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Effect of crude oil carbon accounting decisions on meeting global climate budgets

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Abstract The Intergovernmental Panel on Climate Change quantified a cumulative remaining carbon budget beyond which there is a high likelihood global average temperatures will increase more than 2 °C above preindustrial temperature. While there is global participation in mitigation efforts, there is little global collaboration to cooperatively mitigate emissions. Instead, countries have been acting as individual agents with independent emission reduction objectives. However, such asymmetric unilateral climate policies create the opportunity for carbon leakage resulting from the shift in embodied carbon emissions within trade networks. In this analysis, we use an optimization-based model of the global crude trade as a case study to demonstrate the importance of a cooperative, system-level approach to climate policy in order to most effectively, efficiently, and equitably achieve carbon mitigation objectives. To do this, we first characterize the cost and life cycle greenhouse gas emissions associated with the 2014 crude production and consumption system by aggregating multiple data sources and developing a balanced trade matrix. We then optimize this network to demonstrate the potential for carbon mitigation through more efficient use of crude resources. Finally, we implement a global carbon cap on total annual crude emissions. We find that such a cap would require crude consumption to drop from 4.2 gigatons (Gt) to 1.1 Gt. However, if each country had an individual carbon allocation in addition to the global cap consistent with the nationally determined contribution limits resulting from the 2015 United Nations Climate Change Conference, allowable consumption would further decrease to approximately 770 million metric tonnes. Additionally, the carbon accounting method used to assign responsibility for embodied carbon emissions associated with the traded crude further influences allowable production and consumption for each country. The simplified model presented here highlights how global cooperation and a system-level cooperative approach could guide climate policy efforts to be more cost effective and equitable, while reducing the leakage potential resulting from shifting trade patterns of embodied carbon emissions. Additionally, it demonstrates how the spatial distribution of crude consumption and production patterns change under a global carbon cap given various carbon accounting strategies.

Keywords Embodied carbon · Carbon leakage · Carbon accounting · Climate policy · Carbon budget · Crude trade · Nationally determined contribution limits · COP21

1 Introduction

Through international climate negotiations, such as at the Paris Climate Change Conference in 2015, policy makers have agreed that the average global temperature rise caused by greenhouse gas emissions should not exceed 2 °C above

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the preindustrial average global temperature (UNFCCC 2016). In order to curb the average global temperature rise, climate models have demonstrated a limit to the cumulative emissions that can be sustained by the climate system. This limit is called the global carbon budget. The Intergovernmental Panel on Climate Change (IPCC) reported that this budget is in the range of 870-1,240 Gt CO_2-eq between 2011 and 2050 in order to have a 56% chance of not exceeding this 2 °C temperature increase (IPCC 2014).

Limiting emissions to within the global carbon budget would require substantial greenhouse gas (GHG) mitigation efforts. McGlade and Ekins (2015) used an integrated assessment model to explore the implications of this emissions limit for fossil fuel production (McGlade and Ekins 2015). In their scenario to keep average global surface temperature rise below 2 °C for all years to 2200, they found 2050 GHG emissions must be constrained to 21 Gt CO_2-eq. This is compared to the 48 Gt CO_2-eq emitted in 2010, and a baseline 2050 projection of 71 Gt CO_2-eq given no emissions mitigation. This latter projection would result in almost a 5 °C global average temperature rise (McGlade and Ekins 2015).

While there is general agreement on a cumulative emissions mitigation target, little policy consensus has been reached globally as to how to implement such GHG emissions reductions. Climate policy is a complex issue that involves multiple stakeholders, competing objectives, economic barriers, and issues of equity and responsibilities (Clark et al. 2015). As a result, the current approach has been to allow each country to determine its own contribution toward emissions reduction targets. The most recent United Nations Climate Change Conference, COP21, in Paris resulted in 188 committing to Nationally Determined Contributions (NDCs). Each NDC was developed independently, without regard for the effect one country's mitigation efforts would have on another country.

However, due to the expansiveness of the global commodity trade network, an individual country's NDC has implications for the effectiveness of global mitigation efforts on the macroscale. An important consequence of international trade is that commodities produced in one country may be consumed in another country. This concept of emissions being released in one country to produce goods for the benefit of another country through international trade is referred to as embodied carbon (Kanemoto et al. 2016; Peters and Hertwich 2008). Studies have demonstrated that shifts in production and trade patterns can influence global carbon emissions (Strømman et al. 2009; Weber and Peters 2009).

Embodied carbon emissions present two key impediments in the implementation of NDCs. The first obstacle is that some countries' NDCs are more constrictive than others. As a result, rather than the countries with binding NDCs reducing their consumption and therefore contributing to global emissions reductions, those countries may potentially instead shift the upstream production emissions (embodied emissions) to countries with non-binding NDCs. This shift in trade patterns resulting from asymmetric country-specific emissions targets is referred to as carbon leakage (Bohringer et al. 2012; Condon and Ignaciuk 2013; Felder and Rutherford 1993; Strømman et al. 2009; Weber and Matthews 2007; Wyckoff and Roop 1994). Carbon leakage occurs when action taken by countries to reduce emissions is partially or wholly offset by increased emissions elsewhere in the world. Arroyo-Currás et al. (2015) assessed carbon leakage in the energy sector under various climate policies using an integrated assessment model. The results of the study indicate carbon leakage in the energy sector is likely in the short term due to fragmented climate policies, but could be offset in the future if the initial unilateral climate actions ultimately lead to a cooperative, global idealized climate policy.

The second challenge arising from the trade of emissions embodied in the production of commodities is how to assign responsibility for the emissions. Because some countries are net carbon exporters while others are net carbon importers, each potential emissions tracking mechanism affects countries differently. Tracking emissions relies on carbon accounting methods that traditionally tally only emissions sources within the country. This has expanded in recent years to consider emissions occurring along the supply chain (i.e., carbon footprint or embodied carbon). Some commonly discussed carbon accounting frameworks include location based, where countries are responsible for what is emitted within their borders, production based, where the producer would be responsible for the full life cycle emissions of what they produce, and consumption based, where countries are responsible for all life cycle emissions of what they consume (Steininger et al. 2015). While all methods are theoretically equivalent from a global perspective, they function differently in a fragmented climate policy regime (IPCC 2013). For example, Jakob and Marschinski (2012) argue that the dynamics of fragmented policy regimes need to be better characterized in order to guide policies to effectively reduce global emissions (Jakob and Marschinski 2012). Gonzalez-Eguino et al. (2016) define a fragmented climate regime as being characterized by different climate policies across regimes and sectors that may lead to the relocation of production to regions with less stringent mitigation rules. Several recent studies have used integrated assessment models to demonstrate the potential for carbon leakage associated with such asymmetric climate policies (Arroyo-Currás et al. 2015; Luderer et al. 2015; Otto et al. 2015; Schaeffer et al. 2015).

Importantly, within a fragmented climate regime, the carbon accounting strategy has implications for carbon leakage given the same set of NDCs. For example, under a consumer-based method, the NDC of a net carbon exporter would largely be non-binding and, therefore, provides opportunity for significant carbon leakage. Alternatively, under a producer-based method that same country's NDC could limit domestic economic activity. Therefore, when evaluating the effectiveness of NDCs, it is important to do so within the context of a given carbon accounting mechanism.

This study contributes to the literature by developing a theoretical model to explore the impact of unilateral climate goals on mitigation efficiency based on a case study of the global crude trade. Using an optimization-based approach, we develop a framework that characterizes the potential for NDCs to limit the effectiveness of climate mitigation efforts as compared to a cooperative international climate policy under a strict global carbon budget. Additionally, while under a global climate policy, all carbon accounting methods should yield equivalent mitigation efficiencies (Steckel et al. 2010), the model explores how carbon accounting alternatives further interact with the fragmented climate policy-based NDCs to shift the geospatial dynamics of production and consumption.

The optimization model developed for this analysis demonstrates the influence of shifting trade patterns under different climate policies and carbon accounting strategies. While the model is simplified and theoretical, the results offer meaningful insights into potential emissions mitigation opportunities and demonstrate the importance of globally cooperative climate policies. The analysis extrapolates a simplified economy, focusing on the crude sector as a theoretical self-contained entity. Because crude is a widely traded commodity with a high degree of embodied emissions, the global crude trade is a valuable case study to demonstrate how climate policies and carbon accounting strategy interactions can incentivize or dis-incentivize cost-effective carbon mitigation measures. Davis et al. (2011) found that 37% of global emissions are from fossil fuels traded internationally (Davis et al. 2011). Of the approximately 32.4 billion barrels (bbls) of oil produced each year (4.4 Gt), approximately 64% (21 billion bbls, or 2.8 Gt) is exported from one country to another (BP Statistical Review of World Energy 2015), primarily by vessel movements (17 billion bbls, or 2.4 Gt) (Reuters 2016).

2 Methods

Throughout this study, we analyze annual international crude trade under the modeling constraint of a market approaching a stable equilibrium at a point in the future. This theoretical construct enables us to explore the potential interactions between climate policies, emissions abatement potential, cost of crude as a primary energy source, and the global distribution of consumption under a range of restrictions. While computable general equilibrium (CGE) models characterize the progression of change over time as part of a feedback loop of price, supply, and demand, we use a single-year time scale to understand how the global system would behave at its optimal configuration (i.e., future equilibrium). The analysis begins by estimating the current baseline crude trade network. This crude network is then optimized to demonstrate how shifting trade patterns impact cost and emissions. Finally, a carbon cap is imposed to compare the outcomes of a cooperative global climate policy versus a fragmented climate policy under three carbon accounting strategies (Fig. 1). The production and consumption parameters for the baseline model are from 2014. The global crude trade model in our analysis consists of 62 countries, accounting for 4 Gt of crude (29.3 billion bbls), or approximately 95% of total 2014 production. As a proxy for both price and GHG emissions, we used API gravity, which is a measure of density and is often taken as an indicator of crude quality. All data used to develop the trade network were aggregated from 2014 data whenever possible. Exceptions to this are indicated throughout the methods section.

2.1 Reference trade network

In order to quantify the potential for cost and emissions savings, we first characterized the existing trade network. The volume of crude traded from each country to each other country is known and is compiled in existing, proprietary datasets; however, these datasets are not publicly available and are expensive to obtain. Some of these data are published in aggregate form. For example, the BP Statistical Review contains trade data of totaled crude and petroleum products aggregated by region (BP Statistical Review of World Energy 2015), while other datasets such as the JODI-Oil Database publish total imports and exports by country but do not publish the volume of crude traded between specific country pairs (JODI-Oil World Database 2014). Other datasets have a high resolution of detail, but are only available for limited countries. For example, the EIA maintains a detailed database of crude imports to the USA by country (EIA 2016). A frequently used publicly available data source for international trade analysis is the United Nations database (UN Comtrade Database 2014). While comprehensive, these data are self-reported and therefore may be subject to reporting errors, missing data, or inconsistencies from year to year. As an example of a shortcoming of this dataset, the flows are not balanced, meaning total imports do not necessarily equal total exports; in 2014, petroleum imports totaled 14 billion bbls while exports totaled 12.6 billion bbls, a difference of ~10% (assuming a specific gravity of 0.88, or 140 kg per

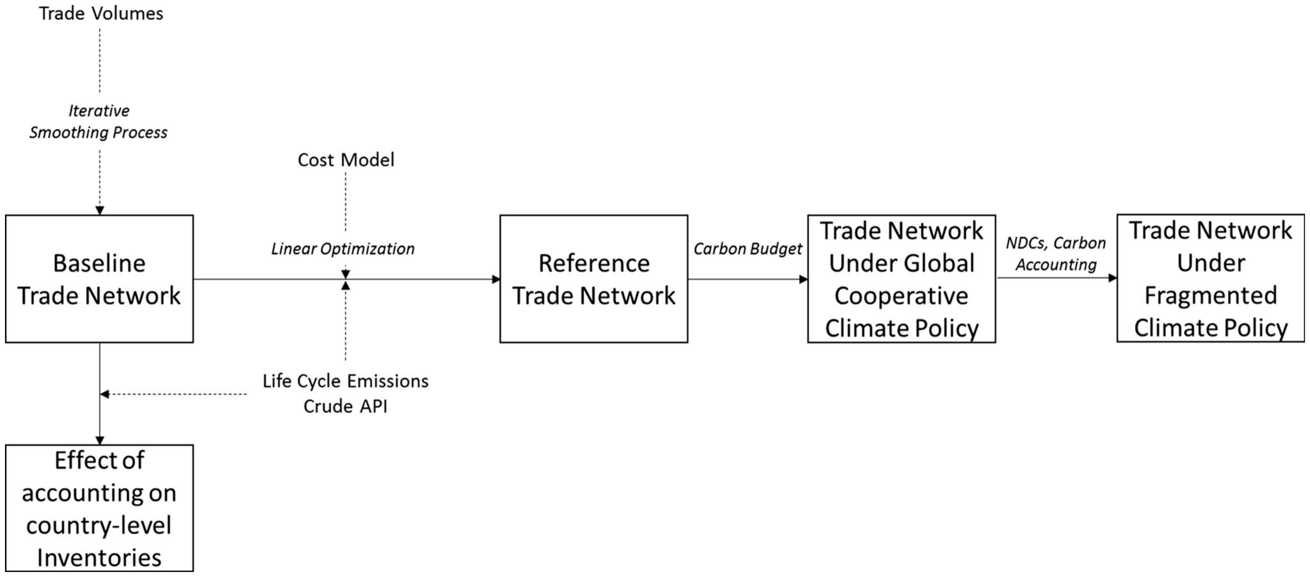

Fig. 1 Flow diagram outlining the progression of the methods described in the following sections

bbl of crude). A summary of the crude trade data sources used in this analysis is outlined in Table 1.

The first objective of this study was to aggregate these various data sources in order to characterize the global crude system, including production, imports, exports, and domestic consumption. By taking advantage of the positive attributes of each dataset, we were able to realistically represent global trade. The 62 countries included were chosen based on the availability and consistency of data for these countries across all datasets, and together represent 95% of total crude production. While there is no clear method for validating this matrix without access to proprietary data, we ensured the system balanced and that the trade ratios (i.e., net importers and net exporters) were accurate through an iterative smoothing process implemented using linear optimization.

To develop this global crude matrix, we first aggregated the UN Comtrade data with two other obtained data sources. From the Comtrade data, we included exports from 2014 reported under the Harmonized Commodity Description and coding system (HS) commodity code 2709 (petroleum oils, oils from bituminous minerals, crude). The second dataset is the IEA's trade balance of OECD countries. This includes import/export data from 2014 for 34 OECD countries, importing from 61 countries and exporting to 30 countries. The third dataset is of port-to-port oil tanker movements in 2015 obtained from Reuters (Reuters 2016). This dataset includes approximately 25,000 vessel movements, with vessel capacities ranging from 56 thousand bbls to 2 million bbls. In aggregating these datasets, we found some trade partners were reported only in one of the datasets, while others were reported in multiple datasets. Where a trade partner pair was reported in one dataset only, we used the reported quantity as the trade value. Where a trade partner pair was reported in two or three of the datasets, we used the maximum of the reported

Table 1 Summary of relevant crude trade data used in this analysis

Data source	Advantages	Disadvantages
BP Statistical Review (BP Statistical Review of World Energy 2015)	Thorough, compiled from multiple sources, balanced	Aggregated by regions, combines crude and products in trade matrix, does not include trade within regions
UN Comtrade (UN Comtrade Database 2014)	Reported by specific trade partner pairs	Self-reported data, reporters are inconsistent across years, imports do not match exports
JODI database (JODI-Oil World Database 2014)	Country-level detail	Imports and exports are aggregated by country, volumes traded between individual countries are not available
IEA OECD matrix (Energy Balances of OECD Countries 2015)	Country-specific trade partners	Does not include non-OECD imports
Reuters vessel data (Reuters 2016)	Comprehensive, port-to-port data	Does not include crude traded by pipeline

values. This was to account for the fact that some of the data were self-reported and therefore might be biased toward underreporting trade values.

In addition to international trade, we added domestic consumption of a country's own production to the trade matrix. To do this, we obtained 2014 production and consumption data by country from the BP Statistical Review of World Energy (BP Statistical Review of World Energy), and filled in missing country production and consumption data from the JODI-Oil database (JODI-Oil World Database 2014). We assumed a country's production minus its exports represented the domestic consumption of domestically produced oil. Therefore, the complete mass balance for any given country must be that annual production plus annual imports minus annual exports is equal to total consumption (refinery inputs). Because the compiled trade partner pair data described above did not balance with the production and consumption data, we followed an iterative process to "smooth" the trade data, thereby producing a self-consistent production, trade, and consumption matrix. This smoothing was done using a linear optimization (Eq. 1). The decision variables were the trade values between partner pair countries. The optimization was constrained such that the ratio of trade among partners should be maintained as closely as possible to the trade ratios from the original compiled trade matrix. The objective of the model was therefore to minimize the sum of the absolute value of the differences between the optimized trade ratios and the original trade ratios. Rather than minimize the differences evenly across the system, however, the differences were weighted by the country's contribution to supply and consumption such that larger consumers and producers were given higher importance in achieving correct trade ratios.

$$\text{Minimize} \sum_{e=1}^{C}\left(\sum_{i=1}^{C}\left(\text{abs}\left(\underbrace{x_{ei}^{\text{TR}} - \sum_{i=1}^{C} x_{ei}^{\text{TR}} \times r_{ei}^{\text{EXP}}}_{\substack{\text{Difference in trade}\\ \text{ratio across each country's}\\ \text{export trade partners}}}\right) + \text{abs}\left(\underbrace{x_{ei}^{\text{TR}} - \sum_{e=1}^{C} x_{ei}^{\text{TR}} \times r_{ei}^{\text{IMP}}}_{\substack{\text{Difference in trade}\\ \text{ratio across each country's}\\ \text{import trade partners}}}\right)\right) \times w_e\right) \quad (1)$$

with respect to

$x_{ei}^{\text{TR}} \in \mathbb{R}$

$\forall i \in \{1,\ldots,C\}, e \in \{1,\ldots,C\}, c \in \{1,\ldots,C\}$

subject to

$$p_c + \sum_{e=1}^{C} x_{ec}^{\text{TR}} - \sum_{i=1}^{C} x_{ci}^{\text{TR}} = u_c \quad \forall c \quad (2)$$

$$p_c - \sum_{i=1}^{C} x_{ci}^{\text{TR}} \geq 0 \quad \forall c \quad (3)$$

where

x_{ei}^{TR} is the volume of crude traded from exporter e to importer i. When the exporter and importer are the same country, this represents crude produced in a country for its own consumption;

r_{ei}^{EXP} is the designated proportion of exporter e's product that can be traded with partner country i;

r_{ei}^{IMP} is the designated proportion of importer i's total imports that can be imported from partner country e;

p_c is the designated production volume of a given country;

u_c is the designated consumption volume of a given country;

w_e is the weight of the exporting country's accuracy importance; and

C is the total number of countries in the trade network.

Equation (2) ensures each country's trade pattern balances such that its production plus its imports minus its exports is equal to its total consumption. Equation (3) ensures no country exports more crude than it produces, i.e., that no re-exports of imported product are allowed in the system (re-exports were <0.06% of total exports in 2014 according to the UN Comtrade Database).

2.2 Cost and GHG emissions associated with trade

2.2.1 API estimates

In this analysis, both cost and emissions are based on the API of crude as an indicator for crude quality. The API gravity is a measure of a crude's density relative to water, and can vary from <27° (heavy crude) to >50° (very light crude). Even within a given oil field, crude API can vary as a function of location and/or age of field production. Different crude qualities can be blended together to create a blended API. Refineries are able to accept a narrow range of blended crude APIs. Based on historical time series data showing input blended APIs averaged by PADD region for the USA between 1985 through 2015, the average API blended in a given region tends to vary by ~3°–7° each year (Figure S2).

To address the importance of crude quality on price and emissions, we compiled a comprehensive database of crude APIs produced within each country. These data were aggregated from the Knovel Crude Oil Assay Database (Speight 2015), a crude oil life cycle assessment conducted by the California Air Resources Board (CARB) which analyzed all crudes imported to California (LCFS Crude Oil Lifecycle Assessment 2015), a report by the International Council on Clean Transportation which compiled data on all crudes combusted within the European Union (Malins 2014), and estimates from the International Energy Agency (IEA 2016). Each of these studies reported several API gravities of crudes from different countries. To determine the average API gravity of crude produced by each country as input to our analysis, we took the average of all crudes within a country in the aggregated dataset. While a production weighted average or maintaining a range of crudes for each producer would have been preferred over using the average value, specific production volume by crude type was not available for all countries. Where a country was not represented within either of these three datasets, we used the average regional API estimated by the IEA (IEA 2016).

2.2.2 *Cost estimates*

Several crude pricing models have explored relationships between crude quality parameters, socio-political issues, and crude pricing differentials (Kaufmann 2016; Kaufmann and Banerjee 2014; Reboredo 2011). These studies suggest that given the cooperative equilibrium nature of our theoretical optimization model, where price differential effects due to country risk, supply shocks, etc., are irrelevant, it is reasonable to assume the crude market is unified. Therefore, we assume the price relationship between benchmark crudes will remain consistent, and that crude API serves as a proxy for crude quality (see SI section S.4). To estimate the baseline 2014 total crude network cost, we compiled cost data from fourteen benchmark crudes, ranging in API from 13 to 38 from Deloitte's 2015 Oil and Gas Price Forecast report (Deloitte 2015). We use a line of best fit to represent the relationship between API and price. The line is fit as a differential between a crude's API/price and that of Brent crude (API 38) such that any price can be inputted for Brent to determine crude price as a function of API for the other crudes. Since this study is based on 2014 data, the 2014 average price for Brent crude oil was used as the baseline.

In this model, shipping costs are estimated based on shipping distance and an oil tanker freight rate of \$.004/tonne-mile. This estimate is based on the Worldscale shipping rate (WS), which is widely used as the basis for shipping price negotiations between a ship owner and a charterer. In this study, shipping distances were modeled using the great circle distance based on a geographically representative subset of port locations from the World Port Index (WPI 2016) (Figure S4). A circuity factor of 1.3 was applied to account for variations from the great circle path (TRB 1997). Because shipping costs and emissions were found to be marginal relative to total life cycle emissions, the results of this study are not sensitive to this simplifying assumption. Additional information regarding shipping cost and port-to-port distances is available in SI section S.3.

2.2.3 *Crude life cycle emissions*

Crude emissions can be quantified according to life cycle stages. In this model, we include upstream (extraction), shipping, midstream (refining), and downstream (combustion) emissions. The relationship between crude and the emissions from these life cycle stages is complex and driven by several different factors such as extraction technique, vent-to-flare ratio, fugitive emissions, refinery configuration, and finished product mix.

We used API as an indicator for crude-specific emissions from each life cycle stage, based on a linear fit of the results in the Oil-Climate Index report (Gordon et al. 2015), which uses the Oil Production Greenhouse gas Emissions Estimator (OPGEE) (OPGEE: the Oil Production Greenhouse Gas Emissions Estimator 2016) model to estimate oil field-specific extraction emissions and the Petroleum Refinery Life Cycle Inventory Model (PRELIM) (PRELIM: the Petroleum Refinery Life Cycle Inventory Model 2016) to estimate midstream emissions. While API alone does not determine life cycle emissions of a given crude, as demonstrated by the Oil-Climate Index report (Gordon et al. 2015), it is highly correlated with life cycle emissions. The exception to this is for upstream emissions, where the linear interpolation for points above the API range used to generate the line would result in negative emissions for very light crudes. To adjust for this, we assumed any crude with API over 45 would have the same upstream emissions factor (i.e., the marginal upstream emissions reduction plateaus for very light crudes), and revised the best-fit line accordingly. While the report is specific to US default refinery configurations, product mix, and transportation end use, we take these emissions to be generally representative of global midstream and downstream emissions in the absence of country-specific additional data.

Several studies quantify emissions from the shipping sector (Corbett and Winebrake 2008; Psaraftis and Kontovas 2009; Third IMO Greenhouse Gas Study 2014 2015), (Endresen et al. 2003). According to a report by the International Maritime Organization (IMO), international shipping resulted in over 800 million tonnes CO_2-eq in 2012. Oil tankers had the third largest fuel consumption (almost 40 million tonnes fuel), surpassed only by container ships and bulk carriers. The oil tanker fleet is comprised of more than 7000 vessels ranging in size from a few thousand dead weight tons (dwt) to more than 200,000 dwt.

Emissions from oil tankers alone were responsible for more than 120 million tonnes of CO_2 emissions in 2012 (Third IMO Greenhouse Gas Study 2014 2015). The IMO study was a bottom up assessment, in which vessels were categorized by fuel type, shipping category, and dwt to develop an emissions estimate.

Shipping emissions in this study are quantified based on the port-to-port distances described above and a tanker's CO_2 emission factor of 0.005 kg/tonnes-km (Third IMO Greenhouse Gas Study 2014 2015). This emissions factor was a bottom up estimate based on crude vessel sizes and the portion of time spent idling at port or otherwise operating in inefficient modes (see SI section S.3).

2.3 Theoretical optimized trade network

The linear models representing the relationship between crude API and cost/emissions can be used both to characterize the existing global system, as well as to assess the changes in cost/emissions resulting from variations in the global crude system. Because cost and emissions are presented as a function of API and distance, using this method, any different pattern of trade can be analyzed as long as the average API blend being produced by each country is known.

After developing the reference global crude system, we then explored how the network would shift as a result of minimizing cost or GHG emissions. To establish this theoretical optimal trade system, we developed a second linear optimization model that considers the potential for redistribution of traded oil based on cost or GHG emissions, while meeting the global crude consumption as established by the reference network:

$$\text{Minimize} \sum_{i=1}^{C} \left(\underbrace{\sum_{e=1}^{C} c_e^{\text{CR}} x_{ei}^{\text{TR}}}_{\text{cost of crude}} + \underbrace{\sum_{e=1}^{C} c^{\text{SH}} d_{ei} x_{ei}^{\text{TR}}}_{\text{cost of shipping}} \right) \tag{4}$$

with respect to

$$x_{ei}^{\text{TR}} \in \mathbb{R}$$

$$\forall i \in \{1, \ldots, C\}, e \in \{1, \ldots, C\}$$

subject to

$$\sum_{e=1}^{C} x_{ei}^{\text{TR}} = u_i \ \forall i \tag{5}$$

where

c_e^{CR} is the cost of crude $= (API_e \times 0.87 + 66) \times .0000073$ (\$/million tonnes);
c^{SH} is the cost of shipping = 1.8(\$Thousand/(tonne-km));
API_e is the average API produced in a given country;
API_i is the target weighted average API consumed by a given country; and
d_{ei} is the distance between exporter e and importer i.

The optimization defined above assumes any country can supply any volume of its assigned (averaged) API crude and each country can refine any API blend. This is the most flexible alternative and results in the upper bound cost and GHG mitigation potential. Constraints can then be added to limit the supply to that of the 2014 reference network:

Supply constraint

$$\sum_{i=1}^{C} x_{ei}^{\text{TR}} = p_e \ \forall e \tag{6}$$

Additionally, a second constraint can be added to limit countries to consuming crude with a blended API consistent with their refinery fleet, as determined by the 2014 reference crude network. This is representative of refinery infrastructure limitations; if a country's crude API blend changes beyond what can currently be processed by that country's refinery portfolio that country would potentially need to invest in refinery updates to reconfigure the refinery to accept the new crude blend:

API blend constraint

$$\sum_{e=1}^{C} \text{API}_e x_{ei}^{\text{TR}} = \left(\sum_{e=1}^{C} x_{ei}^{\text{TR}} \right) \times \text{API}_i \ \forall i \tag{7}$$

2.4 Theoretical trade network under climate policies

By adding additional constraints on the total crude emissions and/or on country-specific crude emissions to the optimization, we can observe how the trade network shifts under either a global or fragmented climate policy with a carbon limit.

2.4.1 Global climate policy

To model a global climate policy scenario in which the international community cooperates to mitigate cumulative emissions to avoid the 2 °C average global temperature increase, we set a global annual carbon cap across the system (refer to SI section S.2). To extrapolate a crude-specific annual carbon cap from the global carbon budget, we considered the current portion of crude emissions; in 2014, the transportation sector contributed approximately 14% of global emissions (EPA 2016). Assuming this portion of total emissions approximately represents crude's contribution to global emissions, we attribute 14% of any global carbon budget as the carbon budget specific to the crude trade. For example, given a global annual carbon cap of 21 Gt CO_2-eq, the associated crude annual carbon cap would be 3 Gt CO_2-eq. The constraint that limits total emissions to the global cap is as follows:

Carbon budget constraints

$$\sum_{i=1}^{C}\sum_{e=1}^{C} x_{ie}^{\mathrm{TR}} \times \left(\mathrm{GHG}_e^{\mathrm{UP}} + \mathrm{GHG}^{\mathrm{SH}} d_{ie} + \mathrm{GHG}_e^{\mathrm{MID}} + \mathrm{GHG}_e^{\mathrm{DWN}}\right) = \mathrm{GHG}^{\mathrm{TB}} \tag{8}$$

where

$\mathrm{GHG}_e^{\mathrm{UP}}$ is the upstream GHG emissions $= (-3.0\times \mathrm{API}_e + 180) \times (.0073)$ (tonne CO_2/tonne crude);
$\mathrm{GHG}_e^{\mathrm{MID}}$ is the midstream GHG emissions $= (-1.4\times \mathrm{API}_e + 81) \times (.0073)$ (tonne CO_2/tonne crude);
$\mathrm{GHG}_e^{\mathrm{DWN}}$ is the downstream GHG emissions $= (-3.3\times API_e + 544) \times (.0073)$ (tonne CO_2/tonne crude);
$\mathrm{GHG}^{\mathrm{TB}}$ is the total global carbon budget;
$\mathrm{GHG}^{\mathrm{SH}}$ is the shipping GHG emissions = 16 (tonnes CO_2/(tonne-km)).

2.4.2 Fragmented climate policy

To do this, we first determined each country's allocated portion of total emissions based on the estimated 2020 GHG targets as determined by each country's nationally determined contribution (NDC) resulting from the Conference of the Parties (COP) 21 in Paris in 2015 (Fenhann 2016). If no 2020 or 2025 estimate was present in the data for a given country, we instead used a 2012 emissions value reported by the World Resources Institute (WRI 2016). These allocations indicate that if a carbon budget exists restricting emissions, each country in turn would have to restrict emissions based on its proportional 2020 emissions targets. For example, if a country's NDC target results in it emitting 10% of 2020 emissions, it would be allocated 10% of any future global carbon budget.

2.4.3 Carbon accounting strategies

For both the global and fragmented climate policy optimization scenarios, we can implement different carbon accounting strategies in order to explore the underlying dynamics of carbon leakage and embodied carbon. In the location-based carbon accounting strategy, the upstream producing country was held accountable for upstream emissions, while the consuming country was held responsible for the shipping, midstream, and downstream emissions (Eq. 9). For simplicity, this assumes all refined products are used in that country, rather than being exported elsewhere. While in this study shipping emissions are attributed to the upstream producing country, in reality currently the responsibility for GHG emissions associated with shipping does not fall within the jurisdiction of any individual country (ICTSD 2010). In a producer-based accounting framework, upstream producing countries are held responsible for all embodied emissions throughout the crude life cycle (Eq. 10). Finally, in a consumption-based accounting framework, the consuming country is held responsible for all embodied emissions, including upstream extraction emissions (Eq. 11). The following constraints can be used to specify a carbon accounting strategy for each country c.

Location based

$$\sum_{i=1}^{C} \mathrm{GHG}_c^{\mathrm{UP}} x_{ic}^{\mathrm{TR}} + \sum_{e=1}^{C} x_{ce}^{\mathrm{TR}} \times \left(\mathrm{GHG}^{\mathrm{SH}} d_{ce} + \mathrm{GHG}_e^{\mathrm{MID}} + \mathrm{GHG}_e^{\mathrm{DWN}}\right) = \mathrm{GHG}_c^{\mathrm{B}} \times \mathrm{GHG}^{\mathrm{TB}}\ \forall c \tag{9}$$

Producer based

$$\sum_{i=1}^{C} x_{ic}^{\mathrm{TR}} \times \left(\mathrm{GHG}_c^{\mathrm{UP}} + \mathrm{GHG}^{\mathrm{SH}} d_{ic} + \mathrm{GHG}_c^{\mathrm{MID}} + \mathrm{GHG}_c^{\mathrm{DWN}}\right) = \mathrm{GHG}_c^{\mathrm{B}} \times \mathrm{GHG}^{\mathrm{TB}}\ \forall c \tag{10}$$

Consumer based

$$\sum_{e=1}^{C} x_{ce}^{\mathrm{TR}} \times \left(\mathrm{GHG}_e^{\mathrm{UP}} + \mathrm{GHG}^{\mathrm{SH}} d_{ce} + \mathrm{GHG}_e^{\mathrm{MID}} + \mathrm{GHG}_e^{\mathrm{DWN}}\right) = \mathrm{GHG}_c^{\mathrm{B}} \times \mathrm{GHG}^{\mathrm{TB}}\ \forall c \tag{11}$$

where

$\mathrm{GHG}_c^{\mathrm{B}}$ is the fraction of total GHG emissions allocated to country c.

If the carbon constraints bound the problem such that meeting demand x_i^{CS} is infeasible, instead of minimizing total cost, we minimize the difference between the calculated consumption and the target consumption x_i^{CS} to maintain consistency between the theoretical optimized consumption patterns and the 2014 reference network (Eq. 12).

$$\text{Minimize} \sum_{i=1}^{C}\left(abs \left(\underbrace{\sum_{e=1}^{C} x_{ei}^{\mathrm{TR}}}_{\substack{\text{calculated}\\ \text{consumption}}} - \underbrace{x_i^{CS}}_{\substack{\text{target}\\ \text{consumption}}} \right)\right) \tag{12}$$

with respect to

$x_{ei}^{\mathrm{TR}} \in \mathbb{R}$

$\forall i \in \{1,\ldots,C\}, e \in \{1,\ldots,C\}$

3 Results and discussion

In this section, we first show the reference trade network resulting from the iterative smoothing process and explore the implications of carbon accounting strategies on country-level emissions inventories. We then demonstrate the cost and emissions reduction potential achievable through shifting trade patterns and show how these patterns are influenced by global and fragmented climate policies.

3.1 Baseline balanced 2014 trade matrix

The baseline 2014 global crude system developed in this analysis includes 62 countries representing 95% of total crude production. The emissions associated with these current trade flows were calculated according to the three different carbon accounting strategies and can be seen in (Fig. 2), based on the estimated crude life cycle emissions (see SI section S.4). Figure 2a shows the emissions by country given producing countries are responsible for extraction emissions and consuming countries are responsible for all other life cycle emissions. In contrast, Fig. 2b shows embodied life cycle carbon emissions being attributed to the upstream producer, while Fig. 2c shows embodied life cycle emissions being attributed to the downstream consumer. For a more detailed look at the impact of carbon accounting method on individual country's emissions profile, see Figure S7. Due to the asymmetric impact of carbon accounting methods on different countries, any global carbon accounting policy should carefully consider equity issues such as economic impact to developing countries. In general, many African countries would be responsible for a significant portion of emissions under a producer-based accounting strategy, while many European and Asian countries would be responsible for more emissions under a consumer- or location-based accounting strategy. Consumer- and location-based strategies yield similar emissions trends because crude life cycle emissions are dominated by downstream combustion (i.e., consumption).

More specifically, for countries that export crude and consume very little crude, such as Algeria, a producer-based approach would result in high crude carbon emissions (Fig. 2b), while location-based (Fig. 2a) or consumer-based (Fig. 2c) approach would result in low crude carbon emissions. Similarly, for countries who are crude importers and produce very little crude such as Ireland and Israel, a location-based and consumer-based approach would yield similar carbon accounting results, while a producer-based approach would result in them being responsible for few crude carbon emissions. This reveals the influence that carbon accounting has on emissions profiles and demonstrates the challenge to adopting a globally agreed upon method for tracking emissions. If countries are not consistent in how they record their emissions, it could be possible for each country to meet mitigation targets under different accounting schemes, without significant change in overall global emissions.

3.2 Reference crude trade network

Using this established reference network as input, combined with the life cycle GHG emissions estimates (see SI section S.4), the developed crude cost model (SI section S.4), the shipping cost as a function of distance and quantity shipped (SI section S.3), we compute an optimized trade network under a variety of constraints (Table 2).

When minimizing by cost, the least cost scenario for any producer country is to reduce exports and use its own crude oil first before importing crude. This allows the total global cost to drop from \$3 trillion to \$2.4 trillion (\$590/t of oil consumed) as a result of reduced transportation, but results in a GHG emissions increase of approximately 4 Gt CO_2-eq. Allowing supply to vary freely but constraining the weighted average consumed API gravity by country to remain the same as in the baseline 2014 network also decreases costs by ~\$230B across the system to \$690/t crude consumed but does not account for technical or resource constraints limiting crude extraction in each country.

Fig. 2 Greenhouse gas emissions from crude trade by country in 2014 assuming **a** location-based, **b** producer-based, and **c** consumer-based carbon accounting strategy

Table 2 Summary of scenario results

	Baseline scenario	Minimize cost scenarios			Minimize emissions scenarios		
		Cost	Cost_SL	Cost_API	GHG	GHG_SL	GHG_API
Cost ($ trillion)							
Shipping	0.14	0.07	0.02	0.00	0.09	0.02	0.01
Crude	2.8	2.3	2.7	2.8	3.35	2.7	2.9
Total	3.0	2.4	2.75	2.8	3.5	2.75	2.9
GHG (Gt CO_2-eq)							
Shipping	0.3	0.15	0.04	0.01	0.19	0.04	0.01
Crude	16.1	20.3	16.4	16.1	10.9	16.4	15.3
Total	16.5	20.5	16.4	16.1	11.1	16.4	15.3
Consumption (billion tonnes)	4	4	4	4	4	4	4
$/tonne oil consumed	750	590	688	693	865	688	715
GHG/tonne oil consumed	4.0	5.1	4.1	4.0	2.8	4.1	3.8

Cost = cost minimized, demand constraints only; Cost_SL = cost minimized, supply and demand constrained; Cost_API = cost minimized, demand and API constrained; GHG = GHG minimized; GHG_SL = GHG minimized, supply and demand constrained; GHG_API = GHG minimized, demand and API constrained

When minimizing total GHG emissions within the system, there are again distinct differences in cost and emissions savings across the three scenarios. When each country is allowed to supply any volume of crude to contribute to satisfying global demand rather than constraining countries to their 2014 production limits, global GHG savings of about 5.5 Gt CO_2-eq are realized for an additional cost of about $500 billion. This translates to a relatively low cost of abatement of $90/t CO_2-eq. When supply is constrained to 2014 production volumes or weighted average API is constrained to 2014 API consumption, there are smaller emissions savings (100 million tonnes of oil and 1.2 Gt CO_2-eq, respectively) while reducing total costs over the baseline ($25 billion and $15 billion, respectively). The tradeoffs in cost savings and emissions reductions are further explored in the supplementary material (see SI section S.6–S.7). Because the largest emission reductions in this emissions-based optimization are achieved in the scenarios without production or API refining limitations, a key result is that the more flexible the crude system, the more opportunity there would be for efficient consumption (low CO_2-eq/t oil consumed). This is important because the more efficient consumption can be, the less total crude consumption would need to be reduced in order to achieve the same climate outcome, as long as minimizing emissions is the priority over minimizing cost.

3.3 Climate policy scenarios

The optimized trade network under an extrapolated crude oil global carbon limit is designed so that each country is allocated a portion of the global budget. The country-specific apportionment is done to approximate the impact of fragmented climate policies as compared to the benefits of global cooperation. This allocation is characterized by the NDCs resulting from COP21, suggesting that the ratio of emissions contributions will remain consistent with the ratio of committed 2020 COP21 targets in the future. While in reality the NDCs do not specify how they will be achieved (i.e., how the oil industry would be affected by each country's mitigation efforts), here we highlight the implications each sector would be reduced by the committed percentage. The percentage of total carbon emissions allocated to each region is shown in Table S1. These limits can either be set as absolute limits, or the model can be run such that a country pays a penalty (i.e., carbon tax) for any emissions above its allocated budget. The latter formulation, with a global carbon budget and payments made to exceed individual country allocations, could be designed to mimic a global cap and trade policy.

In addition to designating emissions allocations by country, the climate policy version of the model must also specify a carbon accounting strategy. As previously discussed, the three main accounting strategies are (1) location based, in which the upstream emissions are allocated to the producer and all other life cycle emissions are allocated to the consumer, (2) production based, in which all embodied life cycle emissions are allocated to the producer, and (3) consumption based, in which all allocated life cycle emissions are allocated to the consumer. In this model, each country tries to stay as close to its demand as possible while remaining within its carbon budget. The results of the optimization are summarized in Table 3, and detailed results can be found in Table S2 through Table S4.

The results in Fig. 3 demonstrate that the trade matrix shifts dynamically depending on which accounting strategy

Table 3 Summary of optimization results under a 3 Gt global annual carbon budget with NDC constraints compared to a 3 Gt global annual carbon budget under global cooperation (no country-specific NDC restrictions), and to the baseline trade network for reference

	Baseline scenario	Global annual crude carbon cap (3 Gt)	Global annual crude carbon cap (3 Gt), with NDC constraints		
			3Gt_L	3Gt_P	3Gt_C
Total cost ($ trillion)	3.0	0.93	0.55	0.55	0.52
Total GHG (Gt CO_2-eq)	16.5	3	3	3	3
Consumption (billion tonnes of oil)	4	1.1	0.77	0.77	0.73
$/tonne oil consumed	750	850	714	714	712
Carbon intensity (tonne CO_2-eq/tonne oil consumed)	4.0	2.7	3.9	3.9	4.1
$/tonne CO_2-eq emitted	190	310	183	183	173

3GT_L = location-based carbon accounting strategy; 3GT_P = production-based carbon accounting strategy; 3GT_C = consumption-based carbon accounting strategy

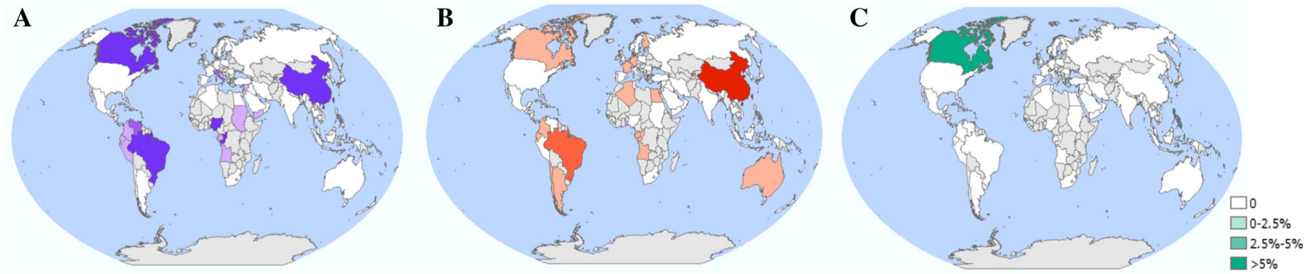

Fig. 3 Crude producing countries by percentage of total production under various accounting strategies with a three Gigaton global crude carbon cap: **a** location-based, **b** producer-based, and **c** consumer-based accounting strategy

is chosen. For example, using a location- or producer-based carbon accounting, the supply is geographically dispersed and supplying countries are constrained by their NDC. In contrast, under a consumer-based accounting strategy, only Canada and the Philippines (the countries with the heaviest and lightest crudes, respectively) produce crude. These results arise as consuming countries attempt to balance high emissions and low costs from heavy crude with the lower emissions and high costs of light crude; because the exporting countries are not responsible for extraction emissions, the heaviest and the lightest API countries are the sole exporters. For reference, Figure S7 shows the average API produced by each country used as input to the optimization.

Regardless of the specific carbon accounting scenario, a strict 3 Gt carbon cap for oil would constrain demand to at most 770 million tonnes per year (an 80% decrease over the 2014 baseline consumption) (Table 3). Under such a restrictive global carbon budget, the carbon accounting strategy used to track emissions becomes influential in determining the structure of the trade network. In the case of crude trade, where emissions decrease as a function of API and price increases as a function of API, countries face tradeoffs in reducing their cost and reducing their emissions. However, in reality, as demand for higher API (lower emitting) crudes increases under a carbon constrained policy environment, the price differential between heavy and light crudes would widen with the high API crudes commanding a premium. Because this is not an economic model, these demand affects are not considered in this analysis, but would likely lead to additional complexities in determining leakage under a fragmented climate policy scenario.

When considering specific accounting strategies, the different methods for carbon emissions attribution influences the total demand that can be satisfied while maintaining a global carbon budget of 3 Gt. For example, models using the location and production-based accounting strategies enable 770 million tonnes of oil demand to be met, while the consumer-based accounting model only allows for 730 million tonnes. Therefore, the ratio of total emissions to total consumption is 4.1 tonne CO_2-eq/tonne of oil consumed, which is higher than the 4.0 tonne CO_2-eq/tonne of oil consumed ratio found for the baseline and 3.9 tonne CO_2-eq/tonne of oil consumed for other two carbon accounting strategies. In other words, consumption-based accounting does not allow the global system to satisfy as much demand as a production-based accounting method would, while also resulting in a 10% higher carbon intensity.

The carbon accounting strategies discussed in the previous paragraph assume each country is allocated a specific fraction of the global carbon budget based on the ratio of COP21 NDC emissions targets for 2020. However, if this allocation constraint is relaxed such that there is a global carbon cap but no country-specific carbon limits, the total demand satisfied increases to 1.1 billion tonnes for a cost of $930 billon ($850/tonne oil consumed). Therefore, without unilateral carbon limits, the volume of demand satisfied increases by over 40%, for a lower cost per unit consumed than under the consumption-based carbon accounting method with country-specific carbon targets. This demonstrates there may be competing influences among the interactions between NDCs and carbon accounting strategies in the long run that could inhibit the cost effectiveness of climate change mitigation efforts. For example, under a producer-based accounting strategy, a developing country with a less constrained NDC could export a significant amount of embodied carbon to countries with more constrained NDCs, resulting in less mitigation than would have occurred under a consumer-based strategy. However, the results of the scenario without NDC-based country-specific carbon budgets show the available crude is consumed by a limited number of countries; only ten countries receive crude, compared to 56 consuming product in the consumption-based model. Therefore, while unilateral policies may be less efficient, they may be used as a mechanism to help ensure equitable distribution of consumption. For example, under consumption-based accounting with NDCs, all countries receive a portion of demand. In contrast, with no NDCs, the optimal solution based on minimizing GHG emissions is for 10 countries to receive a portion of demand. Unilateral policies could also incentivize supply security. Under the production-based accounting strategy with NDCs, all countries contribute to supply, but with no NDCs, the optimal solution is for there to be a single supplier with the highest API. These results demonstrate the importance of considering interactions between national and global policy objectives in achieving effective and equitable carbon mitigation.

The optimization model developed for this analysis extrapolates a simplified economy, focusing on the crude sector as a theoretical self-contained entity. Like many theoretical examples in the literature, it does not take into consideration the competition with other economic activities for factors of production nor does it consider substitution of crude for other products. However, substitution effects from direct crude consumption are likely minimal compared to substitution effects of coal versus natural gas for example. In reality, there are other industries that would be affected by these substitutions such as the petro-chemical sector, which can substitute petroleum-based inputs for natural gas-based inputs.

While not predictive in nature, the results of the model suggest there are important underlying dynamics of fragmented climate policy goals that may impede overall global advances toward carbon abatement. Due to the nature of this optimization model, it represents the extremes of abatement efficiencies gained through global cooperation. This simplified model reveals tradeoffs in GHG reductions and cost savings, as experienced by countries with differing constraints, varied resources, and disparate incentives. In remaining simplified, this analysis is able to isolate the existence of problematic outcomes associated with a fragmented climate policy without relying on highly uncertain, estimated country-specific social-behavioral parameters such as price elasticities and substitution effects. In doing so, this analysis is a demonstration tool; it is not intended to replicate historical trade patterns nor predict future trade patterns or quantify carbon leakage.

4 Conclusion

This analysis uses the global crude trade as a case study to explore the way in which unilateral, fragmented climate policies may unintentionally inhibit the effectiveness of carbon mitigation efforts. While these model results are simplified and theoretical, they offer meaningful insights into potential emissions mitigation possible within the crude trade without affecting consumption. These potential emissions savings primarily evolve by shifting crude production to fields with lighter crudes; emissions reductions from shifting tanker routes are negligible. As a result, current global crude consumption can be achieved more efficiently (a lower carbon footprint) by investing in refinery upgrades to increase flexibility for refining heavier crudes and by incentivizing the purchase of the more expensive lighter crudes through carbon taxes or other market mechanisms (see SI section S.7).

The insights from this study highlight the need for policy makers to understand the implications of the scale of climate policy and the accounting framework on mitigation potential in order to effectively reduce global carbon emissions. While the consumption-based accounting strategy is the most widely discussed in climate negotiations, and all accounting methods should yield the same outcomes under a unified, global climate policy, the IPCC has recognized there are important underlying dynamics that occur under a fragmented climate regime. The results of this study confirm this premise; different countries benefit under different accounting schemes, and the global emissions abatement cost is affected accordingly.

In addition to fragmented climate policies having implications for carbon accounting methods, a fragmented climate policy in which countries independently plan the degree of their own abatement efforts creates unique dynamics that may increase global cost of carbon mitigation. While the NDCs represent the negotiation concept of "common but differentiated responsibilities," a principle that recognizes historical differences in the contributions of countries to environmental problems and differences in their respective economic and technical capacity to tackle the problems (UNFCCC 1992), climate negotiators should consider more nuanced meanings of the tenet and other means of transferring resources and differentiating responsibilities under a unified, global climate policy (Brunnee and Streck 2013; Frumhoff et al. 2015).

Without a globally consistent abatement strategy, it is possible that individual NDCs could be seemingly achieved with minimal real impact on global greenhouse gas mitigation efforts. Furthermore, through this study we find the NDCs and carbon accounting schemes incentivize different patterns of trade. This indicates that although COP21 NDCs might be short-term agreements (to 2025), they influence investments made in infrastructure that could potentially hinder longer-term mitigation efforts. While in the short-term NDCs may protect developing countries by shifting the mitigation responsibility to developed nations, our results show that under a strict global carbon budget, the total cost and consumption outcomes for each country are non-intuitive. Furthermore, these are highly sensitive to the carbon accounting strategy implemented.

Therefore, while the NDCs from COP21 were an important step in committing the global community to address climate change, mitigation efforts could be more efficient and cost effective given a system-level approach rooted in more cooperative and interactive target setting. While this analysis is primarily theoretical, it provides key insights into the dynamics of climate policy at the unilateral and globally cooperative scales. The most important sensitivities that affect these results are the crude reserves and operational supply limitations for each country, the relationship between cost and crude type, and the price elasticity of demand. These parameters could be investigated thoroughly at a technical level in the future. However, for the purposes of this scoping exercise to demonstrate the importance of a system-level approach to climate policy, the simplifying assumptions made in the analysis are appropriate and relevant. Greenhouse gas mitigation to the level at which we would remain within the globally accepted cumulative carbon budget would require extensive social, behavioral, political, and economic shifts. Global cooperation and a system-level policy approach could guide such efforts to be cost effective and equitable.

In addition to further exploring the economic interaction between crude supply and demand by incorporating price elasticities, future work could expand on this model by including additional petroleum-related sectors such as the chemical and plastics industries and consider potential substitution effects of petroleum-based inputs for natural gas-derived feedstocks. Alternatively, this analysis framework could be applied to assess emissions mitigation potential from other globally traded commodities with high degrees of embodied carbon such as food and other agricultural products. Future work could also assess the dynamics of a partially collaborative climate policy in which a subset of countries participates in cooperative mitigation target setting. Finally, this model could be used to explore how country-specific adjustments to the COP 21 NDCs could improve the mitigation potential of a fragmented climate policy.

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