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Colonial contexts and the feasibility of mitigation through transition: A study of the impact of historical processes on the emissions dynamics of nation-states

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A R T I C L E I N F O

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A B S T R A C T

It has long been accepted that the relative affluence and technological efficiency of nations are important contributors to their rate of emissions. These associations have, in turn, driven questions about the feasibility of mitigating anthropogenic greenhouse gas emissions through incremental transition to "business as usual" policy structures in variant social contexts. Here, I explore the extent to which the historical context of colonial relations impacts the feasibility of a nation mitigating emissions per capita, emissions per dollar, and total emissions under current development logics. To do so I examine the structure of variation for 152 nations during the 1960–2018 period. Subsequently, I examine how being situated as an extractive colony in the past serves to moderate the association of GDP per capita with CO_2 emissions per capita, CO_2 emissions per dollar, and total CO_2 emissions in the present. I find that roughly 11% of cross-national variation in CO_2 emissions per capita and CO_2 emissions per dollar, as well as nearly 6% of variation in total CO_2 emissions between 1960 and 2018 is attributable to having been historically subjected to extractive colonial processes. These findings suggest that mitigation of emissions through transition of "business as usual" policy structures appears significantly less feasible for nations positioned as extractive colonies in the past, relative to all others.

1. Introduction

In late 2021 and early 2022 the IPCC once again confirmed it is "unequivocal that human influence has warmed the atmosphere, oceans, and lands" (IPCC, 2021, p.4), and that "[a]ny further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a livable and sustainable future for all" (IPCC, 2022, p. smp-35). While research into socio-political and economic drivers of such change continues to point to the importance of demographic and economic development processes (Rosa and Dietz 2012; Dietz, Rosa, and York 2012; Jorgenson 2014; Dietz et al., 2015), many questions remain concerning the variability of socio-ecological relations across a range of social, political, and cultural contexts. Further, understanding what such variability suggests about policy approaches that offer the greatest leverage for enacting the transition and transformation of political, legal, behavioral, and economic structures successful mitigation and adaptation strategies require remains crucial. Better understanding the nature of such contextual variability is of critical importance, since it is increasingly well recognized that "vulnerability to climate change is a complex…phenomenon that is often influenced by historic development processes, such as structures that originated with colonization" (IPCC, 2022, p.8–8), and that both mitigatory and adaptive possibilities are constrained by the historical contingency of macro-scale development processes. While the IPCC now suggests there is high confidence that settler colonial processes exhibit such an effect, far less research has explored how the structures of extractive colonial processes inhibit or facilitate a nation's ability to mitigate anthropogenic climate change.

Such concerns have motivated the progression of a number of theoretical and empirical approaches to understanding the extent, meaning, and origins of variability in the relationship between socio-economic development and greenhouse gas (GHG) emissions. For instance, arguments concerning environmental Kuznets curves (EKC), ecological modernization, world systems, and unequal ecological exchange, among others have centered on elucidating the ways that economic growth and population dynamics impact emissions, as well as what social factors may intensify or mitigate these processes. Some of these approaches suggest a convergence in the association that social and economic development processes hold with emissions over time as a result of improved technologies, access to global flows of resources and

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information, and growing environmental concern. However, some others suggest a fundamental divergence in socio-environmental relations as a result of historical and contemporary international inequalities (Jorgenson et al., 2019). Thus, while many scholars argue that incremental policy transition will be adequate to mitigate GHG emissions such that the worst effects of climate change are not felt, others argue forcefully that non-linear transformations of social systems must be introduced. Despite their breadth in approach and conclusion these traditions have in common a growing concern with the moderating effect that context and unequal social relations have on socio-environmental processes.

While more than two decades of research into the social drivers of GHG emissions have yielded a number of key insights, here I highlight two lacunae that remain. First, examination of the structure of variation in GHG emissions across political units remains relatively rare. Yet, better understanding how such variation is structured, and how that variation corresponds to social processes is fundamental to addressing concerns about incremental transition and non-linear transformation. Second, the constraints that unequal social relations place on a population's ability to address climate change through the enactment of mitigation policy has been a consistent focus for many theories of the social drivers of climate change. Additional theoretical traditions have become more attuned to such concerns in the last decade as well. Yet, a thorough quantitative study of the role that historically iniquitous social relations play in patterning the feasibility of nation-states successfully mitigating GHG emissions through incremental transition, as opposed to non-linear transformation, remains necessary.

To address these concerns, I construct random intercept models of carbon dioxide emissions per capita (CO_2 per capita), carbon dioxide emissions per unit of economic output (CO_2 per dollar), and total carbon dioxide emissions (CO_2) with unstructured covariance for the years 1960 to 2018. This model structure allows me to examine Variance Partition Coefficients and Proportional Change in Variances associated with a number of predictors of known theoretical and empirical import, as well as an indicator variable for the exposure of a nation to colonial forces in the course of its development. Using a random coefficient model with AR(1) corrections to account for correlation structures of nation-year observations, I also examine the moderating role of extractive colonization in the association between economic development (GDP per capita), and the three emissions measures for the 1960 to 2018 period. I choose to structure the analyses in this way due to the wide acknowledgement of the importance of sustainable development and socio-economic efficiency to mitigation efforts, where CO_2 per capita and CO_2 per dollar are commonly seen as measures of the intensity of emission required to support a nation's economic and demographic expansion, and total CO_2 emissions are an indicator of a nation's success in mitigation efforts in an absolute sense (Jorgenson and Clark 2012). I focus on the moderation of these eco-efficiency measures' association with GDP per capita by their colonial history, as the dynamics of the colonial period are increasingly acknowledged to be critical to the foundation and subsequent development of the contemporary global economy (Pirani 2018). I argue that this fact, and the historical and temporally invariant nature of the colonial indicator variable make it an appropriate test of the constraints that historical processes may place on mitigation efforts.

1.1. Transition, transformation, and social drivers of emissions

There is widespread agreement that substantial changes must be introduced to nearly every policy arena concerned with the dynamics of Coupled Human and Natural Systems (CHANS) if mitigation efforts are to be reasonably successful. To be successful, policy aimed at mitigation of GHG emissions must be able to manage the path dependency and lag effects of historical events, heterogeneity of dynamical processes, non-linearity, spatial and temporal thresholds denoting qualitative changes in system state, and potentially unexpected outcomes of intervention that often characterize CHANS. Further still, such policies must also promote resilience and successful adaptation of the system processes foundational to human well-being (Liu et al., 2007; Mitchell 2009). Whether such changes to the constellation of policies germane to promotion of resilient CHANS will call for transformation of these systems, or can be brought about by incremental transition and reform is a question that has been taken up by an increasingly broad intellectual community (Dietz et al., 2020). Though at the time of this writing the term transformation has been discussed for over 20 years, 70 % of the works on the topic have been published between 2015 and 2021 (Moore et al., 2021). There is also a large body of quantitative social science research concerned with the feasibility of mitigating GHG emissions and climate change under the policy conditions that characterize systems of global production and distribution.

Much of this work has been done in the fashion of early STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology), structural human ecology, world systems, and EKC research into the proportional impact of macro-scale social processes on emissions (Grossman and Krueger 1991; Dietz and Rosa 1994; Dietz and Rosa 1997; Panayotou 1997; York, Rosa, and Dietz 2003a). EKC analysis offered empirical evidence that the rate of emissions associated with economic development has a non-linear quality such that it would be positive at low levels of economic development, but would become negative past a critical inflection point– a trajectory resembling an inverted U. This was suggestive of a process of ecological modernization (Spaargaren and Mol 1992), where systems of development would incorporate an ecological awareness that would incrementally transition them into more sustainable trajectories, mitigating climate change and other environmental impacts in a manner similar to economic modernization's attenuation of inequality (Kuznets 1955).

STIRPAT analyses found evidence that growth in affluence drove emissions at a number of scales, and that when non-linearity was present it led to an attenuation of the positive association between affluence and emissions in some contexts, but not a reversal of the general trajectory as suggested by EKC (Rosa and Dietz 2012). The results of such research seemed to suggest that a transformation of development processes would be necessary if anthropogenic emissions were to be mitigated. Other research, such as that in the tradition of structural human ecology, explored if these associations held for the impact of affluence on emissions measures meant to capture the socio-ecological sustainability of economic development– such as emissions per capita and emissions per dollar. These studies also found affluence to be a consistent driver of emissions, and their findings were often interpreted to suggest transformation in macro-scale social and economic process might be necessary if mitigation efforts are to succeed (Jorgenson and Clark 2012).

Research in these traditions has continued to complicate understandings of social and environmental interactions through incorporation of contextual measures that are related to both emissions, economic expansion, and political structure. Research has consistently found that foreign direct investment (FDI) in a national economy is associated with increased emission of GHGs and other pollutants, even after accounting for the size of the manufacture sector (Grimes and Kentor 2003; Jorgenson 2007; Jorgenson, Dick, and Mahutga 2007). These findings suggest that FDI serves as one mechanism by which environmentally intensive economic processes are typically located in historically disadvantaged nations. Related research has consistently shown that manufacture's contribution to economic development is associated with both energy intensity and emissions across a range of contexts as well (Liddle 2015; Thombs and Jorgenson 2019). Outside the economic sphere, research into the impact of processes involved in the establishment of military structure and political domination has demonstrated that military size is another important contributor to CO_2 emissions, as well as overall energy intensification (Jorgenson et al., 2010a; Clark, Jorgenson and Kentor 2010). Such research suggests that addressing processes that underlie political conflict and domination is another avenue through which emissions may be mitigated.

World systems analysis has also been an important contributor to research on drivers of emissions in variant social, political and economic contexts. Work in the tradition of world systems analysis centers on exploring the political and economic linkages of populations across the globe, through a range of historical periods– often emphasizing the ways these social relations were critical to population growth dynamics, economic and industrial development, and national development processes associated with the system in question (e.g. Cox 1964; Wallerstein 1987). Such analyses have repeatedly suggested that theoretically flexible measures– such as the degree of centrality in trade networks– are both drivers and moderators of emissions, and are indirectly linked to historically contingent and fixed processes such as the establishment, formalization, and subjugation of extractive colonies (York, Rosa, and Dietz 2003b; Greiner and McGee 2018; Jorgenson et al., 2022).

This growing body of literature emphasizes that the context both demographic and economic development occurs in is a critical component to understanding the shape their association with emissions takes. For instance, in addition to the findings noted above it has been found that associations between economic development and measures of emissions are context sensitive to income inequality (McGee and Greiner 2018), gender inequality (Ergas and York 2012; McGee et al., 2020; Ergas et al., 2021) average number of working hours (Fitzgerald et al., 2018), national labor union participation (Alvarez, McGee, and York 2019), trade network integration and world system position (Prell and Sun 2015; Thombs 2018; Jorgenson et al., 2022), and national energy mixes (York and McGee 2017; Sovacool et al., 2020) to name just a few. There are two broad lessons from this body of research I wish to emphasize. First, it has been regularly recognized that many moderators of the emissions-economic development relationship can serve as meaningful levers for transition towards sustainability by way of policy changes in existing social structures and institutions. For instance, if changes to income inequality, working hours, or labor union participation are found to moderate the relationship between emissions and economic development, then policy aimed at changing those conditions might successfully lead to mitigation of emissions through incremental transition and reform. On the other hand, studies of moderators that characterize aggregated units of social organization, such as national trade network integration or energy infrastructures, would suggest that transformational measures are required in order to meet the challenges of mitigation, since making changes to these systems would also entail the reorganization of myriad social relations, at multiple levels of socio-ecological interaction.

The second lesson I highlight concerns moderators that characterize higher order units of social organization, and their meaning for the emissions-development relationship. It is conceivable that these moderators vary in value from one nation to another stochastically. Yet, the systematicity with which moderators such as trade network integration, world system position, foreign direct investment, and energy infrastructure are found to affect the association between development and emissions leads many to understand these disparities, and their influence on the development-emissions relationship, as representative of a series of international inequalities (Givens et al., 2019). Such an interpretation suggests these inequalities are not randomly distributed, but are the result of historical, sometimes path dependent processes in the organization of global economic relations, and calls for climate mitigation policy programs centered on the pursuit of distributive, procedural, and compensatory notions of justice (Ciplet, Roberts and Khan 2015; Khan et al., 2020). Trying to capture the contribution historical processes and lag effects make to variation in the ability of nations to mitigate greenhouse gas emissions through economic growth has proven methodologically challenging, however.

Many cross-national quantitative studies of GHG emission drivers seek to address these concerns by incorporating measures that account for the stratified, global division of labor that has emerged– such as membership in the Organization of Economic Cooperation and Development, world system structure, or assignment of development status according to placement in the distribution of gross national incomes (e.g. high income/low income) (Jorgenson and Clark 2012, Liddle 2015; Jorgenson et al., 2022). While these approaches adequately account for the global division of labor, their time-variance make them difficult to use to explore the presence and character of contingent, historical processes' impact. Rather, they are themselves likely impacted by such processes and events, among other factors.

Like many previous studies of the social drivers of CO_2 emissions, I expect that historic development processes play a role in the association a country's gain in GDP per capita holds with its value of total emissions, emissions per capita, and emissions per dollar. I introduce two novel approaches to explore the validity of this assumption more directly. First, following research into the important role that colonial processes played in configuring the fundamental logics and relations of global trade and production (Khan et al., 2020; Klinsky et al., 2016; Douglass and Cooper 2020; Pisor, Basurto, and Douglass 2022), I suggest that colonial relations represent historic processes with lag effects that influence contemporary associations of emissions, emissions per capita, emissions per dollar, and GDP per capita. Though it is increasingly well recognized that settler-colonialism can interfere with the ability of populations to both mitigate and adapt to challenges presented by anthropogenic climate change (IPCC, 2022, Pisor, Basurto, and Douglass 2022), here I focus on the contingent experiences and historic development process of extractive colonies. Therefore, using random intercept models and Variance Partition Analyses I test the hypothesis (H1) that extractive colonization acts as a historical process with lag effects that impact the association of GDP per capita with total emissions, emissions per capita, and emissions per dollar. If extractive colonization does hold such an influence one would expect it to account for a substantial portion of variance in total CO_2, CO_2 per capita, and CO_2 per dollar. Additionally, previous works have consistently shown aggregate measures characterizing higher level social processes, such as the role of manufacturing in economic development, to be correlated with more intense emissions-development associations. Therefore, I hypothesize (H2) that having been colonized will be associated with different relational trajectories between CO_2 per dollar, CO_2 per capita, total CO_2 emissions, and GDP per capita– such that the associations will not meaningfully attenuate in previously colonized nations.

2. Materials and Method

Data are gathered from the World Bank, World Development Indicators (2021) database, with the exception of the binary operator for extractive colonization. The operator measuring extractive colonial reltaions was manually coded and cross-referenced against the Colonial Transformation Dataset (Ziltener et al., 2017) for nations in Asia and Africa, and a dataset concerning the territory's political and economic development (Wimmer and Min 2006) for all others. Nations that were not subject to extractive colonial processes, e.g. settler-colonial states such as the United States, Australia, Canada, South Africa, New Zealand, and Liberia are coded as non-colonies. Here, settler-colonial nations are defined by settler control of the colonized territory and associated governing bodies, thus they are not exposed to the same historical regularities and contingencies many extractive colonies were subjected to. In alternate models, supporting information settler-colonial nations were coded as separate from extractive colonies and uncolonized nations, and the findings remain consistent with those presented here. Those models are available from the author upon request. The list of extractive colony and non-colony nations is presented in Table 1.

2.1. Sustainable development

The dependent variables are CO_2 emissions per capita, CO_2 emissions per dollar, and total CO_2 emissions. These measures capture changes in what might be considered the social, technological, and absolute dimensions of sustainable development and environmental efficiency. CO_2

Table 1
List of nation state categorizations.

Extractive Colony	Non/ Settler Colony
Algeria, Angola, Argentina, Armenia, Azerbaijan, Bahrain, Bangladesh, Belize, Benin, Bolivia, Bosnia and Herzegovina, Botswana, Brazil, Brunei Darussalam, Burkina Faso, Burundi, Cabo Verde, Cambodia, Cameroon, Central African Republic, Chad, Chile, Colombia, Congo, Dem. Rep., Congo, Rep., Costa Rica, Cote d'Ivoire, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eswatini, Fiji, Gabon, The Gambia, Georgia, Ghana, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, India, Indonesia, Iran, Iraq, Jamaica, Kazakhstan, Kenya, Kuwait, Lao PDR, Lebanon, Lesotho, Libya, Malaysia, Mali, Mauritania, Mauritius, Mexico, Morocco, Mozambique, Myanmar, Namibia, Nepal, Nicaragua, Niger, Nigeria, Oman, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Qatar, Rwanda, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Singapore, Slovenia, South Korea, South Sudan, Sri Lanka, Sudan, Tajikistan, Tanzania, Thailand, Timor-Leste, Togo, Tunisia, Turkey, Turkmenistan, Uganda, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Vietnam, Zambia, Zimbabwe	Australia, Austria, Belarus, Belgium, Canada, China, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Ethiopia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, Jordan, Kyrgyz Republic, Latvia, Liberia, Lithuania, Luxembourg, Malta, Moldova, Mongolia, Montenegro, Netherlands, New Zealand, North Macedonia, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovak Republic, South Africa, Spain, Sweden, Switzerland, United Kingdom, United States.

emissions per capita are suggestive of the impact continual population growth might have the rate of emissions in a society, emissions per dollar is indicative of the intensity of emissions associated with processes behind the production of an economic unit, while total emissions is a measure of the absolute progress made towards decoupling development and pollution. All these measures offer a critical window into the efficaciousness of social efforts to mitigate emissions, and are commonly used in analyses exploring the relationship between economic development, demographic change, and environmental impact (Jorgenson and Clark 2012; Dietz et al., 2010). CO_2 emissions per capita measures annual, population adjusted emissions from the burning of fossil fuels- including gas flaring, the consumption of liquid, solid, and gaseous fuels, and the production of cement in metric tons. CO_2 emissions per dollar measures annual, 2015 U.S. Dollar adjusted emissions from the burning of fossil fuels- including gas flaring, the consumption of liquid, solid, and gaseous fuels, and the production of cement in kilograms. Total CO_2 emissions measures annual unadjusted emissions from the burning and flaring of fossil fuels, and the from production of cement, in kilotons.

2.2. Social and economic development

To capture national levels of economic and socio-demographic development I use GDP per capita, the percentage of the population living in urban areas, and an age dependency ratio. GDP per capita is commonly used as a measure of economic development in cross-national research, and here is measured in population adjusted 2015 U.S. dollars. Urbanization, or the percent of the population living in urban areas, is a measure of the rapidity of social relations and the extent of dense, built spaces such relations often occur within (Bettencourt et al., 2007; Greiner, Shtob, and Besek 2020). The age dependency ratio is a percentage measure that captures the proportion of the population that is of typical working age, 16–64, and is thereby a measure of the proportion of the population likely to be engaged in officially recognized economic activity (York, Rosa and Dietz 2003a). In additional models controls for technology and the economic base of growth processes are included, and the results are found to be consistent with those presented here. The additional models include measures of the percent of GDP drawn from agricultural, forestry, and fishing activites, the percent of GDP drawn from fossil fuel production, and the percent of GDP drawn from the service sector. Inclusion of these variable is consistent with Shi's (2003) method of controlling for technological development. Results of these models are available in Tables S1 and S2.

2.3. International inequality

In addition to the binary extractive colonization covariate, several measures that are typically used to capture the impact of iniquitous international relations are included so as to ensure that qualitative differences in the context of development are being identified independently of the impact these factors might have. These covariates are Foreign Direct Investment (FDI), the percent of GDP drawn of manufacturing activities, the percent of GDP drawn from exports, and military spending.

With the exception of binary indicators for extractive colonization and period, all variables are natural log transformed prior to any additional transformations. Such transformations make coefficients interpretable as elasticities where magnitude and direction represent the proportional change in the dependent variable of interest in response to a 1 % change in the independent variable under consideration. The distributions of these co-variates, adjusted for their value on the extractive colonization variable, are shown in Fig. 1.

2.4. Analytic technique and model structure

The goals of the present analyses are twofold. The first aim is to develop a better understanding of variance structures with respect to equity and efficiency-based, as well as total, emissions measures. This aim contributes to the elucidation of historical lag effects associated with colonial relationships, as well as their contributions to contemporary associations between per capita, per dollar, and total CO_2 emissions, and GDP per capita. Second, this research aims to explore how the historical context of colonial relations moderates the association between GDP per capita, per capita emissions, emissions per dollar, total emissions, and other measures of national development known to impact emissions such as direct investment from foreign nations in economic processes (FDI), the proportion of economic output attributable to manufacture activity, the proportion of economic output attributable to the export of goods and services, and the proportion of the economy directed toward military activity and maintenance.

Two models are used to test the above hypotheses. To evaluate hypotheses concerning historical lag effects (H1) I construct a series of random intercept models. These models can be formally stated as follows:

$$\begin{aligned} y_{ij} &= \alpha_j + \beta_i X_i + e_{ij} \\ \alpha_j &= \alpha + \beta_j \chi_j + \mu_j \\ \mu_j &\sim N\left(0, \sigma_\mu^2\right) \\ e_{ij} &\sim N\left(0, \sigma_e^2\right) \end{aligned} \tag{1}$$

where y_{ij} is the outcome of interest for the ith nation-year in the jth nation; α_j is a vector of nation specific random intercepts; X_i is a vector of the additive effects of the nation-year covariates and β_j a vector of associated fixed effect parameter estimates; χ_j is the additive effect of the binary extractive colonization operator and β_j the associated fixed effect parameter estimates; μ_j is the country level residual term; e_{ij} is the residual for nation-year i nested within nation j; σ_μ^2 is the cross-nation variance term; σ_e^2 represents within-nation, nation-year, variance.

The estimated variance terms of these models are then used to

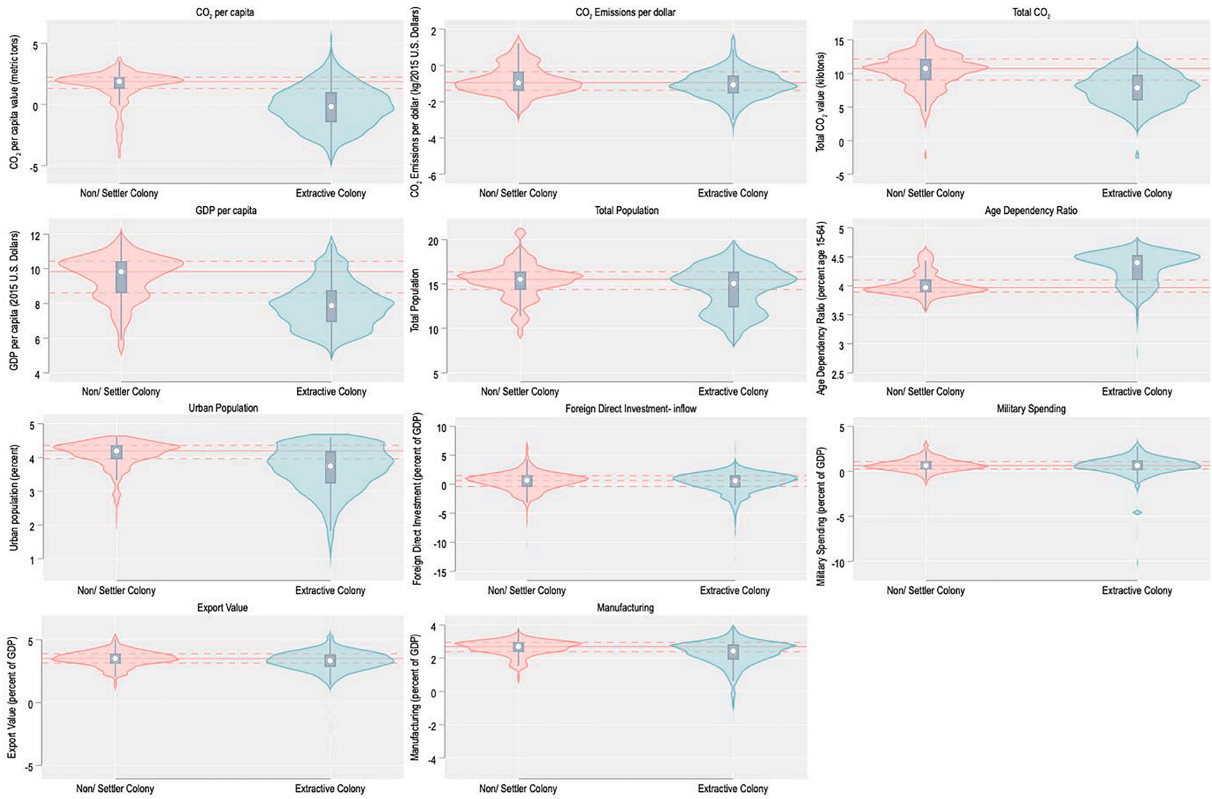

Fig. 1. Distribution of all included variables in extractive colonies relative to all others.

calculate the Variance Partition Coefficient (VPC), τ, which grants insight into the total proportion of the variance in y_{ij} that exists between nations. The VPC can be expressed in the following way:

$$\tau = \frac{\sigma_\mu^2}{\sigma_e^2 + \sigma_\mu^2} \tag{2}$$

The VPC of the respective models can then be compared with one another directly to calculate the Proportional Change in Variance (PCV) as follows:

$$\delta_\mu = \frac{\sigma_{\mu_{k1}}^2 - \sigma_{\mu_{k2}}^2}{\sigma_{\mu_{k1}}^2} * 100 \tag{3}$$

where δ_μ is the cross-unit PCV; $\sigma_{\mu_{k1}}^2$ represents the across nation variance of the initial ($k1$) comparator model, while $\sigma_{\mu_{k2}}^2$ represents the across nation variance of the subsequent (k2) comparator model.

For hypotheses H2 I construct a series of random coefficient models with corrections for first order (AR1) autocorrelation to model the within-group, nation-year correlation structure, and fixed effect estimators for year. The use of both an AR(1) model structure and hierarchical models is beneficial as it enables estimation in the face of unbalanced panels and the inclusion of nations with time gaps in their observations. This ability is the result of the random coefficient model's precision weighted estimation, or "shrinkage", that takes into account the regularity and relative reliability of nation level parameter means (Evans, Leckie, and Merlo 2020). AR(1) corrections are appropriate for longitudinal panel data in which observations nearer to one another in time are more highly correlated than those that are farther from each other in time (Beck and Katz 1995; Jongerling and Hoijtink, 2017). I include fixed effect estimators for period in order to control for contemporaneous, exogenous factors that may influence outcomes across units, such as a global rise in the cost of fuel, or reductions in energy use that may result from novel biological hazards. Random coefficients are used in order to allow the measure of economic development, GDPpc, to vary across nation-groups and be interacted with a binary nation specific, extemporaneous variable (i.e. whether or not a nation was colonized during the course of the contemporary global economy's development). All models use unconstrained variance structures, as likelihood ratio tests indicated such structure offered significantly improved model fit over constrained variance structures. The random coefficient models used in the analyses below can be generally expressed as:

$$\begin{aligned}
y_{ij} &= \alpha_j + \gamma_j\eta_i + \gamma_j^2\eta_i^2 + \beta_i X_i + \zeta_{ij} \\
\alpha_j &= \alpha + \beta_j\chi_j + \mu_j \\
\gamma_j &= \gamma + \beta_j\chi_j + \mu_{\gamma j} \\
\gamma_j^2 &= \gamma^2 + \beta_j\chi_j + \mu_{\gamma^2 j} \\
\zeta_{ij} &= \rho_j\zeta_{(i-1)j} + e_{ij}
\end{aligned} \tag{4}$$

$$\begin{bmatrix} \mu j \\ \mu\gamma j \\ \mu\gamma^2 j \end{bmatrix} \sim N(0, \begin{bmatrix} \sigma_\mu^2 & - & - \\ \sigma_{\mu\mu\gamma}^2 & \sigma_{\mu\gamma}^2 & - \\ \sigma_{\mu\mu\gamma^2}^2 & \sigma_{\mu\gamma\mu\gamma^2}^2 & \sigma_{\mu\gamma^2}^2 \end{bmatrix}$$

$$e_{ij} \sim N\left(0,\ \sigma_e^2\zeta_j\right)$$

$$\sigma_e^2\zeta_j = \sigma_e^2 \begin{bmatrix} 1 & \rho & \rho^2 & \cdots & \rho^{n_i-1} \\ \rho & 1 & \rho & \dots & \rho^{n_i-2} \\ \rho^2 & \rho & 1 & \dots & \rho^{n_i-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho^{n_i-1} & \rho^{n_i-2} & \rho^{n_i-3} & \dots & 1 \end{bmatrix}$$

where y_{ij} is the outcome of interest for the ith nation-year in the jth nation; a_j is a vector of nation specific random intercepts; γ_j is a vector of nation-specific random coefficients, while η_i is a vector of values for

GDPpc in the ith year; γ_j^2 is a vector of nation-specific random coefficients corresponding to the vector of squared values for GDPpc, η_i^2, that allows non-monotonic expression of the association between y and η; X_i is a vector of the additive effects of the nation-year covariates and β_i a vector of associated fixed effect parameter estimates; e_{0ij} is the residual for nation-year i nested within nation j; α is the cross-national grand mean of the intercept; χ_j is the additive effect of the binary extractive colony operator and β_j the associated fixed effect parameter estimates; μ_j is the country level residual term; γ is the cross-national grand mean of the scaling parameter for η, while γ^2 is the cross-national grand mean of the scaling parameter for η^2; $\mu_{\gamma j}$ is the country level residual term for the association of y and η, and $\mu_{\gamma^2 j}$ is the country level residual term for the association of y and η^2; ζ_{ij} is the temporally adjusted residual for nation-year i in nation j; ρ_j is the AR parameter for nation j; e_{ij} is the residual for nation-year i nested within nation j; σ_μ^2 is the cross-nation variance term; σ_e^2 represents within-nation variance.

3. Results

Tables 2.1, 2.2, and 2.3 display the random components of the two-level random intercept model with years nested in nations for CO_2 emissions per capita, CO_2 emissions per dollar, and total CO_2 emissions, respectively. Models 1.0, 2.0, and 3.0 display the variance parameters and variance partition coefficient, τ, for the null model, with no predictor covariates. τ is calculated using equation (2). Models 1.1, 2.1, and 3.1 extend the null models by including the fixed effects control for general period effects. In all six cases the findings suggest that there is a high amount of variation in both emissions per capita, emissions per dollar, and total emissions at the between-nation level, and relatively little to be explained at the within-nation level. Specifically, model 1.1 indicates that τ for CO_2 per capita is 96.9 %, or that nearly 97 % of variation in the emissions per capita's outcome rests at the between nation level. Model 2.1 suggests that τ for CO_2 emissions per dollar is 88.2 %, or that much of the variance in emissions per dollar is attributable to cross-national, as opposed to within-nation, differences. While model 3.1 estimates result in a τ value of 97.9 %, again indicating the majority of emissions variation is attributable to cross-national characteristics. These values suggest a substantial amount of clustering in the outcome variables at the nation-state level, as well as a good deal of inequality in such outcomes.

Models 1.2, 1.3, 2.2, 2.3, 3.2, and 3.3 expand on the VPC analyses performed in models 1.1, 2.1, and 3.1 by exploring the change in VPC that occurs when temporally variant, within-unit additive effects are included. Further, these models allow for the calculation of the PCV, δ_μ, that results from the inclusion of known drivers of emissions and a control for exposure to colonial regimes. Across all models τ is seen to converge on roughly 90 %. Specifically, model 1.3 indicates that when all variables of interest are included 89.4 % of variation in emissions per capita is attributable to cross-national difference, beyond that which can be accounted for by the additive effects of the covariates. Model 2.3 similarly indicates that 89.6 % of the variation in emissions per dollar is attributable to cross-national difference. Finally, model 3.3 proves exceptional, and suggests that 98.4 % of variation in total emissions is attributable to such difference.

I use the variance parameters from models 1.1–1.3, 2.1–2.3, and 3.1–3.3 of Table 2 in order to calculate δ_μ. Models 1.1, 2.1, and 3.1 are considered null models, in that they only include fixed effects parameters to control for shared period effects. Models 1.2, 2.2, and 3.2 display the variance structure parameters for emissions per capita and emissions per dollar after all covariates except for the extractive colony indicator are included. The value of δ_μ for model 1.1 to 1.2 can be interpreted as the proportion of cross-unit variance in the outcome variables accounted for by these covariates. Thus, using equation (3) above, the inclusion of GDP per capita, urbanization, age dependency, FDI, manufacture, exports, and military spending, results in a δ_μ value of 83.21 % ($\delta_\mu = \frac{2.610-0.438}{2.610}*100$). As δ_μ suggests the inclusion of these covariates explains a substantial amount of cross-national variation in emissions per capita, but is far from sufficient for explaining these differences in total. This is even more the case when it comes to cross-national variation in emissions per dollar and total emissions. As the change in variance parameters and calculation of δ_μ from models 2.1 to 2.2 suggest, 10 % of cross-national variation in emissions per dollar is explained by the inclusion GDP per capita, urbanization, age dependency, FDI, manufacture, exports, and military spending ($\delta_\mu = \frac{0.501-0.449}{0.501}*100$). Change in δ_μ from models 3.1 to 3.2 suggests that the inclusion of these covariates accounts for a substantial share of the cross-national variation in total emissions, 23.17 % ($\delta_\mu = \frac{4.724-3.629}{4.724}*100$).

Finally, looking at the difference in variance parameters for models following the inclusion of the extractive colony covariate allows for the examination of how much variance in CO_2 emissions per capita, CO_2 emissions per dollar, and total CO_2 emissions is attributable to a nation having been colonized. δ_μ for change in σ_μ^2 between models 1.2 and 1.3 indicates that just under 11 % of variation in CO_2 emissions per capita is accounted for by including the binary indicator for whether a nation was colonized ($\delta_\mu = \frac{0.438-0.391}{0.438}*100$). Calculation of the δ_μ value for models 2.2 and 2.3 demonstrate that just over 11 % of the variation in CO_2 emissions per dollar is similarly accounted for by the historical fact of extractive colonization ($\delta_\mu = \frac{0.449-0.399}{0.449}*100$). The change in σ_μ^2 value for models 3.2 and 3.3 yields a somewhat smaller δ_μ value of 5.6 %–nevertheless indicating that a sizeable percent of variation in emissions outcomes is tied to cross-national difference in a nation's historical relationship to extractive colonial processes ($\delta_\mu = \frac{3.629-3.423}{3.629}*100$). Taken together, these findings provide support to H1. They also suggest, however, that while variance in total emissions is better characterized by cross-national difference than CO_2 per capita, or CO_2 per dollar, it is less deeply tied to the historical impact of extractive colonialism as well.

Table 2
Variance component models for variance partition analyses coefficient calculations.

Table 2.1 Variance component analyses for CO_2 per capita models				
Variance Terms (CO_2 per capita models)	Model 1.0	Model 1.1	Model 1.2	Model 1.3
σ_e^2(level 1)	0.112	0.083	0.046	0.046
σ_μ^2(level 2)	2.655	2.610	0.438	0.391
τ	0.959	0.969	0.904	0.894
Table 2.2 Variance component analyses for CO_2 per dollar models				
Variance Terms (CO_2 per dollar models)	Model 2.0	Model 2.1	Model 2.2	Model 2.3
σ_e^2(level 1)	0.072	0.067	0.046	0.046
σ_μ^2(level 2)	0.498	0.501	0.449	0.399
τ	0.873	0.882	0.915	0.896
Table 2.3 Variance component analyses for total CO_2 emissions				
Variance Terms (total CO_2 emissions)	Model 3.0	Model 3.1	Model 3.2	Model 3.3
σ_e^2(level 1)	0.253	0.100	0.053	0.049
σ_μ^2(level 2)	4.734	4.724	3.629	3.462
τ	0.949	0.979	0.985	0.984

Notes: All table 1 models are random intercept models. Models 1.0, 2.0, and 3.0 are null models with no predictors. Models 1.1, 2.1, and 3.1 include fixed effects estimators for year. Models 1.2, 2.2, and 3.2 include fixed effects estimators for period and GDP per capita, GDP per capita^2, urban population, an age dependency ratio, manufacturing, FDI, exports, and military spending. Models 1.3, 2.3, and 3.3 include fixed effects estimators for period and GDP per capita, GDP per capita^2, urban population, an age dependency ratio, manufacturing, FDI, exports, and military spending and a dummy for whether a nation has been colonized. In addition to these covariates, models 3.2 and 3.3 include a control for total population size.

Table 3 displays the results of random coefficient models of CO_2 emissions per capita (model a), CO_2 emissions per dollar (model b), and total CO_2 emissions (model c) with fixed effects estimators for year and AR(1) corrections for within-nation correlation structures. All three models are intended to test H2. Model a indicates that when the association between GDP per capita and emissions per capita is made to be contingent on whether or not a nation was colonized, it acquires a nonlinear character. This correlational pattern is suggestive of an EKC, where environmental impact is positively associated with economic development at lower levels of affluence and that association is reduced as affluence grows, until it is eventually found to be directionally negative. To better understand the meaning of these associations we can turn to Fig. 2a. Fig. 2a displays these associations on a natural logarithmic scale and suggests that while there does appear to be an attenuation of magnitude in the association between GDP per capita and emissions per capita, the attenuation never results in a negative association between affluence and emissions. Further, while Table 3, model a and Fig. 2a both suggest that never colonized nations reduce the association of emissions per person and GDP per capita at high levels of affluence, nation's that were historically colonized display a more or less linear trajectory in this association– such that even at extremely high levels of affluence growth in GDP per capita remains associated with growth in emissions per capita.

Table 3
Random coefficient models of CO_2 emissions per capita with fixed effects estimators for year and AR(1) corrections.

Level 1 Covariates	Model a (CO_2 per capita)	Model b (CO_2 per dollar)	Model c (Total CO_2)
GDPpc	2.199*** [1.119, 3.279] (0.550)	1.204* [0.119, 2.289] (0.553)	2.315** [0.993, 3.698] (0.705)
$GDPpc^2$	−0.100** [-0.158, -0.041] (0.029)	−0.100** [-0.158, -0.041] (0.029)	−0.109** [-0.185, -0.034] (0.038)
Urban population	0.936*** [0.777, 1.096] (0.081)	0.941*** [0.781, 1.101] (0.081)	1.135*** [0.892, 1.378] (0.123)
Age dependency ratio	−0.419*** [-0.602, -0.237] (0.093)	−0.421*** [-0.603, -0.239] (0.093)	−0.491*** [-0.721, -0.266] (0.116)
Manufacturing	0.062*** [0.031, 0.093] (0.015)	0.062*** [0.031, 0.093] (0.015)	0.056** [0.023, 0.088] (0.016)
FDI	0.000 [-0.002, 0.003] (0.001)	0.000 [-0.002, 0.003] (0.001)	0.000 [-0.003, 0.004] (0.001)
Exports	−0.000 [-0.024, 0.022] (0.012)	−0.000 [-0.024, 0.022] (0.012)	−0.016 [-0.041, 0.007] (0.012)
Military spending	0.006 [-0.008, 0.021] (0.007)	0.006 [-0.008, 0.021] (0.007)	0.004 [-0.010, 0.020] (0.007)
Total Population	–	–	0.056 [-0.054, 0.167] (0.056)
Level 2 covariate			
Extractive Colony	8.078** [2.719, 13.436] (2.733)	8.071** [2.688, 13.455] (2.746)	7.760* [0.921, 14.599] (3.489)
Cross-level interaction			
Extractive Colony * GDPpc	−2.216*** [3.420, −1.101] (0.799)	−2.213*** [-3.404, −1.022] (0.607)	−2.052** [-3.572, -0.533] (0.775)
Extractive Colony * $GDPpc^2$	0.141** [0.075, 0.207] (0.033)	0.141*** [0.075, 0.207] (0.033)	0.126** [0.040, 0.211] (0.043)
Constant	−12.153	−5.578	−5.092
Variance terms and model fit			
σ^2_{eo}(level 1)	0.102	0.101	0.476
σ^2_{uo}(level 2)	4.390	4.482	9.016
σ^2_{u1}	0.048	0.050	0.120
σ^2_{uou1}	-0.449	-0.461	-0.881
ρ	0.941	0.941	0.987
Log likelihood	3179	3179	2877
Units/Unit-years	152/4468	152/4468	149/4345

Notes: All models include fixed effects estimators for period, treat GDPpc as a random variable to allow for cross level interactions, and allow for unstructured covariance. 95% CI in brackets, se in parentheses.
*** $p < .001$, ** $p < .01$, * $p < .05$.

Model b of Table 3 displays the results of random coefficient models of CO_2 emissions per dollar with fixed effects estimators for year and AR (1) corrections for within-nation correlation structures. Here again model b is intended to test H2. Model b results demonstrate that this association becomes pronounced when moderated by the extractive colonization operator. Model b of Table 3 is suggestive of an environmental Kuznets curve between emissions per dollar and GDP per capita, but it is also clear that the character of these curves is much different for a nation that has never been colonized than for one that has. Fig. 2b graphically displays the shape of these relationships on a natural logarithmic scale. Here it can be seen that, while never colonized nations display a strong attenuation of emissions per unit of GDP at high levels of affluence, historically colonized nations demonstrate a much slower attenuation. Ultimately this suggests that though never colonized nations, on average, have seen improved efficiency in their production processes as they have become more affluent, such an attenuation is less likely for historically colonized nations, regardless of their wealth. Taken together with the results presented in model a, these finding supports H2.

Table 3, model c presents results from random coefficient models of total CO_2 emissions with fixed effects estimators for year and AR(1) corrections for within-unit correlation structures. A further test of H2, model c is meant to explore the impact that historical lag effects from extractive colonial processes are likely to have on the relationship between growth in affluence and emissions at scale. Results of model c once again suggest the existence of an EKC between total emissions and growth, and as in models a and b extractive colonies display a significantly different relationship between GDP per capita and emissions, with the relationship being less intensive in extractive colonies than elsewhere. The graphic display of these relationships is presented in natural logarithmic scale in Fig. 2c. Consistent with previous research (e.g. Jorgenson and Clark 2012) Fig. 2c suggests that the relationship between GDP per capita and total CO_2 emissions remains strong and positive in magnitude throughout the range of observed GDP per capita values. The findings presented here, however, suggest that with respect to total emissions it is nations historically positioned as extractive colonies that are more likely to attenuate emissions at higher values of affluence. Importantly, however, even as extractive colonies attenuate emissions the trend never becomes negative and there are no scenarios in which growth in affluence is estimated to reduce emissions. The results of model 3, then, provide limited support to H2 but also complicate it, as extractive colonies do indeed display different associations between GDP per capita and total emissions than their settler colonial or non-colony counterparts, but it is the former that emit less, overall, as economic development proceeds.

4. Discussion and Conclusion

As with previous research into macro structural dynamics of social drivers of GHG emissions, the findings presented here suggest that incremental policy reform and transition of business as usual development processes are unlikely to bring about the mitigation of CO_2 globally. The potential of transitional approaches to mitigation at the national scale are also consistent in that they appear to be highly context sensitive. Analyses presented here strongly suggest that, among other factors, social forces associated with the historical relations of colonialism play

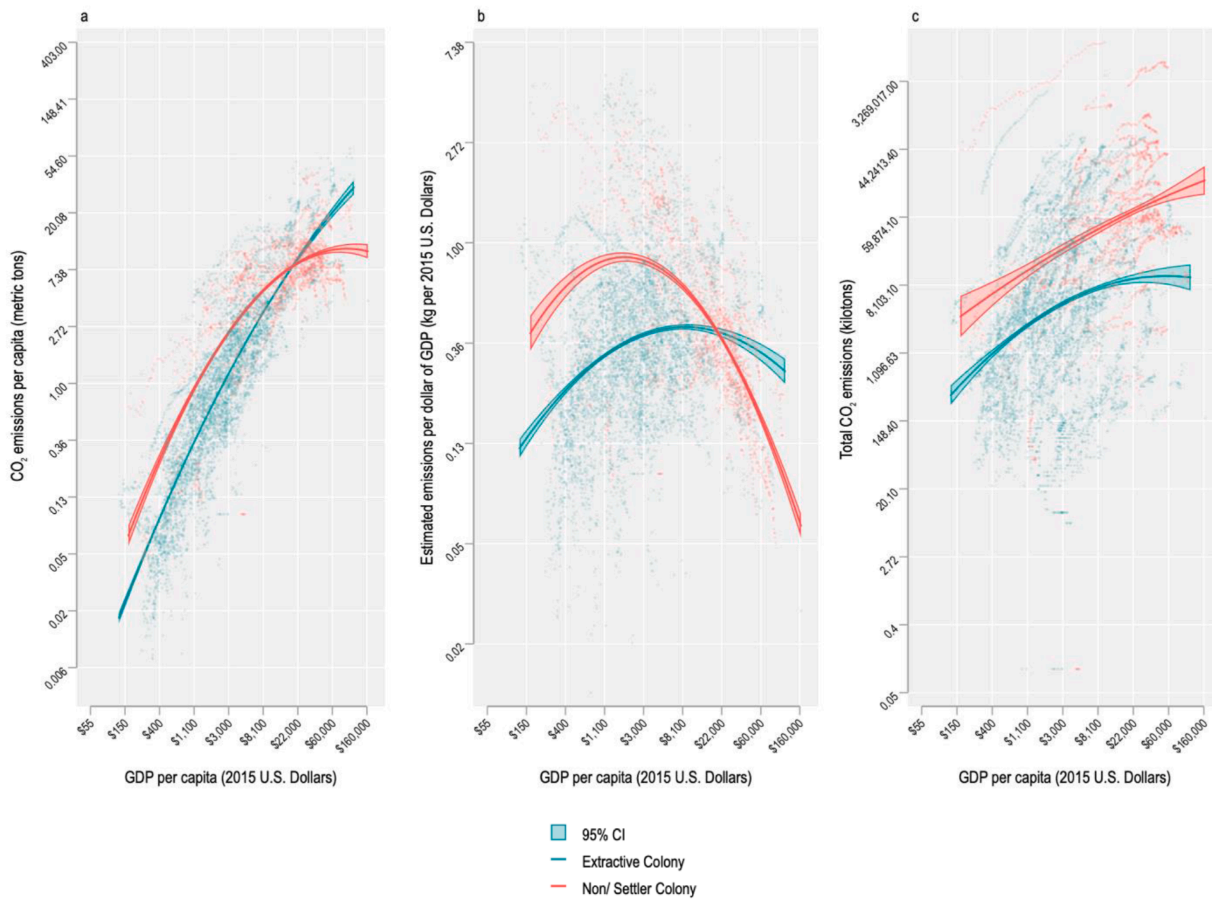

Fig. 2. Fig. 2a displays the association of GDP per capita and CO_2 per capita conditioned upon whether or not a nation was colonized on a log scale. Fig. 2b displays the same information for the association of GDP per capita and CO_2 emissions per dollar. Fig. 2c displays the same information for the association of GDP per capita and total CO_2 emissions. Note that though the scale is natural logarithmic all values have been exponentiated for ease of interpretation.

an important role in understanding the dynamics by which social, economic, and political changes come to alleviate or intensify the environmental impact of social processes. More specifically, the finding that there is an attenuation of the association between GDP per capita, CO_2 per capita, and CO_2 per dollar in never colonized nations, but far less or no attenuation of these associations in colonized nations suggests that this historical structure may need to be grappled with by policy makers and development strategists interested in bringing about both GHG mitigation and economic advance as populations and infrastructures continue to expand around the globe. Considering the findings presented above it appears that, in the majority of nations, transitions that facilitate just GHG mitigation may simply not be feasible given their historical relation with other countries.

Conversely, that total emissions are found to be both lower overall, and to display greater attenuation in historically colonized nations suggests a fundamental imbalance in which type of nation is most likely to contribute, in an absolute sense, to the crisis of climate change. It is possible that the differences in these outcomes are attributable to variation in rates of consumption at a number of analytic levels, as previous research has found embodied emissions to be much higher in economically advantaged nations (Xu and Dietzenbacher, 2014). Additionally, there is evidence that the form of urban development that occurs within a nation plays an important role in its association with emissions and energy use– with nations prone to informal urban development typically displaying less intensive relationships between urbanization, the ratio of emissions to life expectancy, and energy consumption than nations more likely to experience formal urban development (Givens 2015; McGee et al., 2017; Jorgenson et al., 2010b). In combination with the present findings that contemporary social, economic, and political relations are structured such that growing average affluence is also associated with higher emissions per person, and per dollar of economic output, this finding presents fairly strong evidence that concerns of both distributive and compensatory justice will need to be addressed directly if climate change mitigation and adaptation is to be carried out in a reasonably just, equitable manner.

Indeed, it seems clear that in addition to attending to the challenges of technological optimization and behavioral change– often a focus of climate change mitigation– research and policy aimed at reducing anthropogenic emissions must attend to the contingent, historic dynamics of social structure within CHANS (Bernard et al., 2022; Creutzig et al., 2022). Focusing on such dynamics indicates that transformation of many of the international and national relations of trade and distribution that are tied to such histories may be necessary if mitigation is to be successful in the near term.

Further, the results of the VPC and PCV analyses presented above suggest that colonial histories play a significant role in contemporary associations between GDP per capita, CO_2 per capita, CO_2 per dollar, and total CO_2 emissions– accounting for roughly 11 % of the variation in per capita and per dollar outcomes and nearly 6 % of total emissions outcomes. Yet this also indicates that there is much more variation in these outcomes that may indeed be accounted for by other historically contingent, lagged processes. These, almost certainly, are widely distributed across the human and ecological dimensions of CHANS, and may encompass factors such as the imperial regime a nation was exposed to, the long-term characteristics of the ecological systems nation states have immediate access to, or the role of nations in other historical events, such as treaty ratification. Indeed, inclusion of such considerations would likely be a useful extension of the present study, and may better characterize the importance of compensatory and procedural justice in mitigation and adaptation efforts. Additionally, much useful work remains to be done exploring the ways that structural limitations on social actions contributing to climate change mitigation influence, and are influenced by changes in individual and organizational behavior– which also contribute mightily to socio-ecological outcomes (e.g Dietz et al., 2009; Taufique et al., 2022; Vandenbergh and Gilligan, 2017; Vandenbergh, 2018).

While questions remain around what key features of social systems lend themselves to mitigation, what is clear is that better attention to the various scales that the temporal dynamics of social processes function across is necessary to policy and research efforts that can meaningfully engage with national and international climate change mitigation efforts. The analyses presented here have contributed to such efforts by using random intercept and coefficient modeling techniques to explore both the proportion of variation in emissions outcomes attributable to extractive colonial processes of the past, as well as differential relationships between growth of affluence and emissions across nations that were extractive colonies and those that were not. Findings of these analyses, with respect to the history of colonial relations, strongly suggest that a non-linear transformation of social systems at the national and international level is an important component of the successful mitigation of climate change. These findings also provide further support for the importance of including considerations of compensatory, distributive, and procedural justice in any proposed transition and transformation of policy structures aimed at mitigating GHG emissions at the national level.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2022.102609.

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