Applications of a joint CO_2 and CH_4 climate debt metric: Insights into global patterns and mitigation priorities

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A R T I C L E   I N F O

A B S T R A C T

The capacity for the concept of climate debt to inform the response to climate change has been underappreciated. International Natural Debt (IND) is a measure of accountability for climate change that straightforwardly and transparently attributes radiative forcing from extant emissions of the two most significant climate active pollutants (CAPs) – carbon dioxide from fossil fuels and methane – to individual entities such as countries or sectors. Here, we demonstrate how the IND metric readily operationalizes climate debt for a diversity of purposes. We characterize the vast range spanned by the global distribution of IND in total and per capita terms. Then, in a manner akin to carbon intensity, we consider the "efficiency" with which countries have accumulated IND in their pursuit of expanding economic output and diminishing ill-health, revealing priorities and pathways for countries to more effectively convert their future climate debt into income and/or health gains. Next, we forecast the IND consequences from countries achieving the ambitious goal of decreasing their CAP emissions to 80% of 1990 levels by 2050, exposing how the composition of IND, determined by the magnitude and timing of historical emissions, constrains each country's capacity to reduce its climate debt. Lastly, we assess the IND implications from a hypothesized rapid displacement of coal by natural gas for power generation in the United States, identifying the combination of conditions under which such a substitution tilts positive or negative in terms of IND. These applications of IND reveal how the metric can both assess climate debt in comparison to other key metrics and investigate mitigation goals and strategies through scenario exercises. Ultimately, we seek to open an intellectual terrain for climate debt analyses and invite more participatory and inclusive discussions about the consequent political and economic implications of such a multiple CAP and accountability-based perspective.

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1. Introduction

1.1. Background on IND

The United Nations Framework Convention on Climate Change (UNFCCC) enjoins countries to act "in accordance with their common but differentiated responsibilities and respective capabilities" (United Nations, 1992) "in light of different national circumstances" (UNFCCC, 2014). This guiding principal seeks to engender an equitable, efficient, and ultimately effective international response to climate change (Stone, 2004). Efforts to formalize such an approach began with the Brazilian Proposal (UNFCCC, 1997), which emerged during deliberations culminating in the Kyoto Protocol, and continue today as negotiations on a successor treaty progress (Morales, 2013). Yet fully implementing a commensurate framework has proven contentious, partly owing to the lack of an acceptable means for estimating accountability for climate change, otherwise known as "climate debt."

Discussions about climate debt have often emphasized disparities between countries in either cumulative or current emissions of carbon dioxide from fossil fuel combustion and cement production ($CO_2(f)$), the most important climate active pollutant (CAP). Increasingly, scientific research has stressed the substantial roles played by other CAPs, the emissions of which, while also exhibiting substantial country-by-country variation, are garnering attention as additional avenues for intervention (Moore and MacCracken, 2009). Notable among these is methane (CH_4), the second most significant CAP (Shindell et al., 2009). Together, $CO_2(f)$ and CH_4 contributed roughly two-thirds of the radiative forcing (RF), or excess energy in the climate system, from all non-aerosol CAPs circulating in the atmosphere during 2011 (Myhre et al., 2013).

In order to help expand the utility and scope of climate debt, we proposed a metric termed International Natural Debt or IND

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(Smith, 1991; Smith et al., 2013). IND straightforwardly and transparently apportions RF from $CO_2(f)$ and CH_4 to individual countries as a function of each country's unique trajectory of historical emissions, taking into account the quite different atmospheric lifetimes of each CAP. Hence, IND portrays climate debt in terms of a meaningful parameter for measuring anthropogenic perturbation of the climate system – RF – that resides intermediate along the causal chain from source to impact. Additionally, IND avoids recourse to either computationally intensive methods, such as global climate models, which require specialist knowledge and sophisticated tools to engage (Friman and Linner, 2008; Okereke, 2010), or time horizons and discount rates, the selection of which have proven problematic for Global Warming Potential and its analogs (Shine, 2009; Tol et al., 2012). In sum, IND, as an accessible yet realistic measure of climate debt, meets the criterion of being a "good enough tool" for analyzing responses to climate change (Socolow and Lam, 2007).

Our initial survey of IND indicated that such a combined metric, in comparison to $CO_2(f)$-only alternatives, recasts the international narrative on differential accountability while offering fresh analytical opportunities. From an IND vantage, although the bulk of climate debt remains with so-called high-income countries (HICs), the balance of accountability tips somewhat towards so-called low- and middle-income countries (LMICs). At the same time, CH_4 reductions for many emerging economies, relative to most wealthier economies, could result in proportionately rapid and large reductions in climate debt at comparatively lower cost and disruption (Delhotal et al., 2006; Höglund-Isaksson, 2012).

1.2. A climate debt perspective

In this paper, we demonstrate how the IND metric, given its applicability to a diverse set of purposes, can help enable and extend a climate debt perspective which offers valuable insight for a host of questions that consider multiple CAPs. In particular, we share a sampling of IND-based analyses that reveal how the metric can contextualize the global distribution of climate debt and, through scenario exercises, investigate the prioritization calculus for CAP mitigation.

By way of an introduction to IND, we begin by illustrating how the vast range of climate debts borne by countries can be depicted in both total and per capita terms simultaneously. We then suggest how IND can be considered with respect to indicators of economic output and population health in a manner akin to carbon intensity (Jorgenson, 2014; Knight and Rosa, 2011). Both of these characterizations of climate debt serve to highlight equity and efficiency considerations and the relative roles of IND from $CO_2(f)$ versus CH_4. These descriptive applications can snapshot the global distribution of climate debt along important axes; propose rationales and pathways for decreasing climate debt; and track a county's progress in comparison to itself or other countries.

Next, we show how arguments for reducing $CO_2(f)$ versus CH_4 can be clarified by calculating country-by-country IND under an "aspirational reductions" scenario. In this exercise, we forecast the IND consequences of countries achieving a widely discussed yet ambitious goal of decreasing emissions of CAPs to 80% of 1990 levels by 2050 (European Commission, 2011; Executive Department State of California, 2005; Parliament of the United Kingdom, 2008). Under this scenario, for instance, global IND in 2050 would be 93% of its 2005 level with CH_4 comprising 17% of IND instead of 43% as in 2005. The scenario exercise exposes how the composition of IND, determined by the magnitude and timing of historical emissions, constrains a country's capacity to reduce its climate debt, further motivating a globally coordinated approach to mitigating both CAPs.

Lastly, we explore how a question at a sectoral scale can be examined with IND. Energy-related emissions are a major driver of climate debt and among the most discussed targets for mitigation. However, controversy endures about the direction of RF impacts from the expanded use of natural gas (McJeon et al., 2014; Weber and Clavin, 2012). We examine this dilemma for the United State by simulating the change to the country's IND in 2005 that would have occurred from an "alternate histories" scenario during which half of all coal-fired power production had shifted to gas five years prior. The ramifications of this scenario exercise help to elucidate the key parameters and tradeoffs, from the standpoint of climate debt as defined by IND, of selecting between alternative energy sources and their associated infrastructure.

In concert, the applications of IND presented here build upon and further extend the purview of climate debt (Baer et al., 2007; den Elzen et al., 2013; Grübler and Nakićenović, 1994; Höhne et al., 2011; Matthews et al., 2014). Moreover, these examples reveal how IND, as an accessible yet realistic metric, can encourage a range of users to investigate and advance a climate debt perspective.

2. Methods

2.1. Overview of IND

For comprehensive details on the rationale and procedure underlying IND, we refer readers to the main body and supplemental information of Smith et al. (2013). Here, we summarize the most salient features of IND, namely its purview and derivation, beginning with an explanation of notation and nomenclature.

Unless otherwise qualified, "IND" without a subscript specifically refers to climate debt from (1) both $CO_2(f)$ and CH_4 combined, (2) for the year 2005, and (3) in total not per capita terms. Climate debt from only $CO_2(f)$ or CH_4 is denoted $IND_{CO2(f)}$ or IND_{CH4}, respectively, and the percent of IND from $CO_2(f)$ or CH_4 is denoted % $CO_2(f)$ or $\%CH_4$, respectively. We have calculated IND and associated data for 181 countries plus 24 dependencies. For brevity, we use the term "countries" to refer to all 205 of these political entities, which together comprised over 99% of the world's population and economy in 2005. To be clear, IND does not include climate debt from CO_2 emissions related to land use change and forestry (LUCF; see Appendix B for further explanation).

IND measures climate debt in terms of RF, defined as the net impact of a factor, including its direct and indirect effects, on the global energy balance relative to pre-industrial conditions. RF is generally expressed in units of energy per area (e.g., mW/m^2) and in reference to a specific point in time. Therefore, expressed as RF, a given country's IND estimates how much excess energy its still extant past emissions of $CO_2(f)$ and CH_4 are contributing to the climate system in 2005.

We continue to use RFs from the Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment Report (AR4) (Solomon et al., 2007), instead of the more recently released Fifth Assessment Report (AR5) (Stocker et al., 2013), because the former provides RF values for 2005, retaining consistency with our time-series of emissions which span 1950–2005.

AR4 reports RFs from all major anthropogenic sources (Forster et al., 2007). The RF from CO_2, or global IND_{CO2}, was 1560 mW/m^2, which split into its $CO_2(f)$ and LUCF components by the procedure described in Appendix B, yields a global $IND_{CO2(f)}$ of 1123 mW/m^2. The RF from CH_4, or global IND_{CH4}, was 856 mW/m^2. Thus global IND from both $CO_2(f)$ and CH_4 summed to 1979 mW/m^2. For comparison, the RF from all non-aerosol CAPs was 2913 mW/m^2, and the best estimate of net RF in 2005 from all human activity since the Industrial Revolution – including LUCF, the overall

cooling effect of aerosol CAPs, changes in surface albedo from land use, and contrails – was ~1600 mW/m^2.

To reiterate, our purpose is not to calculate the most up-to-date values for IND, but rather, to demonstrate applications of IND and thus encourage a climate debt perspective even as underlying data continually updates. Nonetheless, it is worth noting that post-2005 emissions trajectories will alter the size and distribution of INDs, although, as yet, not in dramatic fashion. Most apparently, $CO_2(f)$ emissions from many LMICs have increased more rapidly relative to most HICs, whereas CH_4 emissions have increased more-or-less uniformly and gently across the board. Hence, the global balance of IND in 2010, relative to 2005, will shift slightly towards rapidly developing economies, driven by their proportionately faster growth in $IND_{CO2(f)}$. In per capita terms, the difference between HICs and LMICs generally will narrow, of course, but remain large.

2.2. Steps to calculate IND

Global $IND_{CO2(f)}$ and IND_{CH4} were attributed to countries by parallel methods. The procedure for a single country and a single CAP was as follows. First, we developed time-series of historical, or "original," emissions from 1950 to 2005. Second, we calculated year-by-year how much of these original emissions remained in the atmosphere in 2005, using the CAP's atmospheric lifetime, and summed these "remaining" emissions from all years. Third, we divided the country's total remaining emissions by the world's to determine what fraction of global $IND_{CO2(f)}$ or IND_{CH4} to assign to the country. Last, having executed this procedure for both CAPs, we summed the country's $IND_{CO2(f)}$ and IND_{CH4} to generate its IND as well as $\%CO_2(f)$ and $\%CH_4$.

For the first step, we developed global and country-level time-series of original emissions by drawing upon datasets which covered as much of the world since 1950 as possible, thus meeting our spatiotemporal requirement, and were free and publicly available; frequently updated; well-documented with estimates of uncertainty; and widely referenced. For $CO_2(f)$, we relied on the Carbon Dioxide Information Analysis Center (CDIAC) (Boden et al., 2010), adjusting time-series to account for changes in nation-state boundaries. For CH_4, we relied on the Emission Database for Global Atmospheric Research (EDGAR) (JRC/PBL, 2010b), backcasting time-series from 1969 to 1950 by ordinary least-squares linear regression. Time-series for both CAPs were updated with Annex I countries' 1990–2005 data from the UNFCCC (2012).

For the second step, we calculated remaining emissions – CAP-by-CAP, country-by-country, and year-by-year – based on the impulse response function for $CO_2(f)$ and the global lifetime for CH_4 as reported and referenced in AR4 (Denman et al., 2007; Joos et al., 2001). In comparison to the world's total post-industrial emissions still circulating in the atmosphere in 2005, approximately 87% of the $CO_2(f)$ and 99% of the CH_4 was emitted subsequent to 1950.

For the third step, we parsed global $IND_{CO2(f)}$ and IND_{CH4}, across countries believing that the practical and theoretical difficulties of determining and assigning emissions previous to 1950 would outweigh any minor improvement in nominal accuracy that might result. The distribution derived from the post-1950 period is therefore used as an estimate of the full distribution of post-1751 total remaining emissions of $CO_2(f)$ or CH_4 in the atmosphere in 2005.

For all countries, the accompanying spreadsheet, *Database IND*, provides the following: IND, $IND_{CO2(f)}$, and IND_{CH4}; total original emissions and total remaining emissions for $CO_2(f)$ and CH_4; gross domestic product at purchasing power parity (GDP-PPP) (World Bank, 2012); and population data (United Nations Department of Economic and Social Affairs - Population Division, 2011; United States Central Intelligence Agency, 2006). The spreadsheet can

function as a template for the use of different, updated, or additional data.

2.3. Uncertainty of IND

As with other composite metrics, IND is subject to uncertainty from the choices and parameters that are embedded within it (Prather et al., 2009). RFs for both CAPs are assessed to have 90% confidence intervals of ±10% (Forster et al., 2007). Although the multi-compartmental nature of the carbon cycle, among other issues, complicates the presentation of uncertainty for the atmospheric lifetime of $CO_2(f)$, the impulse response functions from the five IPCC assessment reports agree with one another within 15% for simulations over a 100-year timeframe (Joos et al., 2013). The 90% confidence intervals for the atmospheric lifetime of CH_4 spans ±15% (Denman et al., 2007).

Emissions inventories constitute the greatest source of uncertainty in IND, compounded by the fact that these uncertainties can only be approximated through expert opinion or cross-comparisons of competing datasets. With that caveat in mind, the 95% confidence intervals for original emissions of $CO_2(f)$ are judged to range from plus-or-minus several percent for most developed countries, ±15% to 20% for China, and more than ±50% for countries with inadequate statistical infrastructure (Andres et al., 2012). The 90% confidence intervals for original emissions of CH_4 vary depending on source category, from around ±10% for the energy sector to as much as ±100% for the agriculture or waste sectors (JRC/PBL, 2010a). For both CAPs, uncertainty widens as time-series go farther back in time, but the calculation of remaining emissions effectively discounts the weight of older emissions, partly abating the contribution of these comparatively less certain data to overall uncertainty.

As just intimated, the accuracy of time-series of original emissions is partially a function of economic significance. Countries with high per capita or total economic output are scrutinized by both their own and international data collection agencies with greater rigor. In 2005, the fifty countries with the largest INDs comprised over 90% of global IND, 90% of global economic output, and 85% of global population size. For this reason, these fifty countries are emphasized in Section 3 and *Database IND* and labeled in Figs. 1–4 and D1.

The analyses that follow are based on central estimates of IND and associated data, with the recognition that there are remaining uncertainties in emissions inventories and other input parameters which will undoubtedly be reduced with time. Accordingly, results are not intended to be definitive but rather first-order approximations that can guide initial decision-making and stimulate further inquiry, even as the particular distribution of global IND across countries may itself change with future refinement.

3. Results and discussion

3.1. Distributions of IND

3.1.1. Total and per capita

Understanding the global distribution of climate debt as captured by IND begins with characterizing individual countries' total and per capita IND values, including the splits between % $CO_2(f)$ and $\%CH_4$. Such an analysis brings into stark relief the significant variation in countries' contributions to the global burden of climate debt.

Fig. 1 depicts climate debt, based on IND for the year 2005, across the vast range of countries' per capita IND (*y*-axis) and total IND (bubble area). Additionally, bubble slices correspond to % $CO_2(f)$ (red) and $\%CH_4$ (blue). The countries included in the figure, all with a population greater than one million and per capita IND
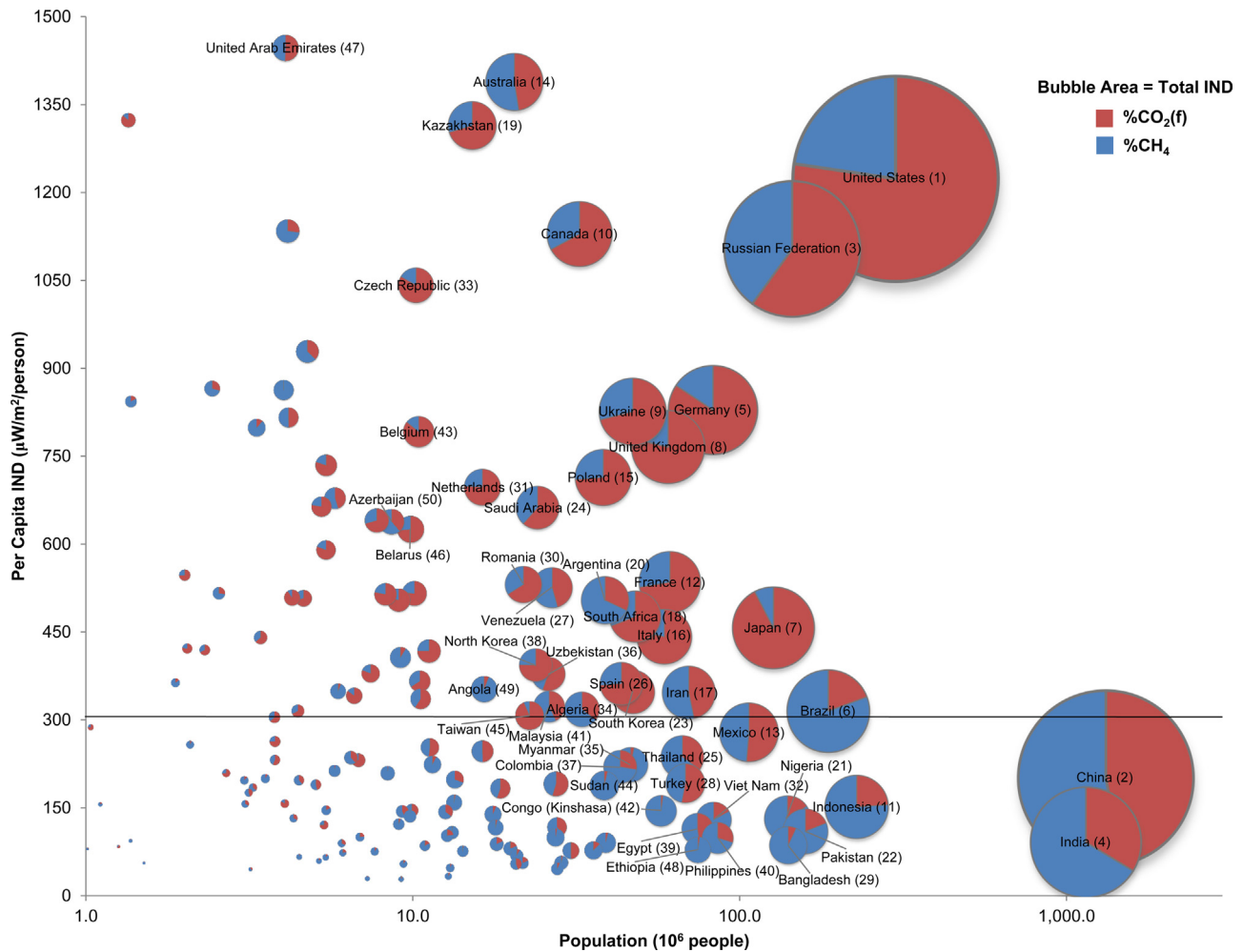
Fig. 1. Total and Per Capita Distribution of IND. Bubble areas are proportional to total IND and divided into slices representing $IND_{CO2(f)}$ (red) and IND_{CH4} (blue). Bubble centers are graphed with respect to per capita IND on the y-axis (linear scale) and population on the x-axis (log scale). The axes are truncated to exclude countries with a population less than one million or per capita IND greater than 1500 $\mu W/m^2$. Consequently, bubbles for 152 countries from the IND database are visible. Labeled are the 50 countries with the largest INDs in 2005 with ranks given in parentheses. The horizontal line at 305 $\mu W/m^2$ represents global per capita IND. Data are from *Database IND*.

less than 1500 mW/m², span a thirty-fold range of per capita IND. The horizontal line at 305 $\mu W/m^2$/person represents global per capita IND in 2005. We proceed with a description of how Fig. 1 helps orient initial comprehension of climate debt, mindful that the size, location, and composition of countries' INDs in the figure will change over time.

At first glance, most apparent are the four largest bubbles, representing the United States, China, Russian Federation, and India. In aggregate, these four countries accounted for ~45% of global IND in 2005. Although possessing the largest INDs, these countries have attained their debts through different means. The United States and Russian Federation are both populous and have high per capita INDs, roughly four times the global average, with $IND_{CO2(f)}$ constituting a majority of IND. China and India, although even more populous, have per capita INDs less than the global average, approximately two-thirds and one-third of the global average, respectively, and IND_{CH4} comprises a majority of IND. With the addition of Germany and Brazil, these six countries alone would account for over half of global IND in 2005.

Continuing with a focus on the fifty countries with the largest INDs (labeled with rank in parentheses), groupings can be defined by bands based on multiples of global per capita IND. Countries with per capita IND greater than three times the global average

($>\sim$900 mW/m²) include the United State and Russian Federation as well as the five countries from the United Arab Emirates to Czech Republic. Australia and the United Arab Emirates carry more IND_{CH4} than $IND_{CO2(f)}$, unlike the other countries in this grouping, reflecting the sizable CH_4 emissions from the agricultural sector for Australia and the energy sector for both countries. The nine countries with per capita IND between two and three times the global average ($\sim$600–900 mW/m²), from Germany to Belarus, exhibit a %CO_2(f) greater than %CH_4 in all cases except Azerbaijan, which has a large natural gas industry. Countries with per capita IND between one and two times the global average ($\sim$300–600 mW/m²), the seventeen countries from France to Taiwan, span a range from possessing markedly more $IND_{CO2(f)}$ than IND_{CH4}, as in the case of Japan and Taiwan, to decidedly more IND_{CH4} than $IND_{CO2(f)}$, such as for Brazil and Angola, mirroring the diverse economic histories of this group. Finally, there are the seventeen countries with per capita IND less than the global average ($<\sim$300 mW/m²), including China and India plus the group from Mexico to Ethiopia. All but two of these have a %CH_4 greater than %CO_2(f), as the proportionally larger agricultural sectors of the group would suggest. Both exceptions, Mexico and Turkey, enjoy a per capita GDP-PPP higher by a factor of two than the other countries in this final group.

Fig. 1 captures a number of key features of the global distribution of climate debt, and its simultaneous appraisal of total IND, per capita IND, %CO_2(f), and %CH_4 begins to suggest ways forward. The figure brings into relief countries with similar INDs, including with respect to %CO_2(f)/%CH_4, who would be logical partners for sharing technological and policy innovations. The size and color of a country's bubble hints at the relative durability of its IND, given that in most cases $IND_{CO2(f)}$ will contract more slowly than IND_{CH4}. These two observations are relevant to prioritizing emissions reductions or guiding emissions trading, though both are complex matters with many factors to consider. Furthermore, the location of a country's bubble could help it to track progress, in comparison to itself or others, as its IND changes over time.

3.1.2. Income and health

The accrual of climate debt can be conceptualized as a country repeatedly borrowing future resiliency from natural systems in order to progressively better the lot of its citizenry (Bhaskar, 1995;

Smith, 1996; Smith et al., 1993; Srinivasan et al., 2008). Research on various measures of humanity's "environmental footprint" indicates that countries differ in how successfully they have transformed impacts on natural resources into improved conditions for their societies (Jorgenson, 2014; Knight and Rosa, 2011). Characterizing climate debt in an analogous manner can bring into focus variation in countries' efficiency of climate debt accumulation and pathways for narrowing these differences (Lamb and Rao, 2015; McMichael and Butler, 2011).

Fig. 2 examines how efficiently countries have translated their climate debt, as measured by IND in 2005, into two major indicators of overall well-being: economic output and population health. Although there is a degree of overlap in the activities that generate CO_2(f) and CH_4 emissions, sources differ sufficiently to prompt separate assessments of the efficiencies of $IND_{CO2(f)}$ (2A) and IND_{CH4} (2B). Economic output is gauged by GDP-PPP (United States Central Intelligence Agency, 2006; World Bank, 2012) and population health by the total amount of ill-health in a country as
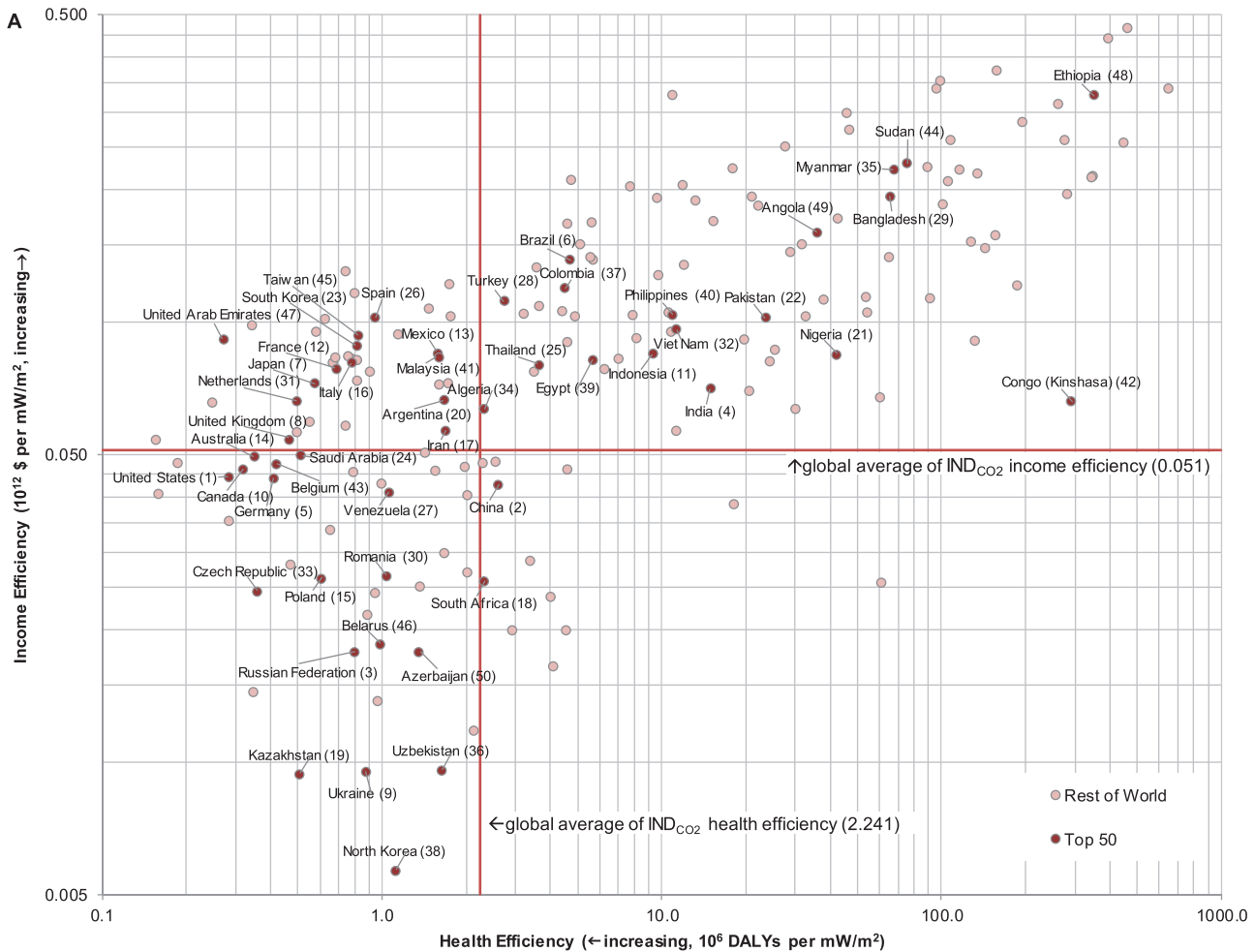

Fig. 2. Efficiency of $IND_{CO2(f)}$ and IND_{CH4} by GDP-PPP and DALYs. Countries are plotted according the efficiency of their $IND_{CO2(f)}$ (2A) or IND_{CH4} (2B) with regards to income (y-axis, log scale) and health (x-axis, log scale) in 2005. $IND_{CO2(f)}$ or IND_{CH4} income efficiency, defined as the ratio of GDP-PPP divided by $IND_{CO2(f)}$ or IND_{CH4}, respectively, increases to the top of the graph. Conversely, $IND_{CO2(f)}$ or IND_{CH4} health efficiency, defined as the ratio of disability-adjusted life years lost (DALYs) divided by $IND_{CO2(f)}$ or IND_{CH4}, respectively, increases to the left of the graph. The horizontal and vertical lines represent global average IND efficiencies and delineate four quadrants of combined income and health efficiency, the most efficient at top-left and the least efficient at bottom-right. Labeled and dark red points represent the 50 countries with the largest INDs in 2005 with ranks given in parentheses. Not graphed are 27 countries that lacked DALY data (see Appendix C for list). In both panels, an additional three countries are off-scale (in 2A: Chad, Mali, and Micronesia; in 2B: Brunei Darussalam, Central African Republic, and Qatar). Light red points represent the remaining 125 countries. The intersection of the two lines represents the world. Data are from *Database IND*. Abbreviations: DALY = disability-adjusted life year; GDP-PPP = gross domestic product at purchasing power parity.
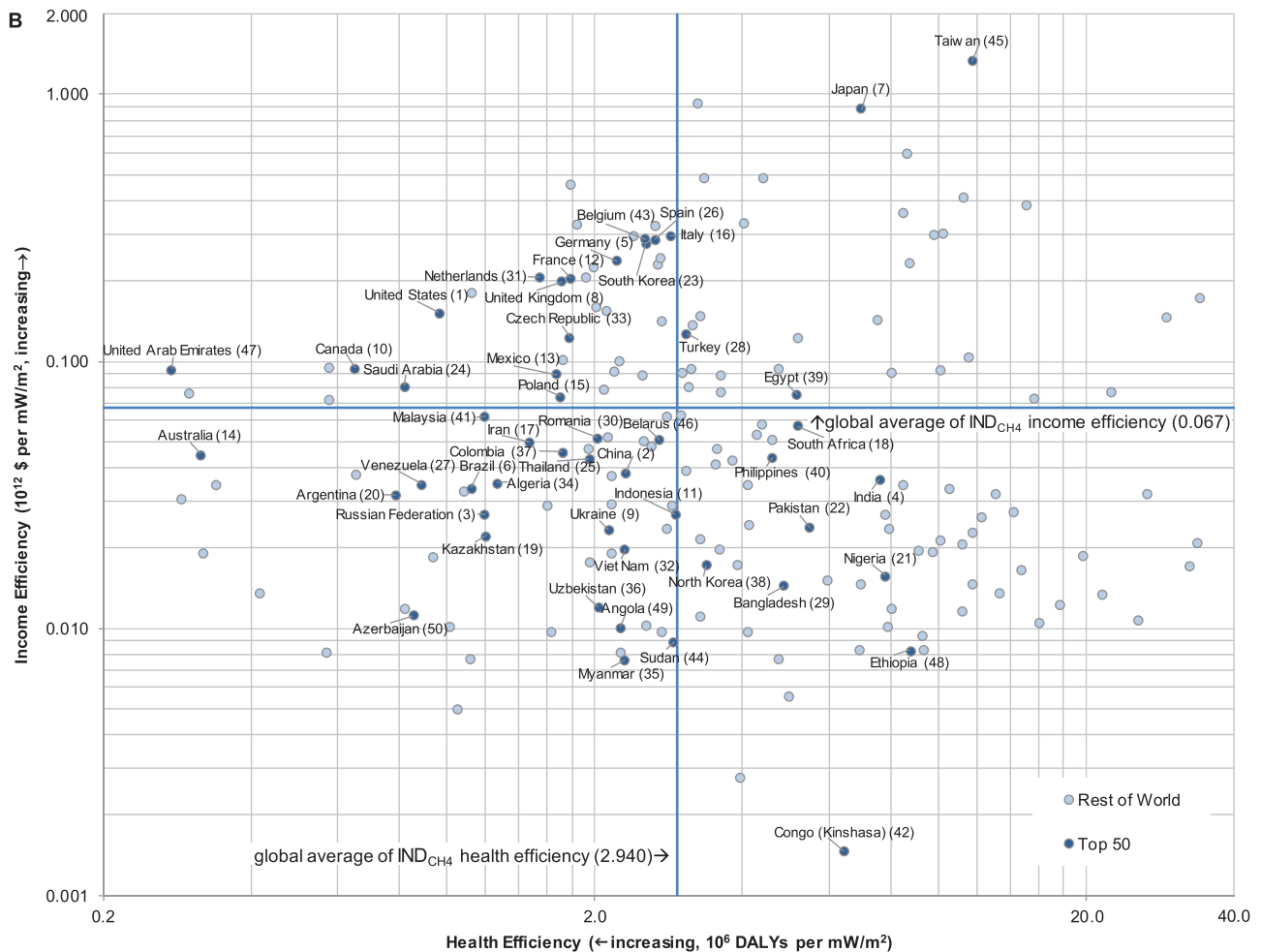
Fig. 2. (Continued)

measured by disability-adjusted life years lost (DALYs) (Global Burden of Disease Study 2010, 2012). The DALY, a widely-used metric for lost healthy life years, is a more accurate estimate of lost health than deaths alone since it accounts for both the degree of prematurity in mortality as well as the severity and duration of morbidity.

Fig. 2 depicts the efficiency of countries' accumulated investments, enabled by climate debt, in expanding economic output while diminishing ill-health. These data are provided in *Database IND*. With regards to the *y*-axes, the more economic output per unit of climate debt (or "income efficiency"), the more efficiently a country has parlayed its borrowing into national income. Conversely, with regards to the *x*-axes, the less ill-health per unit of climate debt (or "health efficiency"), the more efficiently a country has converted its borrowing into wellness.

The horizontal and vertical lines represent global average IND efficiencies and define four quadrants of combined income and health efficiency. The most efficient quadrant at top-left hosts countries with high income and high health efficiencies in comparison to global averages. Correspondingly, the least efficient quadrant at bottom-right hosts countries with low income and low health efficiencies in comparison to global averages.

Viewing both log–log plots of Fig. 2 side-by-side, it is apparent that the health efficiency of $IND_{CO2(f)}$ covers a wider range

($\sim$10,000$\times$) than that for IND_{CH4} ($\sim$200$\times$) and conversely the income efficiency of IND_{CH4} covers a wider range ($\sim$2,000$\times$) than that for $IND_{CO2(f)}$ ($\sim$100$\times$). The distribution of countries in Fig. 2A mostly excludes the bottom-right quadrant (low health and low income efficiencies) but in Fig. 2B includes all four quadrants. Both distributions raise research questions, for example on the direction of causal relationships between income and health (Bloom and Canning, 2000), into which the lens of IND efficiency may prove insightful.

Fig. 2A suggests that "leapfrog" strategies are possible to shift many LMICs in the top-right quadrant (low health but high income efficiencies) into the top-left quadrant (high health and high income efficiencies). If these countries maintained or even moderately increased their $CO_2(f)$ climate debt in order to promote population health, they could catapult to HIC levels of health and income efficiency. It would be advantageous from a global and country-level perspective, doubly so given health co-benefits (Smith et al., 2014), for these LMICs to avoid the fossil fuel intensive pathway of the suite of countries in the bottom-left quadrant (high health but low income efficiencies). Many HICs, it must also be noted, have room for improvement with respect to the income efficiency of their $IND_{CO2(f)}$.

Shifting to Fig. 2B, rapidly and dramatically boosting population health in LMICs, the stated objective of initiatives such as Global Health 2035 (Jamison et al., 2013), would also move many

countries from the bottom-right quadrant (low health and low income efficiencies) into the bottom-left quadrant (high health but low income efficiencies). The sizable number of countries in the lower half of the figure, from the perspective of economic output, have inefficiently accumulated IND_{CH4}, lending additional impetus for research and development into technologies and strategies that either decrease CH_4 emissions, which also has attendant health co-benefits (Shindell et al., 2012), or more effectively convert CH_4 emissions into income gains, and for the countries in the bottom-right quadrant, health gains, as well.

In conjunction with tracking climate debt on its own, the concept of IND efficiency can provide another yardstick by which a country can trace the progression of its climate debt over time either in comparison to itself or in reference to other countries. It must be noted, however, that IND efficiency would improve only as long as the rate at which income expands or ill-health contracts exceeds the rate at which climate debt grows. Though such a scenario remains more desirable than its opposite, more efficiently acquiring climate debt may not correspond to mitigating climate change.

Additionally, facilitating the conversion of societal investments, financed partly by climate debt, into income or health gains is often a complex multifactorial process with time lags. There is also a delay between decelerating emissions growth or outright emissions decreases and reducing IND, since IND carries the burden of past emissions that can only be discharged as a function of each CAP's atmospheric lifetime. It follows that the efficiency of IND_{CH4} would respond more quickly to contracting emissions than the efficiency of $IND_{CO2(f)}$. Appendix D presents an approach to more closely exploring IND_{CH4} by disaggregating it into sector-level contributions.

3.2. Scenario exercises with IND

3.2.1. Aspirational reductions

IND captures the amount of excess RF in a given year attributable to a country's past activities. Given the relative ease of calculating and interpreting IND-based climate debt, IND lends itself to exploring the implications of mitigation goals and strategies through scenario analyses.
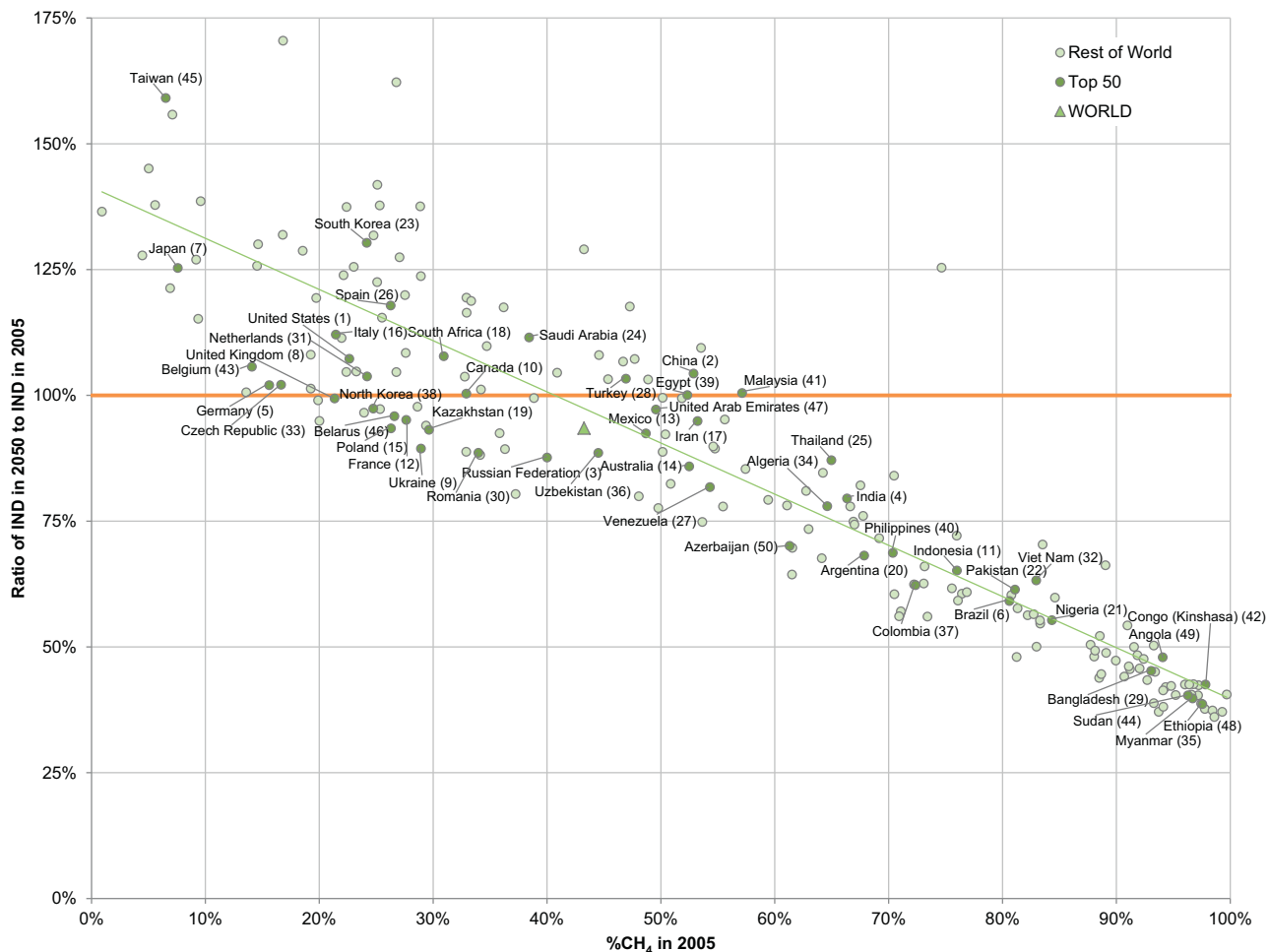

Fig. 3. IND Consequences of Aspirational Reductions in CAP Emissions. Figure depicts the IND consequences of a scenario in which all countries decrease both their CO_2(f) and CH_4 emissions to 20% of 1990 levels by 2050. A country's resulting IND in 2050, measured as a percent of its IND in 2005 (y-axis), is plotted against the country's percent of IND from CH_4 (%CH_4) in 2005 (x-axis). The orange horizontal line represents equal INDs in 2050 and 2005. Countries experiencing an IND increase are above this line and those experiencing an IND decrease are below the line. Labeled dark green points represent the 50 countries with the largest INDs in 2005 with ranks given in parentheses. One country (Turks & Caicos Islands) is off-scale. Light green points represent the remaining 154 countries. The green triangle represents the world as a whole. The linear regression line, calculated using data for all 205 countries, has an r^2 equal to 0.76. Data derived from using *Database IND* as the initial conditions for modeling this scenario.

Fig. 3 conveys how much IND would change under a scenario of "aspirational reductions" in which all countries achieved a proposed goal of decreasing all CAP emissions to 20% of 1990 levels by 2050 (European Commission, 2011; Executive Department State of California, 2005; Parliament of the United Kingdom, 2008). The scenario models each country's future time-series of $CO_2(f)$ and CH_4 emissions as a linear decline commencing in 2006 and attaining target emissions rates in 2050. Initial conditions are based on *Database IND*. Implicitly, rising energy demands are met despite economic and population pressures. Over the 2006–2050 timeframe, the scenario assumes that atmospheric lifetimes, direct and indirect effects, and radiative efficiencies hold constant. These assumptions simplify the climate system but enable a reasonably realistic first-order examination.

Under the aspirational reductions scenario, global IND in 2050 would be 1850 mW/m^2 or 93% of its 2005 level. The respective contributions of $CO_2(f)$ and CH_4 to IND would shift from 57% and 43% in 2005 to 83% and 17% in 2050, as would be expected since $IND_{CO2(f)}$ persists longer than IND_{CH4}. The results for future RFs are in broad concordance with more sophisticated models that simulate similarly aggressive emissions reduction, such as RCP2.6 utilized in AR5 (van Vuuren et al., 2011).

A sizable minority of countries are located above the orange line, which represents INDs that are equal in 2050 and 2005. These countries, despite dramatic emissions decreases, would actually experience a rise in their IND by 2050, and many already possess per capita INDs well above the global average in 2005. Such countries have a high %$CO_2(f)$ or unusually steep recent increases in $CO_2(f)$ emissions, underlining the substantial "hangover" from $CO_2(f)$ contributions to IND while also arguing for these countries to even more drastically decrease $CO_2(f)$ emissions to lower their IND by 2050.

A majority of countries are found below the orange line. These countries would in fact lower their IND by 2050, in some cases quite markedly so. These countries typically have a high %CH_4, or in a few cases, gradually decreasing $CO_2(f)$ emissions. In reality, however, many of these countries are currently increasing $CO_2(f)$ emissions as their economies continue to develop and populations continue to grow. Most such countries are also carrying INDs lower than the global per capita average in 2005, underscoring the question of how to justly apportion obligations to reduce climate debt across the globe.

Although %CH_4 functions well as a shortcut for locating countries on the graph, countries' outcomes under the scenario are in actuality a consequence of their unique historical emissions trajectories of $CO_2(f)$ and CH_4. This explains the variance in the figure, accounting for differing INDs in 2050 among countries with seemingly comparable compositions to their INDs in 2005. For example, South Korea and Poland share a similar %CH_4 in 2005, 26% and 24%, respectively. In addition, the preponderance of both countries' IND_{CH4} is comprised of remaining emissions from recent years.

South Korea's and Poland's historical time-series of $CO_2(f)$ emissions, however, differ strikingly from one another and consequently so does the genesis of each's $IND_{CO2(f)}$. South Korea's $CO_2(f)$ emissions doubled from 1990 to 2005 and remaining emissions from this period account for three-fourths of its $IND_{CO2(f)}$. In contrast, Poland's $CO_2(f)$ emissions decreased by a third over the same years, but remaining emissions from the more distant 1970–1989 period account for almost half of its $IND_{CO2(f)}$.

As a result, though South Korea and Poland have almost identical values for %$CO_2(f)$ in 2005, they begin the aspirational reductions scenario with proportionately much different emissions rates of $CO_2(f)$ in 2005: South Korea's are higher, their decline is steeper, and their contribution to IND in 2050 is larger. These disparities in historical emissions between South Korea and Poland

explain why the former's IND in 2050 expands by 27% while the latter's contracts by 4%.

Under the aspirational reductions scenario, whether a country's IND contracts or expands is determined by the balance between the country's lowering of IND_{CH4} and its raising of $IND_{CO2(f)}$. The modeled decreases in CH_4 emissions lower IND_{CH4} by 2050 for all countries, verifying the swift response of IND_{CH4} to a decline in CH_4 emissions. On the other hand, the modeled decreases in $CO_2(f)$ emissions do not lower $IND_{CO2(f)}$ for any country, in this case reflecting the enduring legacy of past $CO_2(f)$ emissions. The decreases in $CO_2(f)$ emissions prevent $IND_{CO2(f)}$ from rising even further, but their insufficiency also makes apparent the incentive for simultaneously devising viable carbon capture and sequestration technologies (Rubin et al., 2012; Sedjo and Sohngen, 2012).

For the world as a whole, the rise in IND from countries above the orange line is compensated by the fall in IND from countries below the orange line. Consequently, global IND in 2050 remains very similar to that in 2005. But this seemingly favorable outcome for the aspirational reductions scenario does not advocate for its implementation. A global program of climate stabilization pursued through commensurate decreases in emissions intensity across all countries, on the contrary, would exacerbate already stark inequities.

Instead, the aspirational reduction scenario stresses the differing capacities of countries to lower their climate debts. The exercise lays bare the need for coordinated action on both $CO_2(f)$ and CH_4 to address climate change. Firstly, bold decreases in $CO_2(f)$ emissions from countries with a high %$CO_2(f)$ will be necessary to both reduce global $IND_{CO2(f)}$ and offset increases in $CO_2(f)$ emissions from countries aspiring to attain a prosperous level of development. Secondly, decreases in CH_4 emissions from all countries will also be necessary to rapidly reduce global IND_{CH4} and thereby at least postpone and possibly diminish the deleterious impacts of climate change. Thirdly, the immense challenge of the preceding two recommendation endorses efforts to cautiously appraise geoengineering schemes to manipulate the climate system (Lenton and Vaughan, 2009), as well as markedly decrease emissions of other CAPs.

Moreover, the aspirational reductions scenario posits that the global total IND in 2005 could serve as a midcentury objective for capping worldwide climate debt from $CO_2(f)$ and CH_4. It follows that the target for global per capita IND in 2050 would be about 215 μW/m^2/person for the intermediate-fertility population projection from the United Nations Department of Economic and Social Affairs - Population Division (2011), similar to the climate debt carried in 2005 by the average Jamaican, Laotian, or Somali. For the UN's low-fertility and high-fertility population projections, global per capita IND in 2050 would be roughly 30 μW/m^2/person higher or lower, respectively. The target applies equally to countries above and below it in 2005, and offers a vision of what will be required to achieve "convergence" with respect to climate debt.

3.2.2. Alternate histories

The same features of IND which make it an accessible tool for global-level scenario analyses also facilitate the scrutiny of questions at finer scales. As an example of such an analysis, we leverage IND to help define the climate debt contours of the ongoing debate on natural gas in the United States. In particular, IND can help to assess the relative impact, in terms of change in RF, from displacing coal-fired electricity generation with gas-fired alternatives.

Hydraulic fracturing or "fracking" has significantly expanded natural gas production in the United States since the mid-2000s. Coupled with the opportune advances in extraction technology
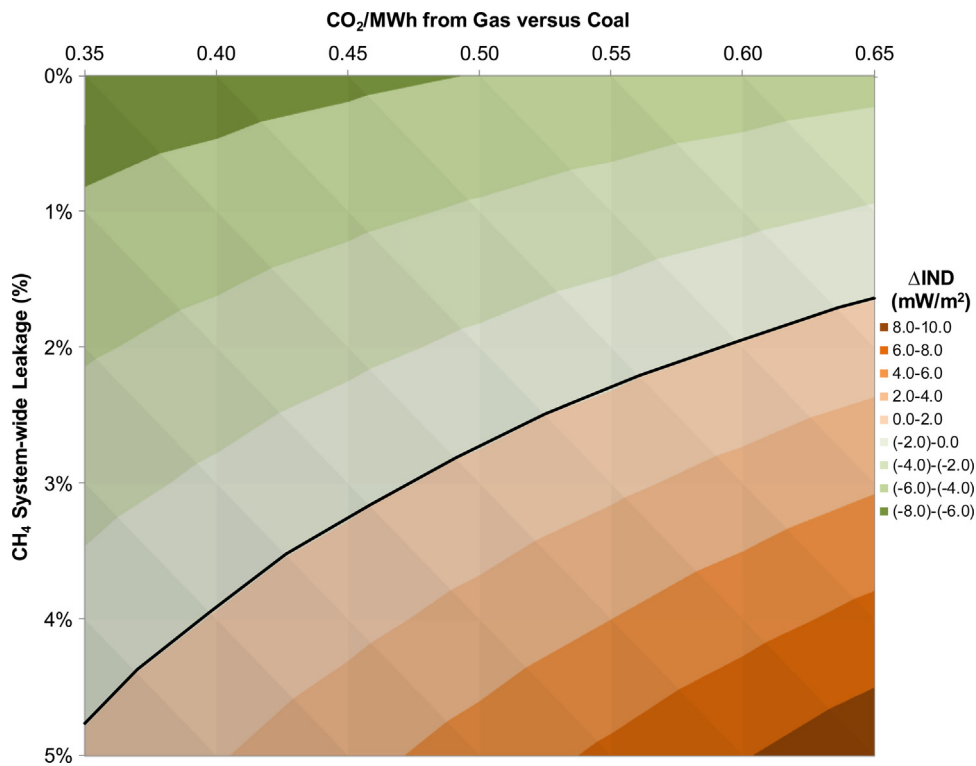
CO$_2$/MWh from Gas versus Coal

Fig. 4. IND Outcomes from Alternate Histories of a Coal to Gas Transition in the United States. Figure depicts the net impact on the United States' IND in 2005 under a scenario in which 50% of the United States' coal-fired electricity generation during 2001–2005 had instead been produced by gas power plants. The colored contour bands (contour interval 2.0 mW/m^2) indicate the change in IND between the various combinations of the scenario and reality. The contour bands range from a decrease in IND (green hues) of −8.0 to −6.0 mW/m^2 at top-left to an increase in IND (brown hues) of 8.0–10.0 mW/m^2 at bottom-right. The y-axis spans the possible range of carbon intensity ratios for gas versus coal power generation. The x-axis spans a continuum of plausible system-wide leakage rates in the natural gas system. The black curve separates the regions of IND decrease, above the arc, from IND increase, below the arc. Data derived from using *Database IND* and associated information (see text) as the inputs for modeling this scenario.

has been a favorable economic, regulatory, and strategic environment for natural gas as an energy source. In addition, gas burns more cleanly than oil and especially coal, producing less CO$_2$(f) per unit energy released, which has led some to pitch natural gas as a "bridge" fuel until renewables become more competitive.

Part of the argument around natural gas concerns whether its greater combustion efficiency might be outweighed by fugitive emissions of CH$_4$ during extraction, transport, storage, and use (Alvarez et al., 2012; Miller et al., 2013). Although natural processes remove CH$_4$ from the atmosphere more rapidly than CO$_2$, the radiative efficiency of CH$_4$ exceeds that of CO$_2$ on a per carbon atom or unit mass basis. Studies on the net impacts of natural gas, including those focused on fracking, have found evidence to support claims on both sides of the argument (McJeon et al., 2014; Weber and Clavin, 2012).

In order to examine the IND implications of shifting the United States' power production portfolio from coal to gas, we developed an "alternate histories" scenario in which half of the country's coal-fired electricity generation during 2001–2005 was instead produced by natural gas power plants. The scenario considers a range of coal and gas power plant types and a continuum of plausible leakage rates in the natural gas system. Instead of attempting to forecast the future, we sought to reimagine the past, asking how the United States' IND in 2005 would have differed had the fracking revolution occurred earlier. This approach has the benefit of drawing on more reliable existing data, subjected to the hypotheses of the exercise, instead of anticipating less certain circumstances far into the future. Additionally, such a strategy may be useful for situations requiring a near term assessment, for instance to meet a target or respond to feedbacks (Rignot et al., 2014; van Nes et al., 2015), whereas assessing longer term impacts would require additional assumptions similar to the aspirational reductions scenario.

Baseline emissions inventories reimagined by the scenario are based on two of the datasets, CDIAC and EDGAR (Boden et al., 2010; JRC/PBL, 2010b), used for developing IND. In the scenario, CO$_2$(f) emissions from coal are replaced by those from gas at a proportion ranging from 0.35 to 0.65. The lower value corresponds to a combined cycle gas plant replacing an average coal plant and the higher value corresponds to an average gas plant replacing a super pulverizer coal plant (USEPA, 2012).

System-wide, i.e., well-to-plant, leakage in the natural gas system can be expressed as a percent of the gas being extracted in order to be combusted at gas-fired facilities. In the scenario, leakage spans a range of 0–5%, encapsulating a plausible range approximately centered around the United States Environmental Protection Agency's (USEPA's) pre-2013 estimate that ~2.25% of natural gas produced over 2001–2005 was lost to fugitive emissions (USEPA, 2008). In 2013, this fraction was revised downwards, to ~1.5% (USEPA, 2013). Other evidence suggests leakage could be several times higher than either of the USEPA's values (Miller et al., 2013), a concern addressed by the higher end of our leakage range.

For simplicity, all coal or gas combusted in a given year was assumed to have been extracted in that same year. Diminished demand for coal resulted in a decline in fugitive emissions of CH$_4$ from coal mines, which during 2001–2005 contributed on average 18.5% of the United States' energy sector's CH$_4$ emissions (JRC/PBL, 2010b; USEPA, 2013).

The scenario exercise recalculated CO$_2$(f) and CH$_4$ emissions over 2001–2005 for both the United States and the world because the United States is such a major contributor to global emissions. This pair of recalculations provided both an adjusted numerator and denominator for re-attributing global IND$_{CO2(f)}$ and IND$_{CH4}$ to the United States.

Fig. 4 presents the difference between the United States' IND as calculated under the alternate histories scenario and the country's

actual IND in 2005 across all combinations of relative carbon intensities (*x*-axis) and leakage rates (*y*-axis). As the green-hued contour bands become darker, they incrementally indicate larger falls in IND. Conversely, as the brown-hued contour bands become darker, they incrementally indicate larger rises in IND.

The upper left corner, where natural gas leakage is lowest and the coal-to-gas shift involves combined cycle gas plants replacing average coal plants, is the most favorable region of IND outcomes, a decrease of 6–8 mW/m^2. The opposite corner, at the bottom-right, where natural gas leakage is highest and average gas plants replace super pulverizer coal plants, is the least favorable region, with IND actually increasing 8–10 mW/m^2. In general, combined cycle gas plants are advantageous, with respect to reducing excess RF, until leakage rates approach the 3.2–4.8% range. For average gas plants to be advantageous, leakage rates must be lower, in the 1.8–2.8% range.

The IND-based scenario analysis, in which half of the United States' coal power production was replaced by gas, defines the range of outcomes possible, over the five year period, in terms of climate debt. Clearly, conclusions pivot on the amount of leakage in the natural gas system and the type of gas and coal plants being swapped. Overall, from one set of extremes to the other, as leakage in the natural gas system decreases or as the combustion efficiency of gas plants relative to coal plants increases, electricity generation by natural gas goes from being unfavorable to favorable in terms of climate debt. The alternate histories scenario provides a template for using IND to scrutinize more elaborate decision analyses, including the incorporation of economic costs, a central issue we have left aside for the time-being, as well as longer time horizons.

4. Conclusions

IND, owing to its straightforward and transparent derivation (Smith et al., 2013), can readily operationalize climate debt to consider issues of equity and efficiency, and to drive scenario exercises that explore the response to climate change from global to sectoral scales. For instance, considering IND in total and per capita terms exposes and emphasizes variations in the size and composition of climate debt that can help orient burden-sharing, guide mitigation approaches, track country progress, and generate hypotheses for further investigation.

Similar to other measures of environmental footprint (Jorgenson, 2014; Knight and Rosa, 2011), the accumulation of IND can be evaluated in comparison to two major indicators of overall well-being—economic output and population health. We put forth a characterization of the "efficiencies" of IND$_{CO2(f)}$ and IND$_{CH4}$ in order to explore how effectively countries have accumulated these two forms of climate debt in the pursuit of expanding economic output and diminishing ill-health. For instance, the distribution of the efficiency of IND$_{CO2(f)}$ hints at the consequence of a "leapfrog" strategy for many LMICs, a number of which have low health but high income efficiencies. If these countries maintained or even moderately increased their IND$_{CO2(f)}$ in order to promote population health, they could catapult to HIC levels of both health and income efficiency. In contrast, the sizable number of LMICs that have inefficiently accumulated IND$_{CH4}$ lends additional impetus for research and development into technologies and strategies that either decrease CH$_4$ emissions or more effectively convert CH$_4$ emissions into income and/or health gains. Overall, IND efficiency provides another yardstick by which to investigate the distribution and evolution of climate debt as countries also simultaneously strive to achieve other goals (Lamb and Rao, 2015; McMichael and Butler, 2011).

IND functions as a natural tool for investigating mitigation goals and strategies. As a measure of climate debt, IND accounts for the

constraints imposed by the magnitude and timing of past emissions and measures the amount of climate forcing in a particular year caused by still-extant emissions of multiple CAPs. Scenario exercises, with appropriate attention to their limitations, can help evaluate the future evolution of IND, propose evenhanded approaches to reducing climate debt, and interrogate the choice between mitigating CO$_2$(f) or CH$_4$ across scales.

Under the "aspirational reductions" scenario, countries linearly decrease their CAP emissions to 20% of 1990 levels by 2050, attaining a target commonly discussed for midcentury (European Commission, 2011; Executive Department State of California, 2005; Parliament of the United Kingdom, 2008). Overall, the exercise posits that, assuming intermediate-term fertility projections (United Nations Department of Economic and Social Affairs - Population Division, 2011), a medium-term, globally averaged, per capita IND of approximately 215 μW/m^2/person would stabilize global IND by 2050.

The aspirational reduction scenario explains how the differing capacities of countries to lower their climate debts is a function of historical emissions trajectories of CO$_2$(f) and CH$_4$. Thus, the exercise lays bare the need for coordinated action on both CO$_2$(f) and CH$_4$ to address climate change. Firstly, bold decreases in CO$_2$(f) emissions from countries with a high %CO$_2$(f) will be necessary to both reduce global IND$_{CO2(f)}$ and offset increases in CO$_2$(f) emissions from countries aspiring to attain a prosperous level of development. Secondly, decreases in CH$_4$ emissions from all countries will also be necessary to rapidly reduce global IND$_{CH4}$ and thereby at least postpone and possibly diminish the deleterious impacts of climate change. Thirdly, the immense challenge of the preceding two recommendations makes apparent the incentive for simultaneously decreasing emissions of other CAPs; devising viable carbon capture and sequestration technologies (Rubin et al., 2012; Sedjo and Sohngen, 2012); and appraising, with due caution, geoengineering schemes to manipulate the climate system (Lenton and Vaughan, 2009).

Although natural processes remove CH$_4$ from the atmosphere more rapidly than CO$_2$, the radiative efficiency of CH$_4$ exceeds that of CO$_2$ on a per unit mass or carbon atom basis, complicating decisions to preferentially mitigate one CAP versus the other (McJeon et al., 2014; Weber and Clavin, 2012). This question can be pursued at a sectoral level through an "alternate histories" scenario in which half of the United States' coal-fired power production had been instead generated by natural gas facilities from 2000 to 2005. The scenario incorporates the carbon intensity ratios of different coal-to-gas plant substitutions and a range of plausible well-to-plant leakage rates in the natural gas system. For such a hypothesized shift to have lowered the United States' IND in 2005, relative to what was the country's actual IND that year, combined cycle gas plants would require leakage rates in the 3.2–4.8% range or less, whereas average gas plants, with their lower efficiency, would require leakage rates at most in the 1.8–2.8% range.

IND was developed to be flexible for users, including with regards to data inputs and calculated outputs. IND can be an appropriate vehicle, as data sources improve and climate science advances, for folding additional CAPs, non-CAP anthropogenic perturbations to RF, and mitigative actions into the climate debt paradigm. The incorporation of a "basic needs" allowance (Costa et al., 2011; Müller et al., 2009), as well as approaches that attribute IND on the basis of where goods and services were consumed, as opposed to where emissions were produced (Hertwich and Peters, 2009; Unger et al., 2010), would further expand the explanatory and analytical power of IND.

Collectively, the analyses presented in this report demonstrate how IND in its present form – as well as updated, expanded, or enhanced – can inform a range of key question on climate change

mitigation. The published literature on climate debt has often involved either philosophically or technically complex approaches to consider or calculate climate debt (Bell, 2011; Caney, 2005; Höhne et al., 2011; Tanaka et al., 2009). Both of these are valuable streams of scholarship that warrant sustained attention, and have contributed to the development of IND. However, the full utility of climate debt as an analytical perspective will remain underappreciated without tools such as IND that can be manipulated by a wide range of analysts. By demonstrating the insights possible from applications of IND, we have sought to open an intellectual terrain for climate debt analyses and invite more participatory and inclusive discussions about the consequent implications of a multiple CAP and accountability based perspective.

Author's contributions

Acknowledgements

Appendix A. List of abbreviations

AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
CAP	Climate active pollutant
CDIAC	Carbon Dioxide Information Analysis Center
CH_4	Methane
CO_2	Carbon dioxide
$CO_2(f)$)	Carbon dioxide from fossil fuels and cement manufacture
CRA	Comparative Risk Assessment Project
EDGAR	Emission Database for Global Atmospheric Research
DALY	Disability adjusted life year lost
GDP-PPP	Gross domestic product at purchasing power parity
HICs	High-income countries
IND	International Natural Debt, climate debt from $CO_2(f)$ and CH_4 combined
IND_{CH_4}	Climate debt from CH_4
IND_{CO_2}	Climate debt form CO_2
$IND_{CO_2(f)}$	Climate debt from $CO_2(f)$
IPCC	Intergovernmental Panel on Climate Change
JRC/PBL	Joint Research Centre of the European Commission/PBL Netherlands Environmental Assessment Agency
LMICs	Low- and middle-income countries
LUCF	Land use change and forestry
RF	Radiative forcing
USEPA	United State Environmental Protection Agency
UNFCCC	United Nations Framework Convention on Climate Change
$\%CH_4$	Percent of IND from CH_4
$\%CO_2$	Percent of IND from CO_2

Appendix B. IND and LUCF

IND does not address at a country-level the net effects on CO_2 from land use change and forestry (LUCF), despite the likely considerable impact of such activities. It has proven difficult to attribute LUCF empirically, owing to incomplete and uncertain time-series of sinks and sources which lack a clear historical baseline analogous to the preindustrial era for $CO_2(f)$, and conceptually, due to ambiguities in deciding which changes were natural versus anthropogenic and what credit to assign for carbon stocks that avoided degradation or passively regenerated. In Smith et al. (2013) we drew on the best available LUCF database, the most recent update to Houghton (2008, 2003), to conduct a region-level analysis of IND from LUCF, $CO_2(f)$, and CH_4. This exercise, though it illuminated the global-level split in IND derived from CO_2 between its $CO_2(f)$ and LUCF components (72% versus 28%, respectively), nonetheless reiterated the challenges outlined above. As research progresses and policy evolves, LUCF may well be more easily folded into the climate debt paradigm. In the meantime, we limit our analyses to IND from $CO_2(f)$ and CH_4.

Appendix C. Countries Without DALY Data

Missing from Fig. 2 are points for twenty-seven countries which lack DALY data (Global Burden of Disease Study, 2010, 2012). Most of these are territories whose statistics are included within those for their ruling country. The twenty-seven are: American Samoa, British Virgin Islands, Cook Islands, Faeroe Islands, Falkland Islands, French Guiana, French Polynesia, Gibraltar, Greenland, Guadeloupe, Guam, Hong Kong SAR, Macau SAR, Martinique, Montserrat, Nauru, New Caledonia, Niue, Palau, Puerto Rico, Réunion, Saint Helena, Saint Kitts & Nevis, Turks & Caicos Islands, United States Virgin Islands, Wallis & Futuna Islands, and Western Sahara.

Appendix D. IND_{CH4} by Sector

Climate debt from $CO_2(f)$ has received more attention than that from CH_4. Indeed, overall $IND_{CO2(f)}$ is larger, growing more rapidly, and less uncertain than IND_{CH4}. Yet the applications in this paper spotlight the opportunities for lowering IND by contracting IND_{CH4}. This observation motivates a closer examination of IND_{CH4} circa 2005.

Global IND_{CH4} is dominated by the agriculture (45%), energy (35%), and waste (16%) sectors, with much smaller input from land use (4%), referring to emissions from forest and grass fires, and industry ($<$1%). Major sources include ruminant livestock and rice cultivation in the agriculture sector; fossil fuel systems in the energy sector; and landfills and wastewater in the waste sector (USEPA, 2006; Reay et al., 2006, 2010). Current inventory methodologies are not comprehensive and atmospheric monitoring of CH_4 suggests emissions from unaccounted sources, such as abandoned landfills and oil/gas wells, may well be large (Brandt et al., 2014).

In order to probe IND_{CH4}, Fig. D1 breaks down IND_{CH4} into its sector-level components. Panel *A* presents the twenty-five countries with the largest IND_{CH4} from all sectors combined and panels *B–D* present the top 25 contributors of IND_{CH4} from the agriculture (*B*), energy (*C*), and waste (*D*) sectors. Rankings are on the basis of total IND_{CH4}. Collectively, these twenty-five countries accounted for 75% of global IND_{CH4} in 2005. These data, and those for all 205 countries, are provided in *Database IND*.

China has the largest IND_{CH4} from all sectors combined and for each of the separate sectors. However, in each case, China's per capita IND_{CH4} is 10–25% lower than the global average. India, with the third largest IND_{CH4}, follows a similar pattern with even lower per capita IND_{CH4} values, half the global average for all sectors combined and 20–70% the global average for the separate sectors. On the other hand, the United States, which has the second largest IND_{CH4} and is ranked in the top four for the agriculture, energy, and waste sectors, possesses in all instances per capita IND_{CH4} values

much higher than the global average. Similarly, Australia, a medium-sized country from the perspective of population or economic size, is a top 25 contributor to global IND_{CH4} from all three sectors and at per capita levels several times the global average.

Focusing on panel *A*, the sectoral decomposition of IND_{CH4} shows a diversity of situations reflecting the distinctive circumstances of each country. Countries with proportionately large contributions to their IND_{CH4} from the agriculture sector often have had major rice or livestock production, for example Bangladesh or Argentina. Major oil and gas producers typically have proportionately large contributions from the energy sector to their IND_{CH4}, for example Nigeria and Russia. Several countries with large areas of tropical forest have sizeable contributions to their IND_{CH4} from land use, most notably Congo (Kinshasa) but also Myanmar, Indonesia, and Brazil.

From a global vantage point, this type of sectoral breakdown can help guide how commitments to reduce CH_4 emissions could be incorporated into international agreements. For instance, remedying leaks from fossil fuel systems or waste disposal sites, sectors which accounted for over half of IND_{CH4} in 2005, could be prioritized initially, in part because decreasing IND_{CH4} from the agricultural sector would likely entail a comparatively slower process of altering food consumption patterns. For individual countries, disaggregating IND_{CH4} can help focus efforts to develop and implement interventions. Indeed, countries with large agricultural components to their IND_{CH4} are already experimenting with different feed compositions to minimize enteric fermentation in ruminant livestock (Eckard et al., 2010) or altered flooding and fertilization regimens to curtail methanogenesis in wet rice fields (Jain et al., 2013). Such technological advances, as well as policy ideas, could be shared between countries with similar portfolios of IND_{CH4}.

Appendix E. Caption for Database IND

The accompanying spreadsheet reports IND and associated data with respect to the year 2005 for 205 countries. In all worksheets, countries are presented in rank order by population size with the population data provided. All data types are presented as total and per capita values, accompanied, for total values, with percent of world (column heading "% World"); for per capita values, with percent of world average (column heading "% Average"); and for both, global ranks (1–205). Population data are from the United Nations Department of Economic and Social Affairs - Population Division (2011). The first tab provides data on IND (including % CO_2(f) and %CH_4), $IND_{CO2(f)}$, and IND_{CH4}. The fifty countries with the largest total IND are highlighted in the first three tabs and these same countries are labeled in Figs. 1, 2, and 4. The second tab provides data on total original and total remaining emissions of CO_2(f) and CH_4 for 2005. The third tab provides data on GDP-PPP (United States Central Intelligence Agency, 2006; World Bank, 2012) and DALYs (Global Burden of Disease Study, 2010, 2012) (for DALYs, *n* = 178; see Appendix C for list of countries lacking data on DALYs). The fourth tab provides data on IND_{CH4} from all sectors and IND_{CH4} from the agriculture, energy, waste, land use, and industry sectors. The twenty-five countries with the largest total IND_{CH4} are highlighted in this tab and also emphasized in Fig. D1. Abbreviations: pp = per person; GDP-PPP = gross domestic product at purchasing power parity; DALYs = disability-adjusted life years lost.

Appendix F. Supplementary data

Fig. D1, a supplementary figure associate with this article, can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2015.08.001.

Database IND, supplementary data associated with this article, can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2015.08.001.

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