The Inequities of Global Adaptation to Climate Change

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Abstract

With efforts to mitigate climate change lagging behind what is necessary to achieve Paris Agreement global warming targets, adaptation to current and anticipated future climate conditions becomes increasingly urgent. This study provides a novel composite adaptation index to assess the relative adaptation performance of nations, using two complementary techniques, a distance to frontier analysis and a dominance analysis. Adaptation performance is closely and positively related to both national income per capita and national greenhouse gas emissions per capita, highlighting global adaptation inequities consistent with the IPCC assessment that nations most affected by climate change are those that are least able to adapt and contribute least to the problem.

1. Introduction

The 2015 Paris Agreement sought to limit global warming to a 2 C increase above pre-industrial levels by the end of the century, with an aspirational increase of 1.5 C. The Intergovernmental Panel on Climate Change (IPCC) (2018) predicted a greater than 50% likelihood that global warming will reach or exceed 1.5 C much sooner, between 2030 and 2052, even for a greenhouse gas emissions scenario that increases at less than the current rate.

The International Energy Agency (IEA) (2021) warned shortly before COP26 in Glasgow that national pledges to reduce greenhouse gas emissions "…fell short of what was called for in the Paris Agreement…" In its *Adaptation Gap Report 2021* launched at COP26, the United Nations Environment Programme (UNEP) (2021a) warned that mitigation efforts to cut greenhouse gas emissions are "…still not anywhere near strong enough…" and called for greater efforts toward planning, financing, and implementation of adaptation, calling adaptation an increasingly urgent global imperative, citing evidence suggesting that adaptation financing needs in developing countries are five to ten times greater than current international adaptation finance flows, and that this gap is growing. UNEP (2021b) predicted that implementation of current mitigation pledges implied a 50% chance of keeping global warming to 2.5 C (with a range of 2.0 C to 2.9 C) by the end of the century. The urgency of adaptation and the inadequacy of needed financial support echo the vews expressed so eloquently in The Stern Review (2006), which argued that the climate will continue changing through the near future, however successful mitigation efforts are, and without early and strong mitigation the costs of adaptation will rise exponentially.

The IPCC (2021) determined that some impacts of climate change are unavoidable due to the longevity of greenhouse gases already in the atmosphere, The IPCC (2022) attributed widespread impacts to human-induced climate change, particularly through increased frequency, severity and duration of a wide range of extreme events. It emphasised the significance of adaptation by noting that near-term actions to mitigate emissions that would limit global warming would reduce projected losses but would not eliminate them. As in previous Assessment Reports, it stressed the inequity of the distribution of the adverse impacts of global warming, with the most vulnerable people and systems being disproportionately affected. Unlike previous Assessment Reports, it highlighted adaptation actions that are effective, equitable, and just. This study examines the effectiveness and, following Stern, the equity of adaptation.

Adaptation, particularly transformative adaptation, requires resources and financing often unavailable in developing countries, but recent climate change financing has gone primarily to mitigation. While mitigation is the preferred way to lower the impacts and costs of climate change, support for adaptation planning, financing, and implementation is critical to keep existing adaptation gaps, defined by the IPCC (2022) as the difference between implemented adaptation and societally set adaptation goals, from widening. UNEP (2021a) documented that planning, financing, and implementation of adaptation remain weak, and only a small portion of the fiscal stimulus to combat the pandemic has targeted climate finance, and a small portion of that has gone to adaptation. The IPCC (2022) documented that recent adaptation progress has been unevenly distributed within and across regions and focused more on planning than implementation.

Adaptation faces constraints that can prevent it from reaching its potential. Adger and Barnett (2009) and Massetti and Mendelsohn (2018) claimed that while adaptation has the *potential* to greatly reduce climate change damage, there is no guarantee this potential will be reached. The distinction between adaptation and adaptive potential suggests an application of the concepts of best practice and dominance to evaluate nations' adaptation performance. Some nations adapt better than others, perhaps because they face fewer constraints to adaptation than others, inadequate resourcing and financing being prominent constraints, limited governance competence another. Analytical techniques have been developed to implement the concepts of best practice and dominance, with empirical performance evaluation applications ranging widely, including the environmental performance of businesses (Trinks et al. (2020)) and nations (Bosetti and Buchner (2009), Matsumoto et al. (2020)). This study applies these concepts to assess the inequity of the climate change adaptation performance of nations.

The potential gains to adaptation can be substantial. The United Nations has estimated that a $1.8 trillion investment in adaptation, including early warning systems, climate-resilient infrastructure, improved agricultural practices, mangrove protection along coastlines, and resilient water resources, could generate $7.1 trillion in benefits through a combination of avoided costs and a variety of social and environmental benefits.

With this background, the study has three objectives. The first is to obtain a set of adaptation indicators and to aggregate these indicators into a composite adaptation index; this appears in Section 4. The second is to provide an analytical framework for quantifying the composite adaptation performance of nations; this is the subject of Section 5. The third is to explore the distribution of the composite adaptation performance of nations, and to illustrate its inequities; this is the subject of the empirical analysis in Section 6.

The paper proceeds as follows. Section 2 surveys the IPCC treatment of adaptation, and the activities that contribute to it and the factors that constrain it. Section 3 surveys the literature on the inequity of adaptation. Section 4 introduces the data, obtained from the University of Notre Dame Global Adaptation

Initiative (2021), used to assess the adaptation performance of nations. Section 5 describes the distance to frontier and dominance techniques used to implement an assessment of nations' adaptation performance. Section 6 presents the empirical findings of the study, which vividly illustrate the inequities of climate change adaptation and provide strong support for the growing emphasis the IPCC has placed in successive Assessment Reports for the need to increase climate change funding, and to reallocate funds from mitigation to adaptation and from developed to developing nations. Section 7 concludes with a summary of the findings and their implications for the climate justice movement.

2. The Ipcc On Adaptation

The IPCC (2001) expressed five reasons for concern about vulnerability to climate impacts, concerns which it has re-evaluated in subsequent Assessment Reports. The reasons involve relationships between global mean temperature increase and five projected adverse impacts: risk of damage to or irreparable loss of unique and threatened systems, the distribution of its impacts, the magnitude of aggregate impacts, the risk of extreme weather events, and the risk of large-scale singular events. These concerns led it to consider the role of adaptation, which it defined as adjustment in natural and human systems to the actual or expected impacts and risks of climate change. It distinguished adaptation from adaptive capacity, which it defined as the *ability* (emphasis added) of a system to adjust to climate change, to moderate potential damages, or to cope with the consequences. It viewed adaptation as a necessary strategy to complement climate change mitigation efforts and noted that the ability to adapt to and cope with climate change depends on wealth, technology, education, information, human and social capital, infrastructure, institutions, management capabilities, and access to resources. Subsequent Assessment Reports have expanded on these drivers, citing new and possibly disruptive technologies and enhanced climate-driven innovation, and a supportive institutional framework.

The IPCC (2001) attributed the difference between actual adaptation and adaptive capacity to maladaptation and constraints to achieving potential adaptation. This distinction was strengthened in IPCC (2007), which stated (p. 886) "[t]he message from the literature is clear: adaptive capacity signals potential but does not guarantee adaptive action", and warned that more extensive adaptation than was currently occurring would be required to reduce vulnerability to future impacts of global warming. It cited regulations and policies, limited governance capacity, availability and distribution of finance, violent conflict, the spread of infectious diseases, and urbanisation as factors that may facilitate or constrain adaptation. This list of constraints has changed little through successive Assessment Reports; the IPCC (2022) cites financial, governance, institutional and policy constraints.

Of particular relevance to this study, the IPCC (2001) asserted that nations with the least resources have the least capacity to adapt and are most vulnerable to climate change impacts, and that the projected distribution of impacts would increase the disparity in well-being between developed and developing nations, with the disparity growing for higher projected temperature increases. The IPCC (2014) noted that differences in vulnerability and exposure that require adaptation arise from non-climatic factors and from multidimensional inequalities associated with uneven development processes, with people who are socially, economically, culturally, politically, institutionally, or otherwise marginalised being especially vulnerable. The IPCC (2018) identified populations and regions at disproportionately higher risk of adverse impacts, including disadvantaged and vulnerable populations, local communities dependent on agricultural or coastal livelihoods, small island developing states (SIDS), and Least Developed Countries (LDCs). It suggested that social justice and equity are core aspects of climate-resilient pathways, that a consideration of ethics and equity can address the uneven distribution of adverse impacts and concluded that international cooperation is critical for developing countries and vulnerable regions. The IPCC (2022) stated that poor and otherwise disadvantaged groups are especially vulnerable because they are highly exposed to climate change impacts and have fewer assets and less access to funding, technologies, and political influence.

These definitions of adaptation, adaptive capacity, and adaptation constraints, and the proclaimed inequity in the distribution of adaptation, have changed little through successive Assessment Reports. A second consistency is the lack of a definition of adaptive readiness, although some of its drivers are mentioned often (e.g., innovation, education, governance).[1] A third consistency involves the lack of acknowledgement of an association between the greenhouse gas emissions of developed countries and the climate change impacts that disproportionately affect developing countries responsible for few emissions. What has changed in successive Reports is the knowledge base, consisting of advances in science and increases in the quantity and quality of evidence in databases and in the scientific, technical, and socioeconomic literatures. This has allowed the IPCC to increase the confidence it attaches to its assessments of the relationship between global warming and its impacts in each successive Assessment Report.

[1] The IPCC (2022) has extolled the significance of *enabling conditions*, including political commitment, institutional frameworks, knowledge, and monitoring and evaluation. These conditions overlap with the adaptation readiness indicators used in this study.

3. The Inequities Of Adaptation

Successive IPCC Assessment Reports have noted the unequal distribution of vulnerability and adaptive capacity among and within nations and stated that climate change is exacerbating existing inequities.

Stern (2006) argued that, historically, rich countries have produced the majority of greenhouse gas emissions and developing countries have suffered the consequences because of their geography, their dependence on agriculture, and their limited adaptive capacity. He continued by stating “[t]here is therefore a double inequity in climate change: the rich countries have special responsibility for where the world is now, and thus for the consequences which flow from this difficult starting point, whereas poor countries will be particularly badly hit”. Stern called on developed countries to honour their existing commitments to provide financial aid to developing countries to support their adaptation efforts.

Füssel (2010) conducted an empirical test of Stern's double inequity hypothesis, by comparing the socio-economic capability and causal responsibility of nations on the one hand, and the vulnerability of nations in four climate-sensitive sectors. He demonstrated the first inequity by showing that some nations have more adaptive capacity than other nations, as measured by their economic capability (GDP per capita) and their social capability (the United Nations Development Programme (UNDP) (2020) Human Development Index). Additionally, nations with the most capability are most responsible for climate change since greenhouse gas emissions (CO_2 emissions per capita cumulated since 1990) are highly correlated with these capability indicators. Füssel asserted that this double inequity "…strengthens the moral case for financial and technical assistance from those countries most responsible for climate change to those countries most vulnerable to its adverse impacts." Diffenbaugh and Burke (2019) reached similar conclusions, finding that many poor countries have been significantly harmed by global warming arising from wealthy countries' energy consumption, either because they lack the resources to adapt, or because they are in warm regions where additional warming is detrimental to health and productivity. They found the ratio between top and bottom deciles of the population-weighted country-level per capita GDP distribution to be 25% larger than it would be without global warming and concluded that since "…wealthy countries have been responsible for the vast majority of historical greenhouse gas emissions, any clear evidence of inequality in the impacts of the associated climate change raises critical questions of international justice".

Khan et al. (2020) examined 25 years of adaptation finance justice, revisiting Stern's call for financial aid flows from developed to developing countries. They defined adaptation finance justice as raising adaptation funds according to the responsibility for climate impacts, and allocating funds putting the most vulnerable first, and concluded that climate justice has not been achieved, with a refusal by wealthy nations to define commitments in relation to responsibility and needs. Alcaraz et al. (2018) proposed the opposite strategy, reallocating the global carbon budget consistent with a 2 C global mean temperature increase using climate justice criteria.

4. The Data

Many of the variables cited above as influencing adaptation to climate change appear in the ND-GAIN country data from the University of Notre Dame Global Adaptation Initiative (2021). These data are therefore used, in a manner guided by the IPCC and related literatures. The ND-GAIN country index is constructed from 36 vulnerability indicators and nine readiness indicators for up to 192 nations over varying time periods concluding in 2019. The vulnerability indicators consist of 12 exposure indicators, 12 sensitivity indicators and 12 adaptive capacity indicators, each measured on [0,1] with low (high) values indicating low (high) vulnerability.[2]

ND-GAIN defines adaptive capacity as "the ability of society and its supporting sectors to adjust to reduce potential damage and to respond to the negative consequences of climate events…" The 12 adaptive capacity indicators "…seek to capture a collection of means, readily deployable to deal with sector-specific climate change impacts". ND-GAIN defines adaptation readiness as preparedness "…to make effective use of investments for adaptation actions thanks to a safe and efficient business environment…" It measures adaptation readiness with three components: economic, governance and social. These interpretations and definitions suggest a strong complementarity between adaptive capacity and adaptation readiness and are consistent with the views expressed by the IPCC. They also support the creation of a composite adaptation index, since adaptive capacity itself is insufficient for successful adaptation without the political, social, and institutional support provided by adaptation readiness.[3]

Consequently, the hypothesis to be tested states that the adaptation performance of nations is a function of their adaptive capacity and features of their institutional environment that enhance or constrain their adaptive capacity, features that the IPCC (2022) calls enabling conditions. To test this hypothesis 12 adaptive capacity indicators and nine adaptation readiness indicators are extracted from the ND-GAIN database for the terminal year 2019. The adaptive capacity indicators are augmented with the adaptation readiness indicators because the IPCC consistently refers to various enabling conditions (e.g., regulatory quality, innovation, and education) as being important elements in the ability of nations to adapt to unmitigated climate change.

Three adjustments have been made to the ND-GAIN data. The 12 adaptive capacity indicators have been transformed because ND-GAIN associates high vulnerability indicators with high vulnerability, and adaptive capacity is one of three components of vulnerability. Since adaptive capacity reduces vulnerability, each adaptive capacity indicator is redefined so that high values of each adaptive capacity indicator are associated with high adaptive capacity, thereby retaining their [0,1] range. Two of the transformed indicators, "improved water source (% of population with access)" and "improved sanitation facilities (% of population with access)" have missing values for 94 and 103 nations respectively, and have been replaced with a new water indicator, the geometric mean of "dam capacity" from ND-GAIN and "average precipitation in depth (mm per year)" from the World Bank's World Development Indicators. This new water indicator combines rainfall with water storage capacity and provides a nearly necessary condition for the original water indicator while increasing coverage from 98 to 134 nations, leaving 11 adaptive capacity indicators.

These three adjustments generate a pair of data matrices, one consisting of 11 adaptive capacity indicators for up to 192 nations, and the other consisting of nine adaptation readiness indicators for up to 192 nations. However, these two matrices contain many missing observations. One adaptive capacity indicator, disaster preparedness, is missing for 56 nations, and two adaptation readiness indicators, social inequality and innovation, are missing for 43 and 44 nations. These three indicators have been deleted, leaving nine adaptive capacity indicators and seven adaptation readiness indicators. If a nation is missing one or more of the nine remaining adaptive capacity indicators, that nation is deleted from the adaptive capacity matrix, and similarly for the adaptation readiness matrix. This leaves an adaptive capacity matrix consisting of nine indicators for 143 nations and an adaptation readiness matrix consisting of seven indicators for 172 nations. In order to merge information on adaptive capacity with information on adaptation readiness into a composite adaptation index, the sample is restricted to nations having values for all 16 indicators, leaving an adaptive capacity matrix consisting of nine indicators and an adaptation readiness matrix consisting of seven indicators, both for the same 134 nations. Summary statistics for the 16 indicators appear in Appendix Table 1.

The data set contains 32 LDCs and 11 SIDS. These nations have been singled out by the IPCC and at COP26 as being victims of climate change caused largely by developed nations, who have lagged in both their mitigation efforts and their financial support to developing nations. This dichotomy has been labelled an equity and ethical issue in consecutive IPCC Assessment Reports, and a justice issue by many, including by Robinson and Shine (2018), Simmons (2020), and Klinsky (2021), who argue that countries most vulnerable to climate change are the least responsible for generating the causal CO_2 emissions.

[2] The ND-GAIN data have been used often to study climate change; among recent studies are Edmonds et al. (2020), Halkos et al. (2020) and Ripple et al. (2022).
[3] Amegavi et al. (2021) used a subset of the database we use to show that adaptation readiness is significantly and negatively related to vulnerability to climate change in 51 African nations. Our results support this finding and point to the significance of adaptation readiness in a larger global sample of nations.

5. The Analytical Techniques

A pair of complementary analytical techniques is used to assess the relative adaptive capacity and adaptation readiness of nations. Each technique is illustrated using adaptive capacity, and the same analysis applies to adaptation readiness. Both techniques identify leading and lagging nations. The first identifies leaders and laggards by using Data Envelopment Analysis (DEA) to exploit the "distance to frontier" concept of Acemoglu et al. (2006) and applied to OECD productivity dispersion data by Andrews et al. (2016) and Berlingieri et al. (2017). The second identifies leaders and laggards by using dominance analysis to identify nations that are structurally similar but perform better than other nations, regardless of their distance to the best practice frontier.

The first technique, DEA, is a linear programming technique developed by Charnes et al. (1978) to assess the relative performance of observations in a sample. Rather than fitting a regression through the data, as most statistical techniques do, DEA constructs a frontier that envelops the data, from above if the objective is to maximise and from below if the objective is to minimise. The frontier consists of best practice observations, and with a maximisation orientation observations beneath the frontier lag best practice by varying degrees. In the current setting higher adaptation indicator values are preferred, and DEA constructs an adaptive capacity frontier that bounds an adaptive capacity set from above. The adaptive capacity frontier consists of best practice nations, those that adapt best, and the interior of the adaptation set contains nations whose adaptation performance lags best practice, or the "best" and the "rest" in OECD productivity parlance.

Let nations be indexed by i=1,…,I, and let a nation's adaptive capacity be tracked across N sectors with sectoral adaptive capacity indicators labelled y_n and indexed by n=1,…,N. In the current application I=134 and N=9. The DEA program that evaluates the aggregate adaptive capacity to cope with climate change of nation "o" is given by the dual pair of linear programs in Figure 1. These programs calculate an endogenously weighted adaptive capacity index ACI for each nation. This index aggregates N individual adaptive capacity indicators y_n into a single adaptive capacity index ACI.

The envelopment program in Figure 1 envelops nations' adaptive capacity data from above and calculates the potential of nation "o" to expand its vector of sectoral adaptive capacity indicators y_o as much as possible, subject to N constraints, one for each sectoral indicator. These constraints bound the expanded vector θy_o above by a nonnegative combination of the most capable nations in the sample. The optimal value of $\theta \in [1, +\infty)$. A value $\theta = 1$ indicates best practice adaptation on the adaptive capacity frontier, with larger values of θ indicating the degree to which a nation must improve its adaptation performance to reach the best practice frontier. θ also forms the basis for an analytically sound measure of a nation's *adaptive capacity gap*, the difference between (or ratio of) its actual adaptive capacity y_o and its potential adaptive capacity θy_o. Deviations beneath this frontier provide an alternative representation of nations' adaptation gaps to the UNEP Adaptation Gap Reports of the same name by replacing a vague "societally set goal" with a best practice that can be estimated empirically. The reciprocal $\theta^{-1} \in (0, 1]$ is a nation's *adaptive capacity index* ACI. A value $\theta = 1$ indicates best practice adaptation, and lower values of θ^{-1} indicating lower levels of adaptive capacity. θ^{-1} provides a ranking of nations based on their overall adaptive capacity to cope with climate change, independently of any other national characteristics.

The multiplier program in Figure 1 calculates for nation "o" a vector of endogenous weights $\nu_n \in (0, +\infty)$ with which to aggregate its sectoral adaptive capacity indicators into its ACI. By the duality theorem of linear programming, at optimum $\theta = \mu$, and ACI can therefore be expressed as an endogenously-weighted sum of its sectoral adaptive capacity indicators, $\theta^{-1} = (\sum_{n=1}^{N} \nu_n x_{ni})^{-1}$ for any nation i=1,...,o,...,I.[4] Endogeneity of weights is central to the analysis, having the virtue of not forcing nations to value sectoral adaptive capacities equally. For a nation with an abundance of sectoral adaptive capacity indicator y_n the program implicitly attaches a large weight to this indicator to maximise its ACI. Conversely, for a nation with a paucity of sectoral adaptive capacity indicator y_n the program implicitly attaches a small weight to this indicator to maximise its ACI. These endogenous weights provide a considerable improvement over the fixed weights used in most composite indices, including the popular UNDP (2020) Human Development Index and the ND-GAIN index. The endogenous weights impose perfect substitutability among component indicators within nations, but with the important advantage that weights, and rates of substitution among component indicators, are allowed to differ across nations according to their circumstances. Weight flexibility is particularly important in the construction of an adaptive capacity index, since nations differ in their exposure, sensitivity, and vulnerability to climate change across sectors. By reflecting different adaptive capacities across sectors that in turn reflect different national circumstances, these weights have the potential to assist in the design of policies intended to allocate climate finance to enhance adaptive capacity in an equitable manner.

However, weight endogeneity has a potential drawback. As the number of choice variables relative to the sample size increases, estimation becomes exponentially more difficult, a situation known as the curse of dimensionality. In our setting the number of adaptive capacity indicators relative to the number of nations in the sample N/I = 9/134 is sufficiently large to hinder evaluation of the adaptation performance of nations. In effect, having nine adaptive capacity indicators gives nations excessive freedom to choose weights in creating their ACIs, resulting in many nations receiving ACI = 1, even though their index may be the consequence of being different rather than excelling. The curse is less severe in the case of adaptation readiness, where N/I = 7/134.

The second technique, dominance analysis, provides information complementary to that provided by DEA.[5] Consider two nations with adaptive capacity vectors y_j and y_k. Nation j dominates nation k if nation j has at least as much adaptive capacity as nation k for all N indicators, that is if $y_{nj} \geqq y_{nk}$, $\forall$ n=1,...,N. Aggregating the inequality over all k = 1,...,I nations generates the number of nations nation j dominates. Reversing the inequality generates the number of nations that dominate nation j. This strategy can be extended by deleting d $\geqq$ 1 adaptive capacity indicators at a time, with replacement, to evaluate dominance with N-d indicators. This provides a way of determining the indicators for which a nation is most or least dominant.

Dominance analysis is independent of the notions of best practice adaptation, adaptation gaps, and adaptive capacity. Rather, it identifies leaders as the most frequently dominating nations and laggards as the most frequently dominated nations. In doing so it identifies role models for dominated nations. These role model nations are relevant because they have similar mixes of adaptive capacity indicators, but with larger indicator values. A nation can dominate other nations by being similar to them and without being best practice, and a nation can be best practice by being different from other nations and without dominating any of them.

This analysis of DEA and dominance analysis has been illustrated with application to adaptive capacity, and the analysis applies equally to adaptation readiness.

[4] These endogenous weights are also called “benefit of the doubt” weights, a term introduced by Melyn and Meusen (1991). Cherchye et al. (2007) provide details on benefit of the doubt composite indices.

[5] The basics of dominance analysis are extracted from a detailed presentation in Tulkens (2006).

6. Results And Discussion

This Section summarises the main findings of the study. Section 6.1 discusses findings based on DEA and Section 6.2 discusses findings based on dominance analysis. Section 6.3 summarises the findings on the inequity of the global distribution of adaptation performance and reinforces the assertions of Stern and the IPCC concerning the double inequity of global adaptation to climate change.

6.1 DEA results

DEA is used to aggregate the nine adaptive capacity indicators into an adaptive capacity index ACI for each nation and to aggregate the seven adaptation readiness indicators into an adaptation readiness index ARI for each nation. This procedure identifies leading and lagging nations in adaptive capacity and adaptation readiness, respectively. The two indices are then combined to generate a composite adaptation index CAI for each nation in two ways, by calculating the geometric mean of ACI and ARI, and by applying DEA to aggregate ACI and ARI. Both procedures identify leaders and laggards in composite adaptation performance, or the ability to enhance adaptive capacity with a supportive institutional environment. The first has the virtue of simplicity, but implicitly treats the two components as being equally important. The second yields information on nations' comparative advantage in adaptation and readiness. The rank correlation between the two composite adaptation indices is calculated to test the concordance of the two strategies.

Results of using DEA to construct ACI and ARI are not reported because of the emphasis the IPCC places on complementarity between capability and readiness. The majority of the most capable and most ready nations are European nations and their Western Offshoots,[6] while most of the least capable and least ready nations are LDCs. For these nations the advantage of having the freedom to choose weights is offset by the disadvantage of having relatively small values of adaptive capacity and adaptation readiness indicators to which weights are attached. The mean adaptive capacity of laggard nations is barely 65% that of leader nations, and their mean adaptation readiness is even lower, at 47% that of leader nations.

Table 1 combines adaptive capacity and adaptation readiness by reporting 21 leading nations and 20 lagging nations in composite adaptation, using the geometric mean of adaptive capacity and adaptation readiness indices to generate CAI. The curse of dimensionality appears for the most capable nations, 19 of which are European nations or their Western Offshoots. Most of the least capable nations are LDCs, primarily sub-Saharan African, South Asian, and SIDS. The laggards' mean CAI value is barely half, 57%, the mean CAI value of the leaders. The picture that emerges is one of European nations and their Western Offshoots being institutionally prepared to exploit their relatively abundant adaptive capacities, and LDCs lacking the economic, governance and social readiness to exploit their limited adaptive capacities. All 134 nations are mapped according to their composite adaptive capacity index CAI in Figure 2. The leaders are located at higher latitudes in the northern and southern hemispheres, and the laggards are located at lower latitudes closer to the equator. White areas indicate nations not among the 134 nations in the data set due to insufficient data.

Results of using DEA to construct a CAI and to identify leaders and laggards are not reported because they are very similar to those using the geometric mean to construct a CAI, with a rank correlation between the two composite adaptation indices of 0.843. A virtue of using DEA to construct a CAI is that, unlike the geometric mean, which weights the two component indices equally, DEA assigns endogenous weights to nations that vary with their circumstances and their relative endowments of adaptive capacity and adaptation readiness in constructing their CAI. A huge majority, 128 of 134 nations, assign zero weights to adaptation readiness, suggesting that most nations, rich and poor, lack the institutional framework that constitutes adaptation readiness, to complement their adaptive capacities. Adom and Amoani (2021) and Arezki (2021) have emphasised the lack of adaptation readiness in Africa, whose nations dominate the CAI laggards, citing limited climate finance absorptive capacity stemming from relatively weak state capacity, inadequate economic governance, weak financial systems, and inefficient transport systems.

6.2 Dominance analysis results

Findings from the application of dominance analysis are collected in Table 2 for adaptive capacity and in Table 3 for adaptation readiness. The dominance relationship is demanding, requiring a nation to dominate, or be dominated, by another nation for every indicator, nine for adaptive capacity and seven for adaptation readiness. Nonetheless, empirical dominance relationships are numerous, particularly for adaptation readiness. As with the results in Table 1, the majority of the most dominating nations in Tables 2 and 3 are European nations and their Western Offshoots, and the majority of the most frequently dominated nations are LDCs.

Twelve of the most dominating nations in adaptive capacity and 17 of the most dominating nations in adaptation readiness appear among the leaders in composite adaptation, and 11 of the least dominating nations in adaptive capacity and 15 of the least dominating nations in adaptation readiness appear among the laggards in composite adaptation. These findings suggest a concordance between capacity and dominance, particularly among leaders, and also demonstrate that frequently dominating nations are not necessarily composite adaptation leaders (e.g., Portugal), and frequently dominated nations are not necessarily composite adaptation laggards (e.g., Angola).

It is worth noting that New Zealand is a high performer, ranking among the leaders in composite adaptation and the leading nation in both types of dominance. This strong showing is consistent with the findings of King and Jones (2021), who augmented the ND-GAIN data with three additional indicators: arable land availability, renewable energy availability, and isolation. They found New Zealand to have the most favourable “starting conditions” to form a “node of increasing complexity”, followed by Iceland, the United Kingdom, Australia, and Ireland. It should be noted that their third additional indicator, isolation, favours island nations.

6.3 Inequity results

Table 4 highlights one dimension of the inequity of global composite adaptation, by listing the GDP per capita of the most and least capable nations ranked by CAI.[7] The most capable nations have mean CAI 75% greater than that of the least capable nations and have mean GDP per capita nearly 15 times that of the least capable nations. This finding is consistent with assertions in IPCC Assessment Reports that adaptive capacity is a function of several factors, the first being wealth, and developing nations cannot afford to invest in composite adaptation. It strongly supports calls for an increase in climate finance and a greatly expanded transfer of this increase from developed nations and international development banks to developing nations, and for a reallocation of the increased funding from mitigation to adaptation.

Table 5 reinforces the inequity of global composite adaptation by shifting attention from an income dimension to a responsibility dimension. The most and least capable nations by CAI are compared according to their greenhouse gas emissions per capita.[8] The most capable nations are also the main source of global greenhouse gas emissions, emitting nearly 3.5 times as much per capita as the least capable nations. Developing nations are not the source of climate change impacts that threaten them. Taken together, Tables 4 and 5 provide a strong confirmation of Stern's (2006) double inequity.

Table 6 combines income and responsibility to provide a holistic confirmation of Stern's double inequity of adaptation performance. The most and least capable nations by CAI are compared according to their generic inequity index GII, constructed as the geometric mean of their income and responsibility indices GDP per capita and GHG per capita. Laggards have mean CAI 57% of that of leaders, and a mean GII 14% of that of leaders. Those nations most capable of adapting to climate change are both wealthy and the source of most causal greenhouse gas emissions, and those nations least capable of adapting are neither wealthy nor the source of emissions. If laggards and leaders are defined more generously as the bottom and top 50 nations based on CAI, the magnitude of the double inequity is barely dented. The mean CAI of redefined laggards rises to 69% of that of redefined leaders, and their mean GII rises to 26% of that of redefined leaders.

The double inequity illustrated in Table 6 is confined to leaders and laggards, but the double inequity affects all nations, with a strong positive correlation between nations' CAI and their GII of 0.684. To illustrate the entire distribution rather than just its upper and lower tails, GII indices for 131 nations are mapped in Figure 3.[9]With few exceptions, the wealthy source nations are European nations and their Western Offshoots, and the poor recipient nations are in Africa, the Sub-Continent, and South Asia. A comparison of Figure 3, which maps GII, with Figure 2, which maps CAI, provides a vivid depiction of Stern's double inequity. With a few notable exceptions, the two maps are nearly indistinguishable.

Tables 5 and 6, and Figures 2 and 3, have a geographical interpretation as well as an inequity interpretation. Composite adaptation leaders are relatively rich and largely responsible for climate change impacts, and are located at higher latitudes in the northern and southern hemispheres (e.g., Canada in the north and New Zealand in the south). Composite adaptation laggards are relatively poor and not responsible, and cluster at lower latitudes close to the equator (e.g., Togo and Papua New Guinea). This geographical interpretation was proposed by Nordhaus (1994), who compared GDP per capita with latitude and temperature for a sample of 77 nations. He found rich nations located in cool latitudes away from the equator and poor nations located in warm latitudes near the equator.[10]

[6] Maddison (2006) introduced the term “Western Offshoots” to categorise the US, Canada, Australia, and New Zealand.

[7] GDP per capita data are 2019 GDP per capita PPP (current international $) from the World Bank (https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD).

[8] Greenhouse gas emissions per capita data are for 2016 sourced from Our World in Data (https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions).
[9] Three nations are deleted in constructing the generic inequity index GII. GDP per capita data are unavailable for Syria, and Bhutan and Gabon report negative greenhouse gas emissions. For explanations for Bhutan’s negative emissions see https://ourworldindata.org/co2/country/bhutan and for Gabon’s see https://ourworldindata.org/co2/country/gabon.

[10] Nordhaus was co-recipient of the 2018 Nobel Prize in Economic Sciences “for integrating climate change into long-run macroeconomic analysis”. In Nordhaus (1977), he originally proposed a global warming target of 2 C above pre-industrial levels now enshrined in the Paris Agreement.

7. Conclusions

The Introduction set three objectives for this study: to create a database of indicators conforming to the IPCC concept of adaptation, to propose analytical techniques with which to assess the adaptation performance of nations, and to explore the distribution of adaptation performance among nations and assess its inequities.

The first objective is achieved in Section 4, in which a database incorporating the adaptation indicators proposed in successive IPCC Assessment Reports is created. These indicators reflect a belief that a supportive institutional environment is essential to the success of adaptation efforts. The database is drawn from the ND-GAIN database, although it is not equivalent to it. The second objective is achieved in Section 5, in which a linear programming distance to frontier technique, DEA, is augmented with a dominance analysis. The two approaches provide complementary insights into global adaptation performance, by identifying leaders and laggards according to different criteria.

The third objective is achieved in two stages in Section 6. In the first stage leading and lagging nations are identified in terms of their relative composite adaptation performance. The overriding impression gained from the distance to frontier analysis is one of very large dispersion in nations’ adaptation performance. The adaptation gap between leading and lagging nations is large, with lagging nations’ adaptation performance on the order of 57% of that of leading nations. The gap is attributable primarily to inadequate adaptation readiness of institutional environments that plagues nearly all nations and is particularly severe among lagging nations. This impression of large dispersion is reinforced when the geometric mean is replaced by DEA to aggregate adaptive capacity and adaptation readiness, with most nations weighting the former more heavily than the latter. The distance to frontier analysis is augmented with a dominance analysis on adaptive capacity and adaptation readiness criteria separately. The significance of adaptation readiness is strengthened in the dominance analysis, in which dominance relationships are roughly twice as frequent with adaptation readiness as with adaptive capacity, attesting further to the importance of a supportive institutional environment.

In the second stage of the empirical analysis composite adaptation leaders and laggards are identified by their location. In terms of both distance to frontier and dominance, composite adaptation leaders are overwhelmingly European nations and their Western Offshoots located in higher latitudes in the northern and southern hemispheres, and laggards are equally overwhelmingly LDCs located in lower latitudes close to the equator. The distance to the equator principle of economic development applies equally well to climate change adaptation performance.

When an income dimension is added to the characterisation, leaders have approximately 15 times the GDP per capita as laggards have. This relationship applies to the entire distribution of nations, not just to the leading and lagging tails; the correlation between income and composite adaptation performance is 0.75. Nations' composite adaptation performance varies positively and strongly with national income, as the IPCC asserts. This finding illustrates one of Stern's double inequities of adaptation; the poorest nations are the least able to adapt to climate change impacts. When responsibility for climate change is added to the characterisation, leaders generate more than three times the amount of GHG emissions per capita as laggards do. This relationship also holds for the entire distribution of nations; national composite adaptation performance varies positively, although not strongly due to a few prominent outliers, with responsibility for climate change. This finding illustrates the other of Stern's double inequities of adaptation; nations least responsible for causal greenhouse gas emissions are least able to adapt to their impacts.

When a combination of income and responsibility is added to the characterisation, Stern's double inequity is clearly revealed. The correlation between a combination of income and responsibility and composite adaptation performance is 0.68. National income and responsibility for climate change vary positively and strongly with composite adaptation performance. Those nations having weak composite adaptation lack the resources to adapt to climate change attributable largely to those nations having relatively abundant composite adaptation. Stern's double inequity is portrayed graphically in Figures 2 and 3, which are barely distinguishable.

A lively literature has emerged regarding climate change as a justice issue. Among the United Nations Sustainable Development Goals is climate justice, "…which looks at the climate crisis through a human rights lens…" This study has treated climate change as an equity issue by providing an empirical confirmation of Stern's double inequity assertion, a positive assertion that can be and has been tested empirically against a measurable alternative of adaptation equality. This empirical approach to climate change as an equity issue contrasts with the popular assertion that climate change is a justice issue, a normative assertion that can be and has been intensely debated but cannot be tested empirically against a measurable alternative until additional measurable components of climate justice are identified and quantified.

Tables

Table 1 Composite Adaptation Indices CAI

Composite Adaptation Indices			
Leaders		Laggards	
Nation	CAI	Nation	CAI
Australia	1	Guinea-Bissau	0.645
Denmark	1	Bangladesh	0.643
Finland	1	Togo	0.635
France	1	Cote d’Ivoire	0.632
Greece	1	Afghanistan	0.615
Iceland	1	Cameroon	0.602
Korea, Repub of	1	Congo	0.578
Luxembourg	1	Burkina Faso	0.574
Netherlands	1	Ethiopia	0.572
New Zealand	1	Pakistan	0.566
Norway	1	Myanmar	0.563
Sweden	1	Mauritania	0.560
Switzerland	1	Guinea	0.557
UnitedKingdom	1	Papua New G	0.553
Germany	0.995	Yemen	0.553
Austria	0.990	Mali	0.539
Canada	0.990	Nigeria	0.533
Georgia	0.981	Sudan	0.528
Belgium	0.976	Eritrea	0.508
Estonia	0.971	Niger	0.436
United States	0.971		
mean	0.994	mean	0.569

Table 2 Adaptive Capacity Dominance Analysis

Adaptive Capacity Dominance			
Leaders		**Laggards**	
Nation	**# Dominates**	**Nation**	**# Dominated by**
New Zealand	55	Yemen	62
Norway	51	Eritrea	60
Iceland	45	Congo	58
Portugal	45	Cambodia	54
United States	43	Niger	42
Greece	42	Sierra Leone	41
Spain	42	Benin	39
Switzerland	41	Madagascar	37
Netherlands	40	Mauritania	36
Turkey	35	Afghanistan	34
Australia	34	Guinea	34
Canada	34	Angola	33
Austria	32	Ethiopia	33
Panama	32	Liberia	33
Finland	29	Sudan	33
Chile	28	Togo	33
Mexico	25	Mali	32
Sweden	25	Bangladesh	31
Argentina	23	Senegal	27
Italy	23	Namibia	26

Table 3 Adaptation Readiness Dominance Analysis

Adaptation Readiness Dominance			
Leaders		Laggards	
Nation	# Dominates	Nation	# Dominated by
New Zealand	110	Afghanistan	99
Norway	110	Nigeria	89
Australia	109	Guinea-Bissau	86
Iceland	104	Zimbabwe	86
Denmark	103	Congo	85
Sweden	102	Eritrea	83
Finland	100	Cameroon	82
Netherlands	96	Pakistan	79
Korea, Repub of	94	Mali	78
Austria	93	Guinea	73
Estonia	92	Nicaragua	72
Ireland	91	Yemen	72
Canada	90	Mozambique	71
Switzerland	89	Sudan	71
Portugal	86	Papua New G	68
Germany	85	Bangladesh	67
United States	85	Myanmar	67
UnitedKingdom	84	Niger	64
Slovenia	83	Angola	63
France	77	Madagascar	63

Table 4 The Inequity of Composite Adaptation

Composite Adaptation and GDP/capita					
Leaders			**Laggards**		
Nation	**CAI**	**GDP/capita**	**Nation**	**CAI**	**GDP/capita**
Australia	1	52031	Guinea-Bissau	0.645	2021
Denmark	1	59897	Bangladesh	0.643	4955
Finland	1	51521	Togo	0.635	2212
France	1	49620	Cote d'Ivoire	0.632	5433
Greece	1	30842	Afghanistan	0.615	2152
Iceland	1	60133	Cameroon	0.602	3901
Korea, Rep of	1	42849	Congo	0.578	3987
Luxembourg	1	119416	Burkina Faso	0.574	2268
Netherlands	1	59675	Ethiopia	0.572	2315
New Zealand	1	45073	Pakistan	0.566	4896
Norway	1	68345	Myanmar	0.563	4940
Sweden	1	55338	Mauritania	0.560	5566
Switzerland	1	73144	Guinea	0.557	2675
United Kingdom	1	49344	Papua New G	0.553	4475
Germany	0.995	56285	Yemen	0.553	3689*
Austria	0.990	58641	Mali	0.539	2420
Canada	0.990	50661	Nigeria	0.533	5353
Georgia	0.981	15623	Sudan	0.528	4363
Belgium	0.976	54918	Eritrea	0.508	1626*
Estonia	0.971	38294	Niger	0.436	1276
United States	0.971	65280			
			*: 2011 and 2013, the latest years available		
mean	0.994	52294	mean	0.569	3623

Table 5 The Further Inequity of Composite Adaptation

Composite Adaptation and GHG/capita					
Leaders			**Laggards**		
Nation	**CAI**	**GHG/capita**	**Nation**	**CAI**	**GHG/capita**
Australia	1	21.39	Guinea-Bissau	0.645	2.36
Denmark	1	8.17	Bangladesh	0.643	1.33
Finland	1	11.49	Togo	0.635	2.05
France	1	5.10	Cote d'Ivoire	0.632	1.31
Greece	1	8.14	Afghanistan	0.615	2.73
Iceland	1	9.61	Cameroon	0.602	8.71
Korea, Repub of	1	12.89	Congo	0.578	9.99
Luxembourg	1	16.87	Burkina Faso	0.574	2.07
Netherlands	1	11.01	Ethiopia	0.572	1.82
New Zealand	1	13.55	Pakistan	0.566	1.98
Norway	1	4.53	Myanmar	0.563	4.14
Sweden	1	4.70	Mauritania	0.560	2.74
Switzerland	1	5.58	Guinea	0.557	3.89
United Kingdom	1	6.96	Papua New G	0.553	7.72
Germany	0.995	9.84	Yemen	0.553	0.87
Austria	0.990	8.21	Mali	0.539	2.64
Canada	0.990	21.42	Nigeria	0.533	2.59
Georgia	0.981	4.29	Sudan	0.528	3.81
Belgium	0.976	9.46	Eritrea	0.508	2.36
Estonia	0.971	15.48	Niger	0.436	2.05
United States	0.971	18.06			
mean	0.994	11.64	mean	0.569	3.36

Table 6 The Generic Inequity of Composite Adaptation

Composite Adaptation and Generic Inequity					
Leaders			**Laggards**		
Nation	**CAI**	**GII**	**Nation**	**CAI**	**GII**
Australia	1	33.364	Guinea-Bissau	0.645	2.185
Denmark	1	22.121	Bangladesh	0.643	2.564
Finland	1	24.329	Togo	0.635	2.128
France	1	15.903	Cote d'Ivoire	0.632	2.666
Greece	1	15.841	Afghanistan	0.615	2.424
Iceland	1	24.037	Cameroon	0.602	5.829
Korea, Repub of	1	23.505	Congo	0.578	6.312
Luxembourg	1	44.889	Burkina Faso	0.574	2.168
Netherlands	1	25.634	Ethiopia	0.572	2.053
New Zealand	1	24.713	Pakistan	0.566	3.115
Norway	1	17.603	Myanmar	0.563	4.522
Sweden	1	16.127	Mauritania	0.560	3.905
Switzerland	1	20.193	Guinea	0.557	3.224
United Kingdom	1	18.533	Papua New G	0.553	5.877
Germany	0.995	23.533	Yemen	0.553	1.789
Austria	0.990	21.947	Mali	0.539	2.529
Canada	0.990	32.941	Nigeria	0.533	3.721
Georgia	0.981	8.188	Sudan	0.528	4.075
Belgium	0.976	22.787	Eritrea	0.508	1.957
Estonia	0.971	24.344	Niger	0.436	1.619
United States	0.971	34.335			
mean	0.994	23.565	mean	0.569	3.233

Appendix

Adaptation Indicators				
Indicator	**Mean**	**Std Dev**	**Min**	**Max**
Adaptive Capacity				
Agricultural Capacity	0.184	0.229	0	1
Child Nutrition	0.820	0.176	0.291	1
Water	0.221	0.189	0.003	0.839
Medical Staffs	0.426	0.354	0.012	1
Protected Biomes	0.569	0.196	0.149	0.875
International Environmental Conventions	0.335	0.250	0	1
Trade & Transport Infrastructure	0.414	0.167	0.118	0.838
Paved Roads	0.489	0.330	0.027	1
Electricity Access	0.846	0.245	0.143	1
Adaptation Readiness				
Economic Readiness				
Doing Business	0.430	0.146	0.134	0.772
Governance Readiness				
Political Stability & Non-Violence	0.531	0.159	0.094	0.855
Control of Corruption	0.404	0.228	0.041	0.924
Rule of Law	0.509	0.188	0.056	0.880
Regulatory Quality	0.490	0.191	0.056	0.906
Social Readiness				
ICT Infrastructure	0.461	0.144	0.209	0.732
Education	0.286	0.211	0.004	1

Appendix Table 1 Summary Statistics

References

1. Acemoglu, D. (2002), “Directed Technical Change”, *Review of Economic Studies* 69, 781-809.

2. Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012), “The Environment and Directed Technical Change”, *American Economic Review* 102, 131-166.
3. Acemoglu, D., P. Aghion, and F. Zilibotti (2006), “Distance to Frontier, Selection, and Economic Growth”, *Journal of the European Economic Association* 4, 37-74.
4. Adger, W. N., and J. Barnett (2009), “Commentary: Four Reasons for Concern About Adaptation to Climate Change”, *Environment and Planning A* 41, 2800-2805.
5. Adom, P. K., and S. Amoani (2021), “The Role of Climate Adaptation Readiness in Economic Growth and Climate Change Relationship: An Analysis of the Output/Income and Productivity/Institution Channels”, *Journal of Environmental Management* 293, 112923.
6. Alcaraz, O., P. Buenestado, B. Escribano, B. Sureda, A. Turon, and J. Xercavins (2018), “Distributing the Global Carbon Budget with Climate Justice Criteria”, *Climatic Change* 149, 131-145.
7. Amegavi, G. B., Z. Langnel, J. Jeffison, J. J. Y. Ofori, and D. R. Ofori (2021), “The Impact of Adaptation on Climate Vulnerability: Is Readiness Relevant?”, *Sustainable Cities and Society* 75, 103325.
8. Andrews, D., C. Criscuolo, and P. N. Gal (2016), “The Best versus The Rest: The Global Productivity Slowdown, Divergence Across Firms and the Role of Public Policy” https://doi.org/10.1787/63629cc9-en
9. Arezki, R. (2021), “Climate Finance for Africa Requires Overcoming Bottlenecks in Domestic Capacity”, *Nature Climate Change* 11, 888.
10. Berlingieri, G., P. Blanchenay, and C. Criscuolo (2017), “The Great Divergence(s)”, OECD Science, Technology and Industry Policy Papers No. 39 https://doi.org/10.1787/953f3853-en
11. Bosetti, V., and B. Buchner (2009), “Data Envelopment Analysis of Different Climate Policy Scenarios,” *Ecological Economics* 68, 1340-1354.
12. Charnes, A., W. W. Cooper, and E. Rhodes (1978), “Measuring Efficiency of Decision-Making Units”, *European Journal of Operational Research* 2, 429-444.
13. Cherchye, L., W. Moesen, N. Rogge and T. Van Puyenbroeck (2007), “An Introduction to ‘Benefit of the Doubt’ Composite Indicators”, *Social Indicators Research* 82, 111-145.
14. Diffenbaugh, N. S., and M. Burke (2019), “Global Warming has Increased Global Economic Inequality”, *Proceedings of the National Academy of Science* 116, 9808-9813 https://www.pnas.org/content/pnas/116/20/9808.full.pdf
15. Edmonds, H. K., J. E. Lovell, and C. A. K. Lovell (2020), “A New Composite Climate Change Vulnerability Index”, *Ecological Indicators* 117 https://doi.org/10.1016/j.ecolind.2020.106529
16. Füssel, H.-M. (2010), “How Inequitable is the Global Distribution of Responsibility, Capability, and Vulnerability to Climate Change: A Comprehensive Indicator-Based Assessment”, *Global Environmental Change* 20, 597-611.
17. Halkos, G., A. Skouloudis, C. Malesios, and N. Jones (2020), “A Hierarchical Multilevel Approach in Assessing Factors Explaining Country-Level Climate Change Vulnerability”, *Sustainability* 12,

https://doi.org/10.3390/su12114438

18. Intergovernmental Panel on Climate Change (IPCC) (2001), *TAR Climate Change 2001: Impacts, Adaptation, and Vulnerability* https://www.ipcc.ch/report/ar3/wg2/
19. Intergovernmental Panel on Climate Change (IPCC) (2007), AR4 *Climate Change 2007: Impacts, Adaptation and Vulnerability, Working Group II Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf
20. Intergovernmental Panel on Climate Change (IPCC) (2014), *AR5 Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* https://www.ipcc.ch/report/ar5/wg2/
21. Intergovernmental Panel on Climate Change (IPCC) (2018), *Global Warming of 1.5 C* https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf
22. Intergovernmental Panel on Climate Change (IPCC) (2021), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers* https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf
23. Intergovernmental Panel on Climate Change (IPCC) (2022), *AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* https://www.ipcc.ch/report/ar6/wg2/
24. International Energy Agency (2021), *World Energy Outlook 2021*. https://www.iea.org/reports/world-energy-outlook-2021
25. Khan, M., S. Robinson, R. Weikmans, D. Ciplet, and J. T. Roberts (2020), “Twenty-five Years of Adaptation Finance through a Climate Justice Lens”, *Climatic Change* 161, 251-269.
26. King, N., and A. Jones (2021), "An Analysis of the Potential for the Formation of ‘Nodes of Persisting Complexity’", *Sustainability* 13, 8161. https://doi.org/10.3390/su13158161
27. Klinsky, S. (2021), “Climate Change is a Justice Issue – These 6 Charts Show Why”, *The Conversation* https://theconversation.com/climate-change-is-a-justice-issue-these-6-charts-show-why-170072
28. Maddison, A. (2006), *The World Economy*. OECD Development Centre Studies https://www.oecd-library.org/development/the-world-economy_9789264104143-en
29. Massetti, E., and R. Mendelsohn (2018), “Measuring Climate Adaptation: Methods and Evidence”, *Review of Environmental Economics and Policy* 12, 324-341.
30. Matsumoto, K., G. Makridou, and M. Doumpos (2020), “Evaluating Environmental Performance Using Data Envelopment Analysis: The Case of European Countries”, *Journal of Cleaner Production* 272, 122637.
31. Melyn, W., and W. Moesen (1991), “Towards a Synthetic Indicator of Macroeconomic Performance: Unequal Weighting when Limited Information is Available”, Public Economics Research Paper 17, CES, KU Leuven, Belgium.

32. Nordhaus, W. D. (1977), "Economic Growth and Climate: The Carbon Dioxide Problem", *American Economic Review* 67, 341-346.
33. Nordhaus, W. D. (1993), "Climate and Economic Development: Climates Past and Climate Change Future", *World Bank Economic Review* 7, 355-376.
34. Ripple, W. J., and six others (2022), "Six Steps to Integrate Climate Mitigation with Adaptation for Social Justice", *Environment Science and Policy* 128, 41-44.
35. Robinson, M., and T. Shine (2018), "Achieving a Climate Justice Pathway to 1.5 C", *Nature Climate Change* 89, 564-569.
36. Salamanca, A., and H. Nguyen (2016), "Climate Change Adaptation Readiness in the ASEAN Countries", Discussion Brief, Stockholm Environment Institute.
37. Sarkodie, S. A., and V. Strezov (2019), "Economic, Social and Governance Adaptation Readiness for Mitigation of Climate Change Vulnerability: Evidence from 192 Countries", *Science of the Total Environment* 656, 150-164.
38. Simmons, D. (2020), "What is 'Climate Justice'? https://yaleclimateconnections.org/2020/07/what-is-climate-justice/
39. Stern, N. (2006), *The Economics of Climate Change: The Stern Review*. H M Treasury, UK.
40. Tilleard, S., and J. Ford (2016), "Adaptation Readiness and Adaptive Capacity of Transboundary River Basins", *Climatic Change* 137, 575-591.
41. Trinks, A., M. Mulder, and B. Scholtens (2020), "An Efficiency Perspective on Carbon Emissions and Financial Performance", *Ecological Economics* 175, 106632.
42. Tulkens, H. (2006), "Efficiency Dominance Analysis (EDA): Basic Methodology", Chapter 18 in P. Chander, J. Drèze, C. Lovell, and J. Mintz, eds., *Public Goods, Environmental Externalities and Fiscal Competition*. New York: Springer.
43. United Nations Development Programme (UNDP) (2020), *Human Development Index* http://hdr.undp.org/en/content/human-development-index-hdi
44. United Nations Environment Programme (UNEP) (2021a), *Adaptation Gap Report 2021: The Gathering Storm.* https://www.unep.org/resources/adaptation-gap-report-2021
45. United Nations Environment Programme (UNEP) (2021b), *Emissions Gap Report 2021: The Heat Is On* https://www.unep.org/resources/emissions-gap-report-2021 https://www.un.org/sustainabledevelopment/blog/2019/05/climate-justice/
46. University of Notre Dame (2021) *University of Notre Dame Global Adaptation Initiative*.https://gain.nd.edu/

Figures

Envelopment Program	Multiplier Program
$\max_{\theta,\lambda} \quad \theta$ subject to $\theta y_{no} - \sum_{i=1}^{I} \lambda_i y_{ni} \leq 0 \quad n=1,\ldots,N$ $\lambda_i \geq 0 \quad i=1,\ldots,o,\ldots,I$	$\min_{\mu,\nu} \quad \mu$ subject to $\sum_{n=1}^{N} \nu_n y_{ni} = 1$ $\mu - \sum_{n=1}^{N} \nu_{ni} y_{ni} \geq 0 \quad i=1,\ldots,o,\ldots,I$ $\mu,\nu_n \geqq 0 \quad n=1,\ldots,N$
Calculating ACI	

Figure 1

DEA ACI Programs

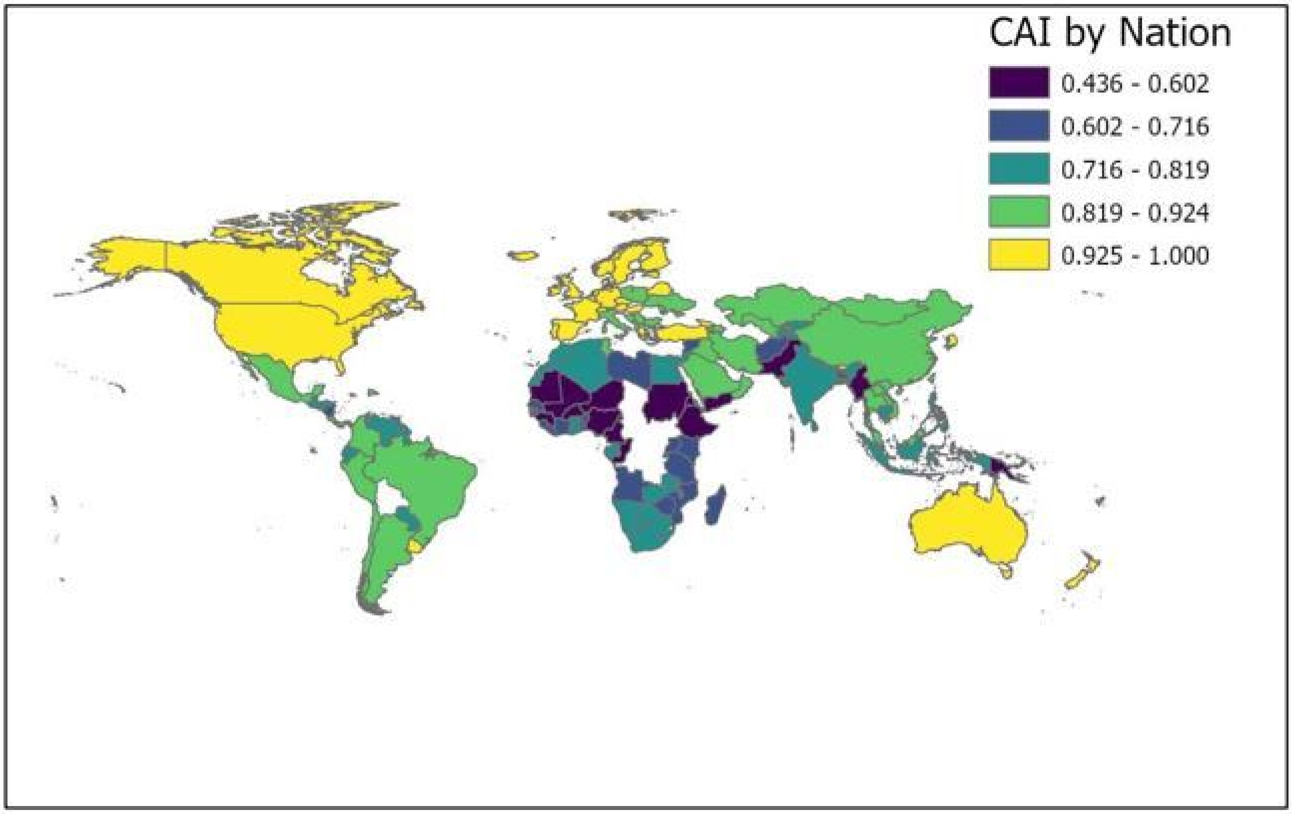

Figure 2

Composite Adaptation Indices CAI by Nation

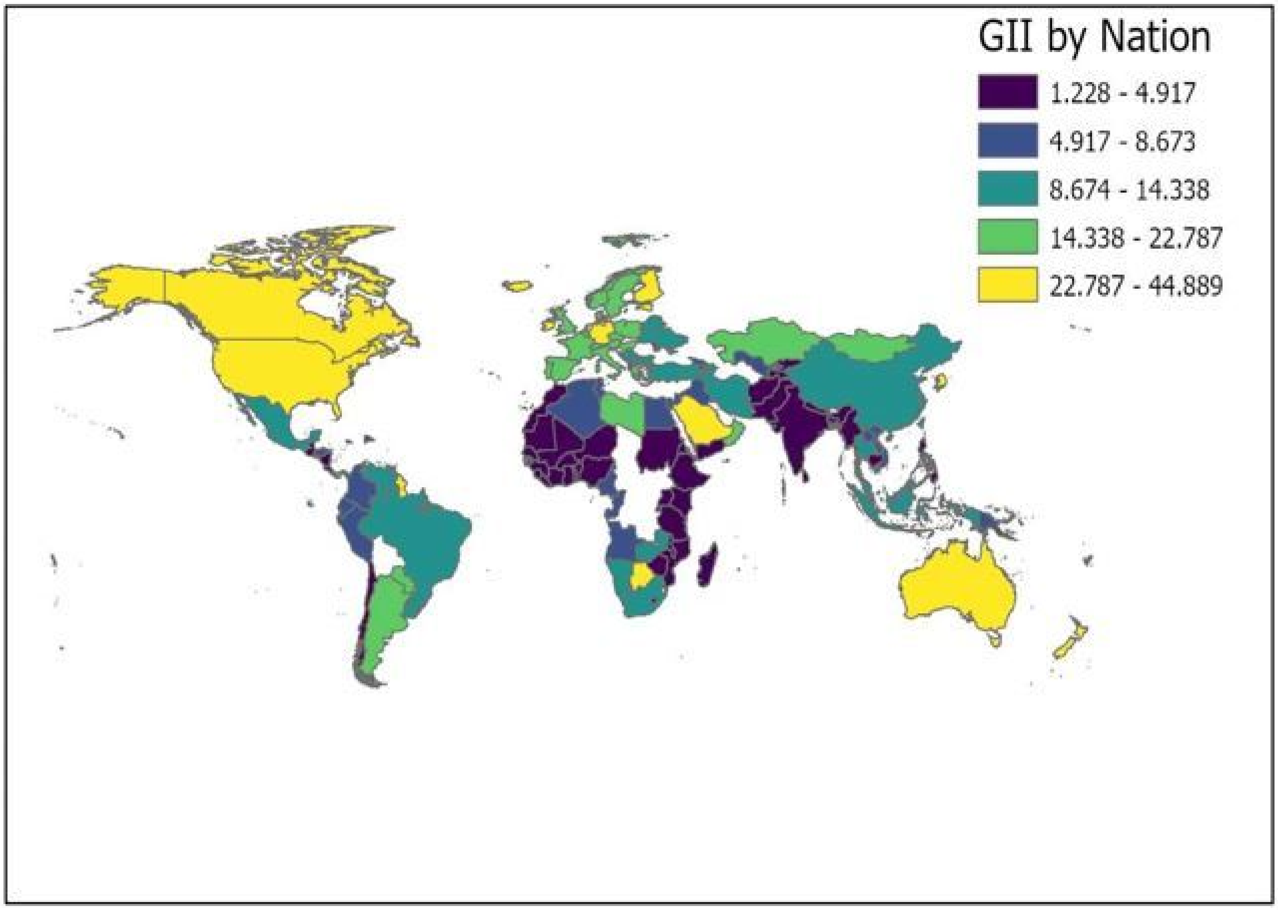

Figure 3

Generic Inequity Indices GII by Nation