Introduction

Carbon dioxide (CO₂) is one of the main GHGs responsible for global climate change (IPCC, 2014). Global CO₂ emissions have steadily increased over the past twenty years (Global Carbon Project, 2017), and the main reason for this growth is continued dependency on fossil energy from coal, oil and natural gas, dependency that also contributes to economic development (Hansen et al., 2017; Jorgenson et al., 2014; Rosa and Diez, 2012). There are, however, important differences in CO₂ emissions among countries in the last several years. On one hand, there is an increasing trend among 101 countries that together are responsible for about 50% of global CO₂ emissions. On the other hand, there is a decreasing trend among the major emitters, including the United States (US) and countries of the European Union (EU), driven by a rapid growth in renewable energy, a decline in coal consumption, and improved energy efficiency (Jackson et al., 2016). The emission reduction trend is encouraging and must be accelerated and spread elsewhere to meet the Paris Agreement and limit climate change (UNFCCC, 2015).

Mitigation policies (e.g., carbon taxes) and technologies (e.g., fuel switch) to reduce GHG emissions may affect vulnerability to the negative impacts of climate change. Similarly, adaptation policies (e.g., watershed planning) and technologies (e.g., air conditioners) that aim to reduce vulnerability may increase or decrease GHG emissions. A well-designed climate policy should aim to reduce both GHG emissions and climate vulnerability together. For example, in urban areas, successful reduction of CO₂ emissions by efficient fuel use can lead to air pollution reduction and health benefits for urban populations (Ramawami et al., 2017). Similarly, vulnerability reduction can produce benefits for GHG emission mitigation. For example, building green roofs that achieve cooler temperatures during the hot days also reduce use of energy for air-conditioning (Sharma et al., 2016; Butler, 2007). In agriculture, Ayers...
and Huq (2009) found similar co-benefits in a waste-to-compost project in Bangladesh where reduction of methane emissions were associated with soil improvements in drought-prone areas. This, in turn, reduced the vulnerability of the population to climate risks. In the energy sector, Hennessay et al. (2017) also showed that development of a smart electricity grid can reduce GHG emissions when connected to a renewable energy source. The smarter grid also reduced vulnerability because it enhanced response to changing conditions and provided more reliable service to the population.

We do know from countries’ Nationally Determined Contribution (NDC) statements that mitigation is a priority strategy for developed countries (Pauw et al., 2017a). In contrast, adaptation is a key climate change strategy for many developing countries. For example, the NDCs of 38 developing countries include quantitative targets for adaptation. Yet, the majority of countries do not consider mitigation and adaptation co-benefits (Pauw et al., 2017b). Thus, a theoretical and practical gap exists between mitigation and adaptation and the realization of them together (Klein et al., 2007 and Pauw et al., 2017b).

This gap is, in part, driven by our limited understanding of the relationship between GHG emissions and climate vulnerability and changes in that relationship over time. Much of the existing literature on this topic examines international equity in the responsibility for emission reduction and associated trade-offs for reduction in climate vulnerability. Althor et al. (2016), for example, found that higher-emitting countries are among the least vulnerable, while low-emitting countries are the most vulnerable to climate change. By 2030, this inequity will significantly worsen. Fussel (2010) suggested that the main cause of the high vulnerability of low-emitting countries is a lack of adaptive capacity and that the food and health sectors are the most vulnerable to the impacts of climate change. In contrast, several studies suggest that high-emitting countries also may be vulnerable to climate change. For example, the World Risk Index identified the Netherlands and Japan at risk from natural disasters (Welle and Birkmann, 2015) while Diffenbaugh (2007) used data on regional climate change, economic capacity and at-risk assets to conclude that China and the United States have high risk of damage by climate change. These contrasting findings correspond to varying definitions of climate risk and vulnerability, and they raise the question of how GHG emissions and climate vulnerability of different countries change over time.

Understanding the link between past and present changes in GHG emissions and climate vulnerability at the country and global level is useful in determining whether and where co-benefits between mitigation and vulnerability reduction exist. It also can identify examples for others to follow. We focus this study on the national scale because we could readily access, thus compare, information on both GHG emissions and climate vulnerability for each country included in our analysis. Thus, our study explores changes in per capita CO₂ emissions from fossil fuel use and changes in climate vulnerability scores (a function of exposure to biophysical impact, sensitivity to climate hazards and adaptive capacity to prepare and respond to climate hazard) in 179 countries from 1995 to 2015. As an initial assessment of the relationship between CO₂ emissions and climate vulnerability, we created a matrix that divides countries into four groups (Figure 1). Each group is characterized by a common direction of changes (positive or negative) in CO₂ emissions and climate vulnerability as illustrated next. Group 1 increases CO₂ emissions while decreases climate vulnerability: failing in mitigation while successful in climate vulnerability reduction; Group 2 reduces CO₂ emissions and climate vulnerability: successfully achieving co-benefits of mitigation and climate vulnerability reduction; Group 3 reduces CO₂ emissions while increases climate vulnerability: failing in reducing vulnerability while successful in mitigation; and Group 4

![Figure 1: Matrix that divides countries into four groups. Each group is characterized by a common direction of changes (positive or negative) in CO₂ emissions and climate vulnerability. DOI: https://doi.org/10.1525/elementa.342.f1](https://doi.org/10.1525/elementa.342.f1)
increases CO₂ emissions and climate vulnerability: failing in both mitigation and climate vulnerability reduction. For each group of countries, we analyze vulnerability in six sectors: water, human health, food, infrastructure, human habitat and ecosystem services. For selected nations, we explore five-year period changes in mitigation and climate vulnerability reduction from 1995–2015 and discuss factors that likely contributed to these increases or decreases. Such information can point to particular co-benefits of mitigation and vulnerability reduction and identify mechanisms and policies to promote co-benefits for a greater number of countries.

Methodology and data

Climate vulnerability scores

We obtained country-level data on climate vulnerability from the Country Index of the Global Adaptation Initiative at the University of Notre Dame (ND-GAIN) (Available online at http://index.gain.org). The ND-GAIN is an established metric used by scholars and policy makers to study climate vulnerability and adaptation opportunities in different countries and regions (Chen et al., 2015; Chen et al., 2016). The ND-GAIN Country Index differs from others because it allows to evaluate twenty years of trends (1995–2016) in climate vulnerability across six areas (food, water, health, ecosystem services, human habitat, and infrastructure). Climate vulnerability is defined as a predisposition of human society to experience impacts from climate hazards (IPCC, 2012). Other vulnerability indices were built for different purposes and use different definitions of climate vulnerability. For example, the Climate Vulnerability Monitor (DARA, 2012) is a data-driven tool that captures present (2010) and future impacts (2030) of climate change and the carbon economy; the World Risk Index focuses on natural disasters and social vulnerability (e.g., Welle and Brikman, 2015); and other studies capture the distribution of social vulnerability (sensitivity and adaptive capacity) across the world (Yohe et al., 2006, Gall, 2007). ND-GAIN climate vulnerability scores are constructed from thirty-six indicators covering three components of vulnerability including: i) exposure to future impact of climate change (e.g., changes in crop yields); ii) sensitivity, or the degree to which human society is affected by climate variability, capturing, for example, populations that are sensitive to a climate hazard due to their location (e.g., in a low-lying coastal area); and iii) adaptive capacity, referring to an ability to respond to and prepare for negative consequences of climate change (e.g., access to electricity or areas of protected biomes). These three components of exposure, sensitivity and adaptive capacity span across six life supporting sectors for a total of six indicators per sector (Supplementary Table 1).

Climate vulnerability scores range between 0 (least vulnerable) and 1 (most vulnerable). Component scores (exposure, sensitivity and adaptive capacity) are computed by aggregating normalized indicators. The normalization follows the proximity-to-reference approach, that identifies a upper and lower reference value for each indicator and scales each indicator to 0–1 in proportion to distance from the reference value. Reference values were adapted from well-established goals (e.g., UN sustainable development goals) or, for indicators without an accepted goal, the value for the best performing country are used as reference value for each indicator.

Climate vulnerability scores are available annually from 1995 to 2016. (Where data are missing, values are filled by linear interpolation across time.) Some of the indicators in the Country Index negatively correlate with Gross National Income (Chen et al., 2016), and this corresponds with general knowledge that economic growth and development to some extent reduce vulnerability to climate change. The Country index does not explicitly account for within-country vulnerability variation.

We divided countries into three vulnerability categories (low, medium and high), which were determined using 33rd and 66th percentile as a cut-off point. The global mean climate vulnerability score in 2015 was 0.42. Of the 179 countries analyzed, 66 were less-vulnerable (low category), with vulnerability scores ranging from 0–0.362. Sixty-three countries were mid-vulnerable (mid category), with vulnerability score ranging from 0.363–0.467 and 56 countries were highly-vulnerable (high category), with vulnerability score ranging from 0.467–0.7.

Carbon Dioxide emissions

Data on CO₂ emissions from fossil fuel combustion at the country level from 1995 to 2015 were taken from the Emission Database for Global Atmospheric Research (EDGAR 4.2) (Olivier et al., 2016). The EDGAR database is a joint project of the European Commission’s Joint Research Centre (JRC) and the PBL Netherlands Environmental Assessment Agency. Country-specific CO₂ emission totals include emissions of fossil fuel use and industrial processes (cement production, carbonate use of limestone and dolomite, non-energy use of fuels and other combustion, chemical and metal processes, solvents, agricultural liming and urea, waste and fossil fuel fires). The estimate does not consider CO₂ emissions from short-cycle biomass burning (such as agricultural waste burning), large-scale biomass burning (such as forest fires) and carbon emissions/removals of land-use, land-use change and forestry. In all analyses, we used the fossil fuel CO₂ emissions per capita, calculated with the population data from the World Population Prospects (UNDP, 2017). We only focus on CO₂ emissions from fossil fuel and industrial processes because of its key role in climate change, but we acknowledge that the other GHG emissions, such as nitrous oxide and methane should be considered as well. Yet, comprehensive data for these other GHGs over a 20-years period were not available for all countries at the time of this study.

Exploratory statistics

For each country and for individual sectors for vulnerability, we calculated the relative change in CO₂ emissions and climate vulnerability between 1995 and 2015 and the rate of change over that period of time. We used descriptive and exploratory statistics, including the Spearman non-parametric correlation coefficients to summarize directions and strength of the relationship between the two measures. In total, we performed calculations for 179
countries, for which a complete data set of both climate vulnerability and fossil fuel emissions were available.

**Results**

*Spatial pattern in CO$_2$ emissions and climate vulnerability changes*

Between 1995 and 2015, per capita CO$_2$ emissions from fossil fuel use and industrial processes consistently increased in 127 countries, on average by 46%. Figure 2 shows that the largest increase in CO$_2$ emissions over that time period occurred in countries of Southeast and West Asia, South America, and East Africa. Countries that increased per capita CO$_2$ emissions by more than 50% between 1995 and 2015 were responsible for about 30% of the global CO$_2$ emissions in 2015. In contrast, CO$_2$ emissions declined in 52 countries over the past twenty years, and these countries were responsible for about 34% of global CO$_2$ emissions in 2015 (a percentage was estimated from the EDGAR CO$_2$ emissions inventory for 2015).

According to the country-level vulnerability index, climate vulnerability has decreased in 164 countries between 1995 and 2015, and, on average, countries reduced their vulnerability by 7% over that period. Figure 3 illustrates that between 1995 and 2015, the largest decrease

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**Figure 2:** Relative change (%) in fossil fuel CO$_2$ emissions per capita between 1995 and 2015. Negative numbers (blue shades) and positive numbers (red and pink color) indicate decrease or increase in CO$_2$ emission, respectively. Data are taken from the Database for Global Atmospheric Research (EDGAR 4.2). Data deficient countries are shown in white. DOI: https://doi.org/10.1525/elementa.342.f2

**Figure 3:** Relative change (%) in climate vulnerability score between 1995 and 2015. Negative numbers (blue colors) and positive (red and pink color) indicate reduction and increase in climate vulnerability, respectively. Data are taken from the Country Index of the Notre Dame Global Adaptation Index (NDGAIN). Data deficient countries are shown in white. DOI: https://doi.org/10.1525/elementa.342.f3
in climate vulnerability (more than 15%) took place in China, Vietnam and Morocco. In contrast, 15 countries have seen increases in climate vulnerability. These include eleven countries that are among the most vulnerable to the impact of climate change overall, such as those in Sub-Saharan Africa and Papua New Guinea. Increase in climate vulnerability also occurred in four countries of the European Union that are categorized as less vulnerable to climate change: Germany, Italy and the United Kingdom.

**Association between changes in CO\textsubscript{2} emissions and climate vulnerability**

Globally, the relationship between per capita CO\textsubscript{2} emissions and climate vulnerability was negative every year over the past two decades, although the correlation coefficient varied over time. For example, there was a strong negative correlation in 1995 and in 2015 with $r = -0.827$ ($p = 0.01$) and $r = -0.820$ ($p = 0.01$), respectively. These negative associations suggest that countries with higher per capita CO\textsubscript{2} emissions (e.g., the United States) are less vulnerable, while more vulnerable countries (e.g., Eritrea) have lower per capita CO\textsubscript{2} emissions. This finding corresponds with a common understanding of an unequal distribution of vulnerability and CO\textsubscript{2} emissions around the world (Chen et al., 2015; Althor et al., 2016). Further, during the 1995 and 2015 period, the relationship between changes in per capita CO\textsubscript{2} emissions and climate vulnerability was non-linear and negative ($r = -0.192; p = 0.05$). This implies that an increase in CO\textsubscript{2} emissions can be associated with decreases or increases in climate vulnerability.

**Figure 4** shows a pronounced negative relationship between changes in per capita CO\textsubscript{2} emissions and climate vulnerability between 1995 and 2015 in a majority of countries (n = 122, Group 1). About half of them are emerging economies, including China, India and Brazil. Based on the 2015 vulnerability score, Group 1 is composed of 78% mid- and highly-vulnerable countries (e.g., countries with a high level of exposure to biophysical factors such as flooding and a low level of financial, technical and social capacity to prepare and respond to disaster), while less-vulnerable countries (i.e., countries with low level of exposure to biophysical factors and high capacity to prepare and respond) comprise just 21% of Group 1. Together, these countries are responsible for approximately 65% of global CO\textsubscript{2} emissions in 2015, and, on average, they reduced vulnerability by 9% between 1995 and 2015 (Figure 5). Countries in Group 1 also are reducing vulnerability across the six sectors composing

**Figure 5**: Characteristics of four groups: Contribution of group to the total CO\textsubscript{2} emissions in 2015 (CO\textsubscript{2}), and % share of countries in each group within three vulnerability categories: less, mid and highly vulnerable in 2015. Countries are divided into vulnerability categories based on following cutoff points in the climate vulnerability index: 0.362 (33\textsuperscript{rd} percentile), 0.467 (66\textsuperscript{th} percentile). Mean climate vulnerability score in 2015 was 0.42. The total number of countries analyzed was 179, of which 66 were less vulnerable, 63 mid vulnerable and 56 highly vulnerable. DOI: https://doi.org/10.1525/elementa.342.f5
the vulnerability index with the largest rate of change in the ecosystem services (i.e., increasing areas of protected biomes) and human habitat (i.e., improving infrastructure of cities to deal with flooding, or heat waves) sectors (Figure 6).

A decreasing trend in both CO$_2$ emissions and climate vulnerability ($n = 42$, Group 2) is evident among one-third of the 179 countries. Group 2 countries comprise mostly less-vulnerable countries (65%) and, to a less extent, mid- and highly vulnerable countries (35%). The contribution of countries in Group 2 to global CO$_2$ emissions in 2015 was 26%, and, on average, they reduced vulnerability by 6% between 1995 and 2015 (Figure 5). Group 2 includes large emitters such as the US and countries of EU as well as the countries of former Soviet Union. Decreasing CO$_2$ emissions in these countries is due to a decline in energy intensity and an increasing share of renewable energy over the past twenty years (Global Carbon Project, 2017). These changes had a positive impact on reduction of all six vulnerability supporting sectors (Figure 6), and, similarly to Group 1, we observe the largest reduction in the areas of ecosystem services and human habitat.

For some countries, a decrease in CO$_2$ emissions is associated with increasing climate vulnerability ($n = 9$; Group 3). Group 3 countries comprise 67% less-vulnerable countries and 34% of the mid- to high-vulnerable countries. Less-vulnerable countries, together with mid- and highly-vulnerable countries in Group 3, are responsible for 9% of global CO$_2$ emissions (Figure 5). The largest increases in climate vulnerability occurred in less-vulnerable countries such as UK, Italy, Germany and Japan, but it is important to note that these changes did not result in shifts from one vulnerability category to another (e.g., from low to mid vulnerability). On average, we observe an increasing trend in vulnerability in the human health and food sectors in Group 3 (Figure 6). The vulnerability score of the ND-GAIN Country Index shows a strong negative correlation with per capita Gross National Income (GNI) ($r = -0.63$). There is a broad consensus that economic growth and development contribute to vulnerability reduction and that wealthier countries may have more resources to apply toward climate change adaptation. Here, we show that vulnerability can increase in wealthy countries. This can be driven by increasing income inequality (Dorling, 2015), for example, and other factors, such as social and political changes. This finding is in line with previous research that suggests differential vulnerability of people and places is often rooted in development processes (O’Brien et al., 2006).

Failure in both adaptation and mitigation is visible among six countries ($n = 6$, Group 4). Group 4 is comprised of mostly highly-vulnerable countries in Sub-Saharan Africa and Papua New Guinea in the Pacific Ocean, where reduction of vulnerability is particularly important (Figure 5). Although they have a negligible contribution to cumulative CO$_2$ emissions globally (less than 1% of the global CO$_2$ emissions), these countries did not reduce CO$_2$ emissions per capita nor did they use fossil fuels to reduce their vulnerability. In particular, we observe increased vulnerability in human health and food sectors, similarly to Group 3, but at a higher rate (Figure 6).

To explore if components of vulnerability (sensitivity versus adaptive capacity scores) were driving the results described above, we also examined the relationship of those components separately against greenhouse gas emissions (see details in Supplementary materials; Figure

**Figure 6:** Average rate of change in vulnerability of six life supporting sectors, during 1995–2015 for four groups of countries (see Figure 1). Sectors includes all sectors (all), water (WA), human health (HH), food (FD), infrastructure (IN), habitat (HA) and ecosystem services (EC). DOI: https://doi.org/10.1525/elementa.342.f6
Select but diverse countries are reducing both climate vulnerability and CO$_2$ emissions

S1 and S2). The results of those sub-analyses showed that the general mitigation – climate vulnerability reduction relationship is consistent across vulnerability components.

**Changes in per capita CO$_2$ emissions and climate vulnerability in five-year periods**

To explore variation in changes in per capita CO$_2$ emissions and climate vulnerability in five-year periods during 1995 to 2015, we analyzed patterns among seven selected nations (Figure 7) that differ in geography and economic development levels. Figure 7 shows that the largest reductions in vulnerability have been achieved by highly- and mid-vulnerable countries, such as Malawi and Mexico (Figure 4, Group 1). These improvements (i.e., reduced vulnerability) are associated with small increases in CO$_2$ emissions per capita. This is in contrast to a large increase in CO$_2$ emissions associated with equally large climate vulnerability improvements in China (Figure 4, Group 1). One possible explanation is that most vulnerable countries are focusing on reducing vulnerability in the food and water sectors, which are responsible for a much smaller amount of CO$_2$ emissions than fossil fuel combustion (Chkravarty et al., 2009).

In some of the most vulnerable countries, an increase of CO$_2$ emissions is correlated with an increase in vulnerability, such as in the case of Papua New Guinea (Figure 4, Group 4). Although CO$_2$ emissions per capita for Papua New Guinea are relatively small (1.04 t/yr CO$_2$ per capita), the relative increase of these emissions is comparable to India (Figure 4, Group 1) (1.84 t/yr CO$_2$ per capita). At the same time the vulnerability of Papua New Guinea increased over the past twenty years, particularly in the food sector, possibly triggered by increasing population, and occurrence of severe drought during the past two decades (Bourke et al., 2016).

In less-vulnerable countries, such as Denmark (Figure 4, Group 2) and the United Kingdom (Figure 4, Group 3), a decrease in CO$_2$ emissions is associated with a different vulnerability outcome. In Denmark, climate vulnerability has been decreasing despite the country’s having a higher level of exposure to biophysical events (e.g., sea level rise or annual runoff) than the United Kingdom, where vulnerability is increasing. One of the reasons for such differences may lie in social and political changes that affect adaptation efforts, including population increase in coastal cities or increase in dependency on imported energy (DEFRA, 2017).

**Discussion and Conclusion**

Much of the previous research on the co-benefits of mitigation and climate vulnerability reduction focuses on case studies and individual economic sectors within one or a few countries. To our knowledge, the present study is the first global quantitative assessment of this relationship. It shows that most of the countries around the world are successful in reducing climate vulnerability, but they are failing in mitigation efforts. This finding corresponds with current policies that emphasize vulnerability reduction through infrastructure, such as sea walls and water conservation projects (NYC Mayors Office, 2017). It further suggests that reducing GHG emissions while simultaneously reducing vulnerability to climate change is challenging for countries, regardless of their vulnerability status. Indeed, 122 out of 179 countries, contributing to 65% of global CO$_2$ emissions, fail in mitigation while reducing their vulnerability. The failure to reduce CO$_2$ emissions implies

![Figure 7: CO$_2$ emissions (tons per capita) and climate vulnerability scores in five-years for seven selected nations (CHN-China, DNK-Denmark, GBR-Great Britain, IND-India, MWI-Malawi, MEX-Mexico and PNG-Papua New Guinea). The size of the circle corresponds with change of emissions between 1995 and 2015. The dark to light blue color indicates lower values of vulnerability, while orange and red are moderate to high vulnerability scores, respectively. DOI: https://doi.org/10.1525/elementa.342.f7](https://doi.org/10.1525/elementa.342.f7)
that countries around the world will need to implement additional strategies to reduce negative impacts of climate change in the future, because climate change impacts will be larger than if countries had been more aggressive at GHG emission reduction. Growing evidence suggests that mitigation of greenhouse gas emissions can avoid the cost of adapting to more severe climate impacts in future (ICLEI, 2018). It is important to note that countries also reduce their vulnerability as a result of policies and changes outside their control, including for example population changes, global markets, or trans-boundary air pollution policies (IPCC, 2007).

The minority of countries reducing both climate vulnerability and GHG emissions may have lessons for other nations. These 42 countries can serve as models for co-benefit generation in other countries. However, comparing the countries by geography, demography and simple economic features did not indicate a unified approach or pattern in achieving such co-benefits. An economic transition involving increased use of renewable energy and reduction of high-carbon industries are likely contributing factors (Global Carbon Project, 2017). Better understanding of the drivers of reduction in GHG emissions and climate vulnerability over time will help guide policy decisions to design climate policies that maximize synergies between mitigation and climate vulnerability reduction.

Interestingly, a majority of countries around the world are able to reduce vulnerability in ecosystem services, regardless of changes in their emissions, suggesting that this reduction is not linked to countries’ fossil fuel use and economies. In contrast, countries need economic investment for improvements in their health sector and food security to reduce climate vulnerability.

Our study shows that a failure to reduce vulnerability exists among wealthy and less-vulnerable countries, as well as poor and highly-vulnerable countries. Large emissions of CO\(_2\) do not appear to lead to reductions in vulnerability driven by political changes and social development. Earlier research suggested that less-vulnerable countries are suffering large damages due to climate change because of their large share of climate-sensitive economic sectors (Mendelsohn et al., 2006). In contrast, some highly-vulnerable countries in Sub-Saharan Africa and the Pacific Ocean are failing in climate vulnerability reduction and mitigation efforts. These countries are already experiencing the negative impacts of climate change and have realized few or no reductions in vulnerability over the past two decades. Failure to reduce climate vulnerability in these countries will have impacts beyond national boundaries (Magnan et al., 2015). For example, some human populations may be trapped in the most vulnerable regions while others move to minimize the negative impacts of climate change. This will reshape the social and economic structures of different countries and re-distribute vulnerability.

This study has several limitations. A number of indices of national vulnerability to climate change exist (Welle and Birkmann, 2015; DARA, 2012) and they often measure vulnerability to climate change differently. Selection and aggregation of indicators that capture biophysical and social vulnerability drive these differences. The indicators in the NDGAIN Country Index are based on the recent literature and consultation with scholars and climate adaptation practitioners. The vulnerability indicators are actionable, meaning that the government or the private sector could take actions and changes in one or more indicators over time. The NDGAIN Country Index does not preferentially weight one indicator more than any other. The key strength of the equal weight approach is its simplicity and understandability. The alternative of using unequal weights, i.e., signifying which indicators are more important than others in different national and local circumstances, is not easy to formulate or defend and can be based only on subjective considerations. Users of the NDGAIN Country Index can assign their own weights and simulate indicator variation through the online “what if” tool (https://gain-visualization.crc.nd.edu/).

When analyzed the relationship between sensitivity and adaptive capacity and CO\(_2\) emissions we found that a majority of countries are increasing CO\(_2\) emissions while reducing sensitivity and adaptive capacity scores. Yet, reducing the sensitivity of a country to a climate hazard may be more difficult than enhancing country adaptive capacity. This is because sensitivity indicators measure characteristics related to topography (e.g., population living in flood zones) and demography (e.g., large elderly population), and these are less correlated with economic development. In contrast, adaptive capacity indicators (e.g., access to electricity, or medical resources) are highly correlated with Gross National Income (Chen et al., 2016) and thus can be manipulated with economic progress. We did not examine how selection of different indicators would affect the adaptation-mitigation relationship, though this would be an interesting analysis and a logical next step for future studies. A different index might identify different leaders and laggars in the mitigation-climate vulnerability reduction relationship, but the relatively large number of indicators should make our global analysis relatively robust.

Another limitation of our study is our sole consideration of CO\(_2\) emissions. Other GHG emissions, such as methane (CH\(_4\)) and nitrous oxide (N\(_2\)O), contribute to climate change and should be considered as well. Some studies (e.g. Fussel, 2010) using limited datasets on emissions from land-use change suggest that some highly vulnerable countries also have high GHG emissions due to land-use change. Future studies should use per capita CO\(_2\) emissions especially for developing countries as new data becomes available.

Despite these limitations, our study provides a global and country-level portrait of mitigation and climate vulnerability reduction and its dynamic changes over time. It also suggests that global climate policy should move beyond allocating responsibilities for GHG emissions. It is essential that all countries (least to most vulnerable) around the world shift from one-sided climate change policy (adaptation versus mitigation) and start prioritizing strategies that lead to reduction in both GHG emissions and climate vulnerability simultaneously. Our analysis can serve as a starting point to identify where and why these co-benefits occur today.
Data Accessibility Statement

Datasets analyzed during the current study on climate vulnerability, 1995–2015 are available at Notre Dame Global Adaptation Initiative website https://gain.nd.edu/our-work/country-index/download-data. Dataset for per capita CO2 emissions per capita, 1995–2015 are available at EDGAR website: http://edgar.jrc.ec.europa.eu/overview.php?v=CO2andGHG1970-2016&dst=CO2pc.

Supplemental files

The supplemental files for this article can be found as follows:

- **Table S1.** Indicators for vulnerability measures in ND-GAIN Country Index. DOI: https://doi.org/10.1525/elementa.342.s1
- **Text S1.** Association between sensitivity, adaptive capacity scores and per capita CO2 emissions. DOI: https://doi.org/10.1525/elementa.342.s2

Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: MG, ES and JH.
- Contributed to acquisition of data: MG.
- Contributed to analysis and interpretation of data: MG, ES, JH.
- Drafted and/or revised the article: MG, ES and JH.
- Approved the submitted version for publication: MG, ES and JH.

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