two grade levels. The assumptions of school effectiveness research are not supported: no link between grade level and attitudes toward environmental preservation was found. The hypothesis is rejected.

H3. To test for nonlinearity, we added quadratic terms to the linear regression (Fig. 3). The model including the quadratic terms showed improved fit (AIC = -328.72 ; BIC = -308.04) compared to the linear-only model (AIC = -314.69 ; BIC = -280.66). Additionally, a likelihood ratio test indicated that the inclusion of five quadratic terms

significantly improved model fit ($\Delta\chi^2 = 14.03$, $df = 5$, $p = .016$). The model including only linear terms explained 50.47% of the observed heterogeneity (R^2), whereas the inclusion of non-linear terms increased the explained heterogeneity to 53.11%. The hypothesis of nonlinear moderator effects is supported. In the following, we examine each of the five potential moderators individually (H5–H9). We analyze each of the five potential moderators in detail.

H4. Consistent with our contextualist hypothesis, the random effect meta-analysis revealed substantial heterogeneity across 61 countries in grade 4 (Fig. 1) and 44 countries in grade 8 (Fig. 2). In primary school, the β coefficients vary with a standard deviation of $\tau = 0.059$ across countries ($Q(61) = 839.78$, $p < .0001$, $I^2 = 92.93\%$), and in grade 8, the standard deviation is $\tau = 0.047$ ($Q(44) = 490.97$, $p < .0001$, $I^2 = 90.66\%$). These findings confirm that the SES–environmental attitude

link varies significantly across national contexts, suggesting that macro-level conditions shape how social advantage translates into environmental concern. The hypothesis is supported.

H5. In the meta-regression, neither linear nor nonlinear moderation effects of GDP on the relationship between SES and students' attitudes toward environmental preservation could be identified, *ceteris paribus*. Thus, with regard to the degradation hypothesis, there is no evidence supporting a GDP effect. The hypothesis is therefore rejected.

H6. HDI was a positive moderator in the model including only linear effects ($\beta = 0.205$, $p = .044$), indicating that the association between student SES and environmental attitudes is stronger in countries with higher levels of human development; this effect was not observed when non-linear effects were included. In the nonlinear meta-regression

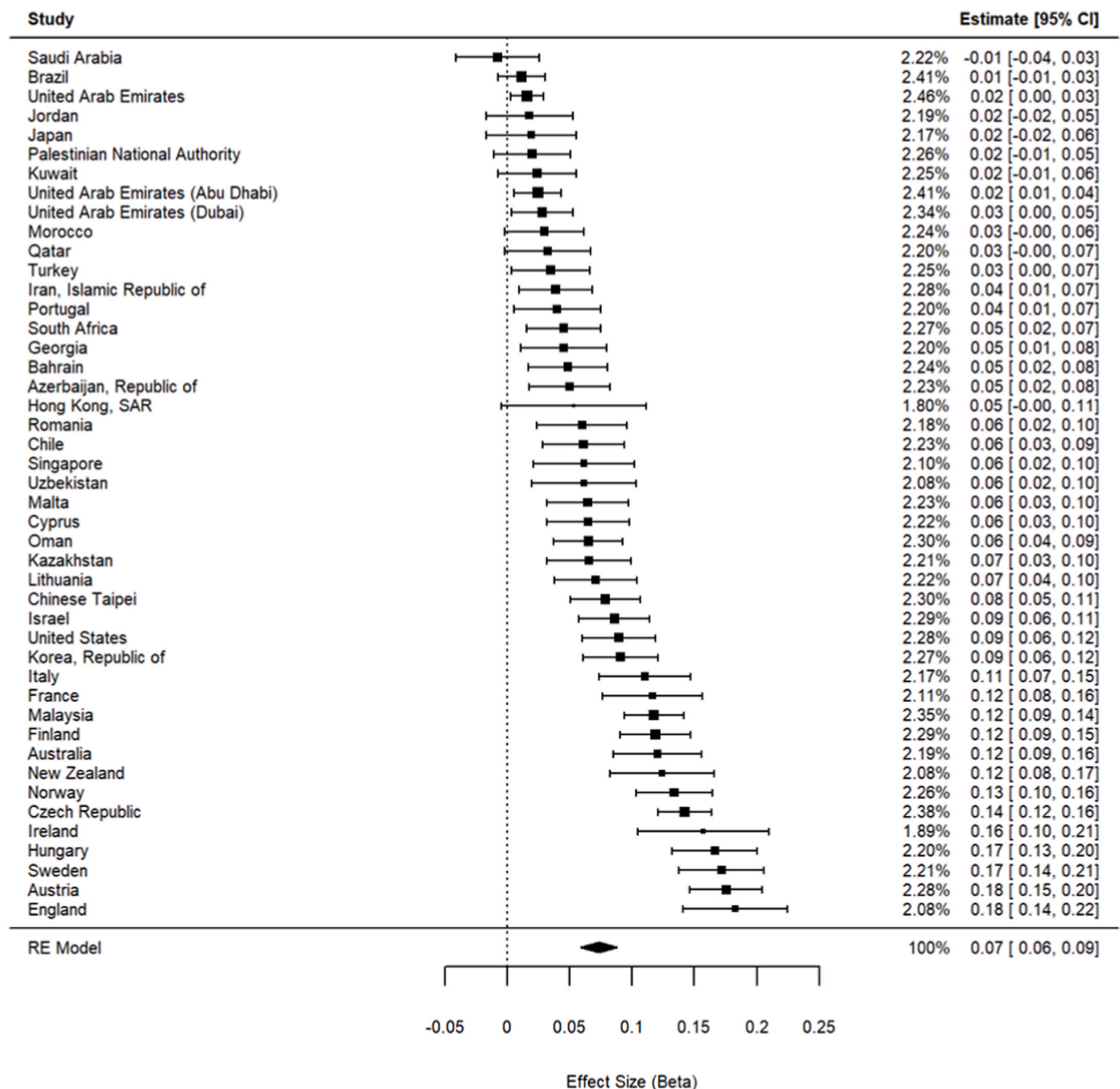


Fig. 1. Country-Specific Effects of Socioeconomic Status (SES) on Environmental Attitudes (8th Grade).

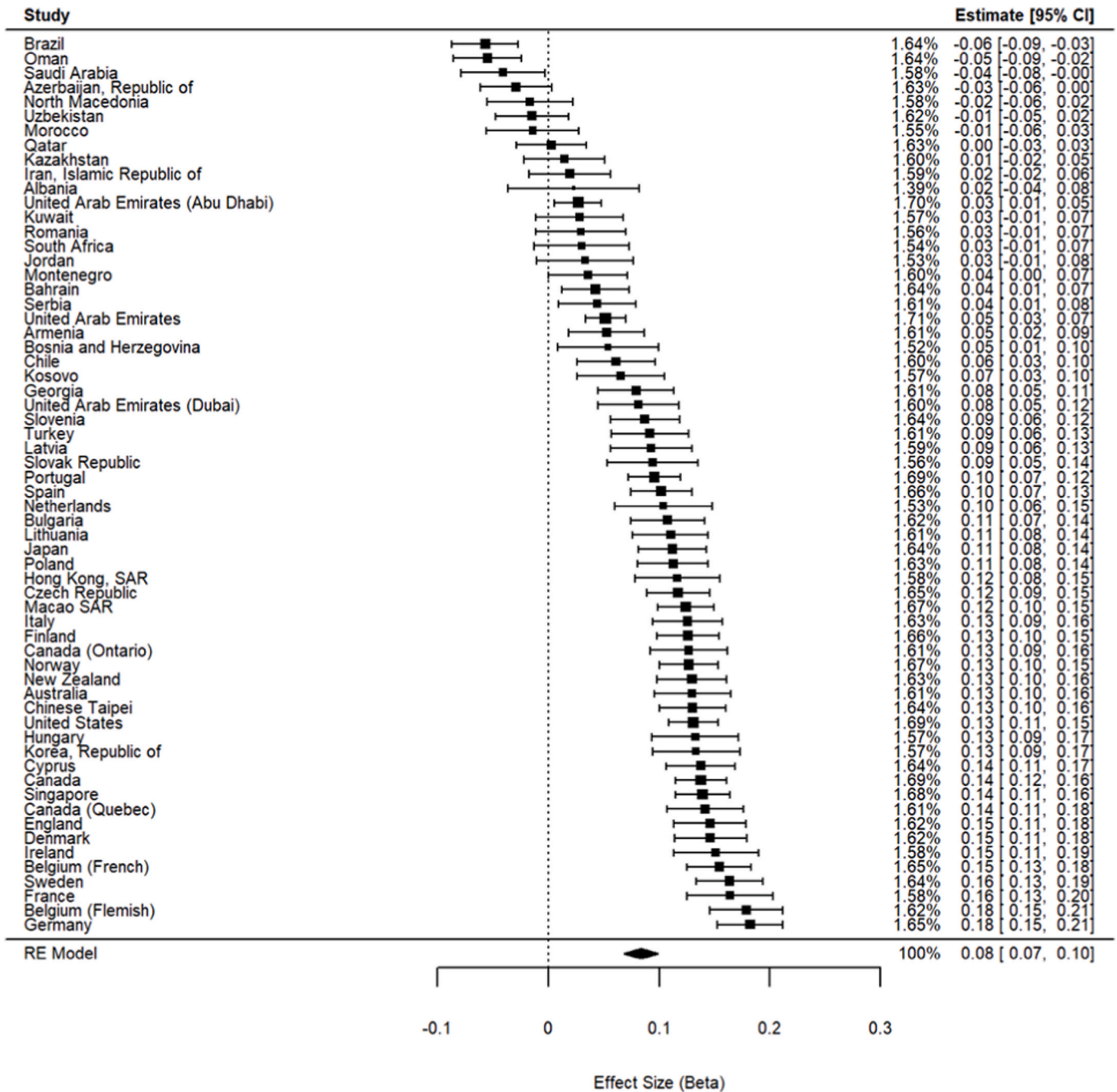


Fig. 2. Country-Specific Effects of Socioeconomic Status (SES) on Environmental Attitudes (4th Grade).

model, however, no significant association was found ($\beta = 0.0014$, $p > .10$). Thus, with regard to the HDI-related degradation hypothesis, partial support is found: HDI strengthens the relationship between SES and students' attitudes toward environmental preservation in a linear, but not in a nonlinear, manner.

H7. Income inequality in a country, measured by the GINI coefficient, is associated with a weaker relationship between SES and students' attitudes toward environmental preservation in a linear ($\beta = -0.0011$, $p = .073$), but not in a nonlinear ($\beta = -0.0025$, $p > .10$), manner, suggesting a potential weakening of the SES–environmental attitude link in more unequal societies. The linear effect was no longer observed when non-linear effects were included. The (post-)materialist hypothesis is therefore partially supported: income inequality in a country is associated with a looser association between SES and students' attitudes

toward environmental preservation in a linear, but not in a nonlinear, manner.

H8. Press freedom exerts a nonlinear ($\beta = 0.0138$, $p = .012$), but not a linear ($\beta = 0.0005$, $p > .10$), effect on the association between SES and students' environmental attitudes, suggesting that the association between SES and environmental attitudes increases more sharply in countries with either very high or very low press freedom. The extended degradation hypothesis is therefore partially supported: the relationship between SES and students' attitudes toward environmental preservation systematically varies with a country's level of press freedom, but in a nonlinear rather than a linear manner.

H9. No evidence was found for an association between academic freedom and the SES–environmental attitudes link. The assumptions of

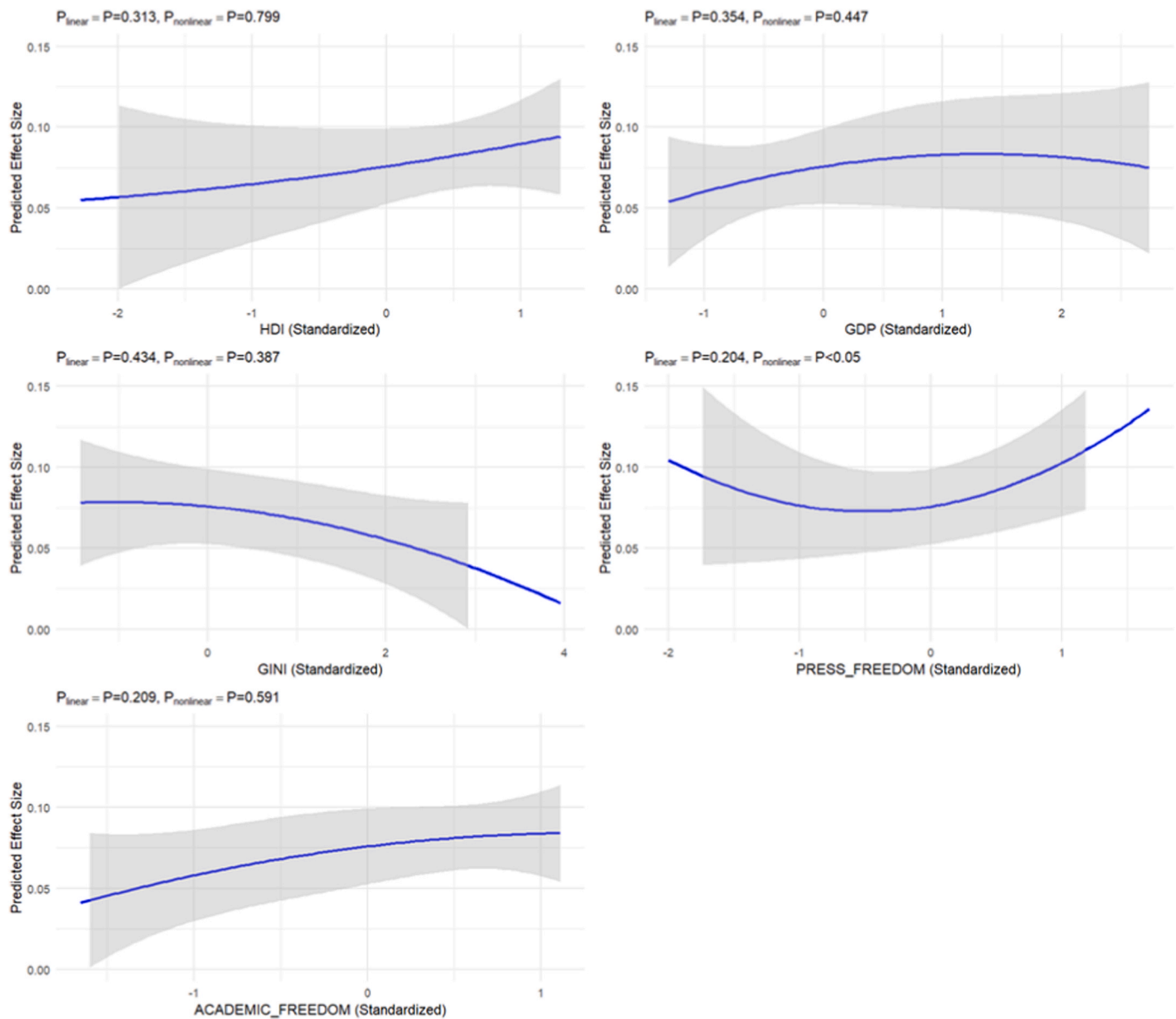


Fig. 3. Linear and Quadratic Effects of Country-Level Indicators on the SES–Environmental Attitudes Relationship.

the helix model are not supported, neither linearly nor nonlinearly. The hypothesis is rejected.

H10. In the meta-regression model excluding non-linear effects, we found significant linear effects for HDI and income inequality (GINI). However, when non-linear effects were additionally included in the meta-regression, these linear effects were no longer observed. The only effect that remained robust was the non-linear effect of press freedom. This pattern suggests that relevant moderation effects may be inherently complex and potentially driven by higher-order interactions that are not adequately captured in standard linear or additive meta-regression models. Consequently, the exploratory meta-CART ML model identified a hierarchical interaction among country-level moderators that condition the strength of the relationship between student SES and environmental attitudes (Fig. 4). The first and most decisive split was based on press freedom, with countries below the threshold of 61.69 exhibiting a modest but statistically significant effect ($\beta = 0.040$, $SE = 0.006$, $p < .001$; $K = 47$ countries). Among countries with greater press freedom, further segmentation occurred according to GDP per capita. In contexts where GDP was $\leq 36,551.42$ US\$, the SES–environmental

attitude association was stronger ($\beta = 0.085$, $SE = 0.007$, $p < .001$; $K = 29$). The largest effect was observed in countries with both high press freedom and high GDP, where SES disparities in environmental attitudes reached their peak ($\beta = 0.140$, $SE = 0.007$, $p < .001$; $K = 29$). The findings suggest that the intersection of press freedom and GDP amplifies socioeconomic stratification in attitudinal outcomes. The data-driven model suggests that, in particular, the extended degradation hypothesis can explain the relationship between students' SES and their attitudes toward environmental preservation. Our hypothesis is confirmed.

6. Discussion

This study investigated how students' socioeconomic status (SES) relates to their environmental attitudes across 65 countries, involving nearly 700,000 students. Our findings confirm a consistent positive link between higher SES and stronger environmental values, while highlighting how schooling and institutional contexts shape this relationship. This is particularly relevant for “just sustainabilities,” which emphasizes equity in environmental transitions (Agyeman, 2013).

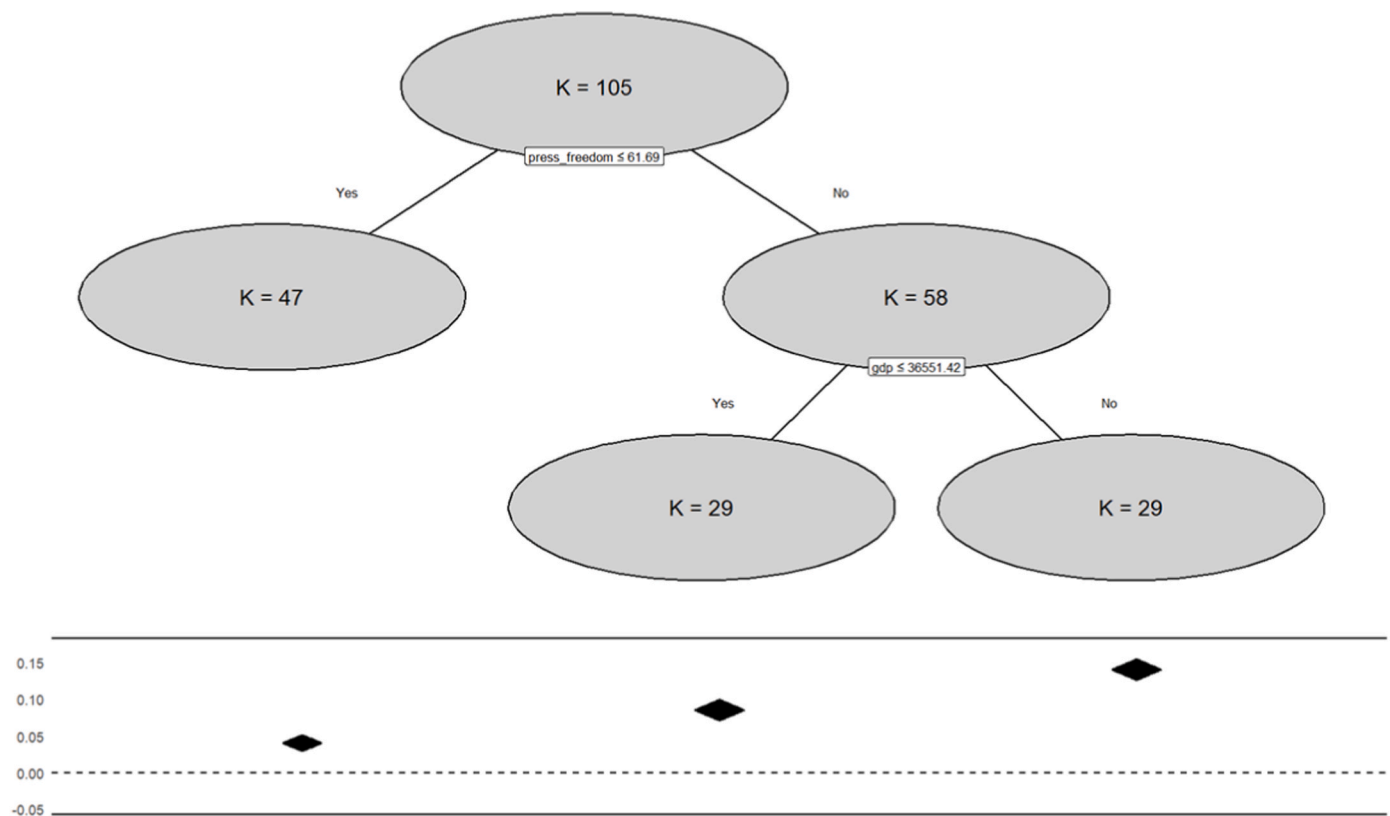


Fig. 4. Meta-CART Tree Predicting Effect Sizes of SES on Environmental Attitudes Using Country-Level Moderators.

A key insight is that higher-SES students consistently show stronger environmental values from as early as Grade 4. This supports the affluence hypothesis, suggesting that socioeconomic advantages provide more opportunities for environmental learning and action. Importantly, this gap does not narrow as students progress through school, suggesting that schools per se may have limited capacity to mitigate these disparities.

The SES–environmental attitude link varies significantly across countries, with no consistent moderation by GDP alone, confirming that national wealth is an insufficient mechanism on its own. Instead, the results reflect the distinct macrostructural pathways outlined in our framework. While the dimensions of capacity and distribution exert moderate linear effects, as shown by the fact that the association slightly weakens in countries with higher Human Development Index (HDI) and income equality (GINI), institutional openness regarding the freedom of information and inquiry emerged as the more decisive institutional boundary condition or enabler. Press freedom emerged as a more significant factor, showing stronger SES–attitude associations in countries with either very high or very low media freedom. More broadly, the findings provide partial support for the nonlinear logic implied by the Environmental Kuznets Curve framework. Rather than observing uniform linear effects of development-related indicators, the results suggest that the relationship between SES and environmental attitudes is context-dependent and may operate through threshold or interaction-based mechanisms, particularly regarding press freedom. In contrast, academic freedom showed no consistent influence.

Our machine learning analysis revealed a striking paradox: countries with both high press freedom and high GDP exhibited the strongest SES-based stratification in environmental preservation attitudes. This suggests that conditions typically supportive of environmental concern might also amplify inequality in who holds these concerns, challenging the idea that development inherently leads to more inclusive sustainability. While prior research (e.g., Bättig & Bernauer, 2009; Neumayer, 2002) posit that institutional openness and political freedoms act as

universal catalysts that empower publics to develop pro-environmental values, our cross-national analysis reveals that this ‘democracy effect’ is highly stratified. Institutional openness in the form of freedom of information and inquiry does not automatically democratize environmental concern. Instead, it functions as an accelerator of existing inequalities: in highly affluent settings, a free press, in particular, provides an informational infrastructure that is disproportionately leveraged by high-SES families, thereby widening the attitudinal gradient between privileged and marginalized youth. Consequently, institutional openness is not a neutral enabler of public awareness, but a contextual moderator that can reinforce environmental engagement as a positional good of the socioeconomically advantaged.

These findings have several implications for sustainability policy and education. The confirmed link between SES and environmental concern suggests that current sustainability education may disproportionately benefit privileged youth. This reinforces concerns that climate action could become a “democracy of the rich and powerful,” where only privileged youth gains voice and agency (Morgan, 2012). To address this, policies and curricula must intentionally broaden access and relevance. From an environmental justice perspective, the study underscores that each context exhibits a unique pattern through which sustainability solutions can be actualized and wicked problems addressed (Agyeman, 2013; Morgan, 2012). It advocates for place-based, justice-centered education that connects sustainability to lived realities, especially for marginalized communities (Morales-Doyle, 2017). Such approaches have the potential to bridge the SES–attitude gap by making environmental issues more immediate and actionable for all students.

The ideal of ‘just sustainabilities’—a better quality of life for all within planetary limits (Agyeman, 2013)—remains elusive, as environmental concern is not equitably distributed, and macro-level factors can intensify stratification. The challenge is to foster pro-environmental attitudes in socially inclusive and context-sensitive ways, perhaps through whole-school sustainability models and transformative

pedagogies.

In sum, this study robustly demonstrates that SES is a key global predictor of student environmental attitudes, with national context shaping this link. While affluence and institutional development can foster concern, they can also solidify existing inequalities. Achieving just sustainabilities thus demands democratizing access to environmental education and voice, embedding equity and empowerment within climate literacy efforts.

7. Limitations and future research directions

Despite its robust methodology and extensive dataset, this study has several limitations that suggest avenues for future research. A key limitation is the use of the number of books at home as a sole proxy for socioeconomic status (SES). While this proxy is established in large-scale educational assessments, it inadequately captures the complexity of SES by omitting factors such as parental income, education, or occupation (Heptt et al., 2022). In addition, the increasing prevalence of digital reading technologies such as e-readers may gradually alter the interpretation of the “number of books at home” indicator.

However, research suggests that this measure continues to capture broader aspects of family cultural and educational resources and remains widely used in international large-scale assessments (Heptt et al., 2022). Future studies should therefore incorporate multidimensional SES indicators to gain a more nuanced understanding of socioeconomic influences. Future research should also examine potential educational mechanisms underlying the relationship between SES and environmental attitudes. For example, environmental education exposure, science literacy, school sustainability practices, and civic learning opportunities may help explain how socioeconomic advantage translates into stronger environmental preservation attitudes. Longitudinal and mediation-based designs would be particularly valuable for clarifying these developmental pathways. Future research should also investigate whether the socioeconomic stratification observed in environmental attitudes translates into inequalities in pro-environmental behaviour across different national contexts. Future studies should further investigate potential nonlinear and threshold-based dynamics underlying the Environmental Kuznets Curve framework, particularly by examining how combinations of economic development, inequality, and institutional openness jointly shape environmental attitudes across developmental contexts. Furthermore, the analysis is based on cross-sectional data, which precludes causal inferences about the development of environmental attitudes over time.

The advanced methods employed in this study, however, offer tremendous potential for future inquiry. Individual Participant Data (IPD) meta-analyses, in particular, allow for a more precise investigation of the relationships identified here. By harmonizing and pooling data from various international studies, researchers can trace the developmental dynamics of environmental attitudes from childhood to adulthood, identifying critical periods of attitude formation. This may include data from international large-scale assessment studies examined over time (Pietsch et al., 2025), as well as primary studies using different longitudinal or cross-sectional data sets (Campos et al., 2023). In this regard, it is also promising that IPD meta-analyses enable additional follow-up from longitudinal studies and the inclusion of variables not reported in primary studies (Maxwell et al., 2024). Future research should also consider incorporating direct measures of environmental policy stringency or institutional quality (e.g., Jaeger et al., 2023; Yaman & Cetin, 2025) as additional country-level moderators, which would allow for a more direct examination of the governance mechanisms through which national institutions shape the social stratification of environmental attitudes.

Statistical power is an important consideration in meta-analytic moderator analyses. Simulation studies indicate that machine-learning approaches such as Meta-CART generally achieve adequate power when the number of studies exceeds approximately 40 (Li et al., 2020).

In the present study, the analysis includes 65 countries and samples in grade 4 and 8, exceeding this threshold. Moreover, prior work has shown that the statistical power of moderator tests in meta-analysis depends primarily on the number of studies rather than the number of individual observations within studies (Hedges & Pigott, 2004). The relatively large number of country-level units in this study therefore provides a suitable basis for detecting contextual moderation effects.

Consequently, the application of meta-analytical machine learning techniques like Meta-CART opens new horizons. These methods can uncover complex, non-linear interactions among individual, school, and national factors that often remain hidden in traditional regression models. To test the sensitivity of meta-analytical findings and quantify the relative importance of predictors, even in small samples, a classification and regression tree approach, like meta-forest (van Lissa, 2020), seems promising.

8. Conclusion

This study systematically addressed the global socioeconomic divide in youth environmental attitudes, providing empirical clarity to the theoretical debates regarding the affluence and environmental degradation hypotheses (Diekmann & Franzen, 1999; Inglehart, 1995). By analyzing data from nearly 700,000 students across 65 countries, we identified a consistent and statistically significant positive association between socioeconomic status (SES) and attitudes toward environmental preservation (Reynolds & Komakhidze, 2022). These findings strongly support the affluence hypothesis, suggesting that material and cultural security enable the prioritization of long-term ecological concerns as early as the age of nine. Furthermore, contrary to the aspirations of educational effectiveness research (Kyriakides et al., 2018), our results indicate that this SES-based gap does not narrow as students progress from primary to secondary school. This suggests that schools, in their current institutional form, may have a limited capacity to mitigate the impact of family background on the formation of environmental values.

The most significant contribution of this research is the identification of a structural paradox: the widest disparities in environmental preservation attitudes appear in affluent nations characterized by high levels of press freedom. While institutional enablers like a free press and high GDP are theoretically viewed as drivers of environmental awareness (Martínez-Zarzoso & Phillips, 2020), our machine learning analysis reveals that these conditions may simultaneously amplify socioeconomic stratification in attitudinal outcomes. This challenges the assumption that national development and institutional openness inherently lead to more inclusive sustainability (Aral & López-Sintas, 2022). Ultimately, the results underscore that achieving just sustainabilities requires moving beyond standardized environmental education toward justice-centered, place-based approaches that democratize access to ecological engagement for all youth, regardless of their socioeconomic privilege.

CRedit authorship contribution statement

Marcus Pietsch: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization. **Nurullah Eryilmaz:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rolf Strietholt:** Writing – review & editing, Writing – original draft, Validation, Data curation. **Ronny Scherer:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation. **Matheus Monteiro Nascimento:** Writing – review & editing, Writing – original draft, Investigation. **Simone Abels:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Daniel Fischer:** Writing – review & editing, Writing – original draft.

Software and reproducibility

All analyses were conducted using R (Version 4.4.2) (R Core Team, 2024), primarily using the metafor and metaCART packages. The full analysis plan, data processing scripts, and replication materials are available from <https://osf.io/hn6gr/>.

Consent for publication

All authors have reviewed and approved the final manuscript and consent to its publication in Journal of Environmental Psychology.

Availability of data and codes

Data and materials are available at: <https://osf.io/hn6gr/>

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Declaration of competing interests

We do not have any competing interests.

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N/A.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvp.2026.103085>.

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