The equitable allocation of greenhouse gases

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Abstract

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National Emissions Inventories (NEI) use Production-Based Accounting (PBA), which include only emissions generated within a nation's territory. Thus, there are presently no considerations of indirect emissions linked to imported products in national accounts of greenhouse gas emissions. International trade has undermined climate policy to date — as much as 30% of global emissions are linked to production for export and are therefore not subject to mitigation policy. Furthermore, conventions are often mistakenly conflated with responsibility for climate change. This research proposes a weighting metric rooted in normative ethics to allocate Emissions Embodied in Trade (EET) between trading partners — Equity Weighted-Based Accounting (EWBA). Additionally, this study quantifies subsistence and luxury emissions. The metric is constructed to weigh EET inversely to how vital a given trade is for each country taking part. Need to engage in trade is quantified using use-value for money and products exchanged in a given trade, derived from the relation between human welfare and income and its mapping onto products purchased. New NEIs are then computed and compared with those by PBA and CBA. It is found that EWBA emissions suggest higher abatement responsibility than PBA emissions for most affluent countries, though usually less than if EET were divided equally between producers and consumers. EWBA provides a policy-ready alternative to PBA that is arguably fairer than CBA. If adopted as the convention in international climate policy, NEIs computed using EWBA would better reflect responsibility for climate change and emissions abatement, yielding more equitable and effective climate policy.

"Imagine a gigantic, colossal banquet. Hundreds of millions of people come to eat. They eat and drink to their hearts content, eating food that is better and more abundant than at the finest tables in ancient Athens, or Rome or even in the palaces of medieval Europe. Then one day a man arrives wearing a white dinner jacket. Not surprisingly the diners are in shock. Some begin to deny that this is their bill. Others deny that there even is a bill. Still others deny that they partook of the meal. One diner suggests the man is not really a waiter, but is only trying to get attention for himself or to raise money for his own projects. Finally the group concludes that if they simply ignore the waiter, he will go away. This is where we stand today on the question of global warming. For the past 150 years, industrial civilization has been dining on the energy stored in fossil fuels and the bill has now come due. Yet we have sat around the dinner table denying that it is our bill, and doubting the credibility of the man who delivered it."

Naomi Oreskes and Erik M. Conway (Merchants of Doubt, 2010, pp. 266-267)

"Free traders seek to maximize profits and production without regard for considerations that represent hidden social and environmental costs. They argue that when growth has made people wealthy enough, they will have the funds to clean up the damage done by growth. Conversely, environmentalists and some economists, myself among them, suspect that growth is increasing environmental costs faster than benefits from production — thereby making us poorer, not richer."

Herman E. Daly (The Perils of Free Trade, 1993)

"We can't solve problems by using the same kind of thinking we used when we created them."

Albert Einstein

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In memory of my mother, who instilled in me a strong sense of justice and compassion.

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Abbreviations

CBA	**C**onsumption **B**ased **A**ccounting
EABA	**E**qual **A**llocation **B**ased **A**ccounting
EET	**E**missions **E**mbodied in **T**rade
EWBA	**E**quity **W**eighted **B**ased **A**ccounting
GDR	**G**reenhouse **D**evelopment **R**ights
GHG	**G**reen**H**ouse **G**as
IPCC	**I**ntergovernmental **P**anel on **C**limate **C**hange
MRIO	**M**ulti **R**egional **I**nput **O**utput
NEI	**N**ational **E**missions **I**nventory
NS/NL	**N**on **S**ubsistence / **N**on **L**uxury
PBA	**P**roduction **B**ased **A**ccounting
SPI	**S**ocial **P**rogress **I**ndex
SRBA	**S**hared **R**esponsibility **B**ased **A**ccounting
UNFCCC	**U**nited **N**ations **F**ramework **C**onvention on **C**limate **C**hange

Chapter 1

Introduction

1.1 Policy pitfalls

Accounting conventions used to calculate national greenhouse gas (GHG) emissions inventories are fundamentally problematic. Reforms to emissions accounting conventions are necessary to ensure that outcomes of international climate policy are equitable. Conventions are often mistakenly conflated with implications of responsibility for climate change. The United Nations Framework Convention on Climate Change (UNFCCC) has made clear in their convention for accounting that the use of territorial emissions is just that — a convention to facilitate the standardised data collection and comparison between countries[1](para.9)[2](sec.1.4), and should therefore not be conflated with notions of responsibility which are outlined by ethical arguments like the notion of "common but differentiated responsibilities" and the "polluter pays principle". An obvious solution to remedy this conflation is to consolidate the accounting convention used with the a more thoughtful definition of responsibility for climate change. Ideally, accounting conventions should reflect responsibility for damage inflicted by historic emissions as well as to abate damage through the mitigation of GHG emissions, or alternatively pay for adaptation measures when mitigation is unsuccessful and damages are already inflicted or inevitable.

National Emissions Inventories (NEI) use Production-Based Accounting (PBA), which include only emissions generated within a nation's territory — referred to as territorial emissions. Thus, there are presently no considerations of indirect emissions linked to imported goods and services in national accounts. International trade has greatly undermined climate policy to date — as much as 30% of global emissions are linked to production for export — and by Consumption-Based Accounting (CBA) of GHG emissions, most developed countries participating in the Kyoto Protocol have missed their targets[3–5]. In order to safeguard against further dislocation of emissions through trade, reforming accounting conventions is an obvious solution. Proponents of reform insist that some consideration of consumption be taken into account in national emissions inventories. MultiRegional Input-Output (MRIO) analysis has provided the mathematical basis to investigate trade balances of emissions and formulate standardised accounts of consumption-based emissions[6] — referred to as "footprint" emissions. Assigning all Emissions Embodied in Trade (EET) to final consumers may not be politically viable nor totally equitable since affluent developed countries are the benefactors of the current territorial accounting convention and there are indeed economic benefits associated with being a major exporting country. Reforms to emissions accounting conventions are necessary to ensure that outcomes of international climate policy are both effective and equitable.

It is prudent that a compromise be reached between PBA and CBA that ensures affluent developed countries are held responsible for their "fair share" of emissions embodied in imports while reflecting equity considerations on a trade-by-trade basis. Ideally, an accounting metric should be sensitive to the shared benefits of production and consumption as well as the relative need to engage in a given trade. Several alternatives to the two extreme conventions, PBA and CBA, have been proposed. Some are technologically inclined, by weighting EET to optimise emissions intensities globally, nations are held more responsible for consuming relatively more carbon intensive commodities[7], named Technology-adjusted CBA (TCBA). Others have attempted to weight emissions to be proportional to economic benefit as defined by monetary value coupled to raw inputs and value added along a supply chain[8] and between bilateral trading partners[9], however these approaches appear problematic in the application and implications of equity. For example, assuming the employment of TCBA as an alternative metric and its dissemination into a border tax, optimising international manufacturing to favour the consumption of products with lowest carbon intensities does not take equity into direct consideration. Indirectly, if successful, this would lower global emissions and hence mitigate damage inflicted by climate change upon vulnerable populations. On the other hand, it may also result in regressive policy, passing the burden of extra manufacturing costs and taxes on to the consumer where the poorest will be most greatly affected. If lower emissions intensities of manufacturing bring about better environmental regulations in general, this would be an indirect positive effect, though if only emissions were used as a metric of success in manufacturing and other environmental or social damage incurred as a result, this would be an indirect loss of equity. Additionally, NEIs derived using TCBA insinuate peculiar notions of abatement responsibility where some highly-consumptive affluent nations are rewarded greatly (in a relative decrease in national accounts) for certain trade habits that seem disproportionate to the actual benefit of their choices. Regarding the latter metrics mentioned, using monetary value is not necessarily proportional to economic benefit. This is becoming a well-known phenomenon in welfare economics, with many economists offering alternative measures of welfare over Gross Domestic Product (GDP), including welfare indices like the Social Progress Indexwww.socialprogressimperative.org/ and "Capability Theory" as proposed by Amartya Sen[10]. Furthermore, all alternative accounting metrics proposed thus far do not differentiate between individual trades (either by product or country) and hence are not sensitive to the basis of need for engagement in trade alluded to above. I assert that responsibility for any environmental damage should consider the circumstances of the behaviour — reflected in an accounting metric — with those more obligated to trade relatively less responsible than those who trade for less vital reasons.

Here I propose a weighting metric to allocate allocate EET between trading partners that is both applicable and rooted in normative ethics. I show that starting from an intuitive ethical assertion, one can empirically derive and quantify responsibility for emissions embodied in given bilateral transactions. New NEIs are then computed and compared with PBA and CBA conventions.

1.1.1 The Kyoto Protocol and steps for effective post-Kyoto policy

The two main pitfalls of Kyoto can be categorised as follows:

1. Limiting the scope of emissions reductions to only a subset of countries, predominately those in the developed world, allowed for dislocation or "burden shifting" of emissions,

instead of domestic reductions reflecting actual and permanent reductions, they ballooned off and sought refuge in unmonitored regions

2. National inventories tabulated using PBA as dictated by the UNFCCC allowed the displacement of emissions in trade to be kept off the books in countries bound to emissions reductions targets

The resulting effect of Kyoto was a net rise in global emissions since consumption and coupled emissions grew in the countries bound to Kyoto reductions and to make these reductions, these countries dislocated their manufacturing to countries with higher production emissions intensities.

Growth in consumption as well as in emissions intensity of manufacturing employed to meet additional demand are both independent drivers of emissions growth[1]. Even if consumption had not grown during this period, global emissions would have still risen due to an overall increase in emissions intensity, hence a "net" increase in global emissions.

It is clear that the moral and practical case — "common but differentiated responsibilities", as outlined by the UNFCCC when formulating the Kyoto Protocol — was such that affluent countries who have benefited most from past emissions would have to act first (Annex 1 countries), while poorer less developed countries (non-Annex 1 countries) would not have to participate in abatement measures until sufficient mitigation in the developed world had brought their emissions per capita to a more equitable level.

Although the Kyoto Protocol failed to restrict emissions growth, the intent to distribute the burden to mitigate on those who are responsible and have the capacity to act is sensible. Employing an accounting metric that properly captured the emissions coupled to consumption would have helped make the policy effective. There is a growing body of literature proposing alternatives to PBA with the aim of making post-Kyoto policy effective by limiting the displacement and net growth of emissions due to dislocation of manufacturing via international trade[11]. This effect is referred to as "carbon leakage" or "emissions off-shoring".

[1]It is common in the literature to use the Kaya identity to describe the nature of emissions generation, which expresses anthropogenic emissions as the product of its drivers: human population, wealth per person, energy consumption per unit wealth, and emissions intensity (emissions per unit energy). see Davis and Caldeira[5] for a discussion of using the Kaya identity to interpret emissions generated by consumption.

1.2 Literature Review

1.2.1 International trade undermines climate policy

It is important to elaborate on the recent findings of studies outlining the anatomy of EET. Most recently and holistically, Kanemoto and colleagues[3] have shown that trade has facilitated substantial transfers of GHGs and other polluting emissions between countries, most importantly a large transfer of emissions burden from the developed world to the developing world (coupled to the dislocation of manufacturing). Under the framework of the Kyoto Protocol, select countries have reported decreases in emissions, some meeting their targets, however when accounting for consumption-based emissions, these countries, barring Russia and Ukraine[2], have not only failed to meet their targets but have increased their emissions. It can be concluded that Kyoto has failed to decrease world emissions and has indeed worsened the problem of emissions growth, granting affluent countries the political and social license to continue with business as usual.

Kanemoto and colleagues found that sectors exhibiting reductions domestically are generally offset by growth in the same sectors abroad[3], which shows the outsourcing of emissions clearly. They also found that burden shifting of non-CO_2 gases occurs more strongly than for CO_2. It follows that current mitigation efforts have been thwarted by what was originally perceived as a minor oversight to be dealt with at a later date — emissions burden shifting must be implemented into future international climate agreements, else emissions outsourcing will continue to grow with growing international trade, as is the current trend. Whether this be accomplished through reforms to accounting conventions in international policy or by self-regulation of willing nations using consumption-based monitoring is a moot point and all options have their respective shortcomings, be it blind spots in any accounting convention[12] or a general lack of collaboration.

[2]Russia and Ukraine experienced notable economic decline during the Kyoto Protocol period, and due to strong coupling of economic growth and emissions generation, it follows that this recession was responsible for their decline in emissions.

1.2.2 Accounting metrics in GHG inventories

As explained in section 1.1, GHG emissions accounting by convention uses Production-Based Accounting (PBA), which only includes emissions generated within a nation's boundaries, referred to as territorial emissions or direct emissions. The extreme alternative to PBA is the polar opposite — including all emissions embodied in goods and services consumed within a nation's boundaries — Consumption-Based Accounting (CBA)[5, 13], referred to as footprint emissions or upstream responsibility. CBA emissions are computed by adding emissions embodied in imports and subtracting emissions embodied in exports from territorial emissions. Any compromise that shares Emissions Embodied in Trade (EET) — and likewise responsibility for climate change attributed to those emissions — between producers and consumers is referred to as Shared Responsibility Based Accounting (SRBA)[14]. The benefits and drawbacks of PBA, CBA, and various options for SRBA are summarised in table 1.1.

Other accounting metrics include extraction-based accounting — which assigns all emissions to the country from where fossil fuels have been extracted[15] (only covering CO_2 emissions), and income-based accounting — which allocated emissions along a supply chain proportionally to how much they earn[16, 17] (also known as supply based accounting or downstream responsibility).

1.2.3 CBA versus PBA

The strengths and weaknesses of PBA versus CBA have been discussed at length[8, 13, 14, 18]. In brief, PBA places all responsibility on manufacturing parties, which is evidently inequitable especially in the case where wealth is decoupled from emissions and high levels of consumption are facilitated by importing goods from poorer countries which are then assigned responsibility through territorial emissions accounting (which accounts only for emissions generated with a nation's boundaries as dictated by the UNFCCC). On the other hand, CBA places all responsibility on the consumer, providing no incentive directly for the producer to lower their emissions intensity of production. Countries who manufacture substantial amounts of goods for export — most notably China of which a third of their emissions is linked to production for export —

	National Emission Inventory (NEI) accounting methods	
	Pros	*Cons*
Producer-based accounting (PBA)	Simple and straightforward to calculate with readily available statistics	Distracts policy from actual consumption of a nation responsible for driving emissions and facilitates carbon leakage
	Consistent with GDP accounting methods	Places full responsibility for emissions embodied in goods on manufacturing nations
	Low uncertainty associated with data and calculated values	Makes manufacturing nations less likely to engage meaningfully in reduction negotiations since they feel exploited
Consumer-based accounting (CBA)	Responsibility placed on demand-side behaviour (more normative approach since emissions are driven by consumer demand)	Neglects economic benefit gained by producer by placing all responsibility on consumer
	Encourages cleaner production through informing and incentivizing consumer behaviour (indirect benefit that would require other policy)	High data requirement
		High uncertainty associated with calculations (linked to aggregation of sectorial data in IO tables)
Technology-adjusted CBA (TCBA)	Informs policy makers where most efficient and lowest impact manufacturing nation are located for given commodities	Uncertainty in trade alternative, approximated by taking average emissions intensity of sector as baseline alternative
	Incentivises (disincentivises) manufacturing in countries with relatively lower (higher) production emissions intensity	Fails to incorporate, at least directly, any consideration of ethics and endangers incentivising production at the cost of equity
	Politically palpable to technologists since it is totally positive and valueless basis for burden sharing	Does not directly address issues of responsibility for generated emissions
Shared responsibility-based accounting (SRBA)	Directly addresses and makes explicit the shared responsibility of producer and consumer actors in trade	High uncertainty in data collected and amplified by calculations (same drawback as CBA)
	Can allow for explicit discussion of equity implications of industrial-scale trade	Ambiguity and variation in formalisms may be subject to criticism (still improvement on PBA and CBA)
	Encourages a more equitable formalism of sharing EET that engages both sides to negotiations	Applying theory and implementing as policy more complex and involved compared to CBA

Table 1.1: Pros and cons of different GHG accounting metrics

feel that it is unfair to attribute these emissions to them and insist that countries consuming the goods be responsible for their embedded emissions[19, 20].

It can be argued that through consumer choice to buy lower GHG embodied goods, a signal can be sent to manufacturers since those with lower emissions intensities will be preferred over others. However without domestic and internationally harmonised policy — for example, using a internationally harmonised border carbon tax harmonised — CBA will not be effective. Consider the following — even if consumers are held entirely accountable, without perfect market elasticity, they will not feel the brunt of the added costs, and those costs that are passed down will impact lowest income people the most, resulting in regressive policy.

The question still remains: is CBA fully equitable? There are indeed benefits to being a producer — exporting goods and services garners income and access to global markets provides the basis for economic growth for industrialising countries. Should they be held partially accountable for emissions discharged when producing for export? How does the "polluter pays principle" apply here in this more nuanced context of global equity and the history of industrialisation? Developed countries who have emitted the vast majority of emissions historically[21–23] are in this sense indebted to less developed countries[24]. If one agrees that the developed world in a place of privilege owing to the benefit of a period of extensive fossil fuel consumption much greater than the developing world, then PBA would undoubtedly represent an ethical travesty. Moving beyond historical precedents and compensatory justice, which are largely removed from politically viability[3], perhaps the emissions burden should be allocated proportionally to economic benefits associated with trade — as in income-based[16, 17] or beneficiary-based[9] accounting. Is this truly equitable? Is "economic benefit" objective and is monetary value a reliable measure for it (even when purchasing power parity (PPP) adjusted) for all countries for all kinds of trade? What about countries whose populations live in abject poverty? Would income received via its exports not be deemed more necessary than if that country were already well-off? Or if the products being bought were clearly destined for consumption in luxury goods? In order to resolve these issues, SRBA is necessary and is the most progressive, although most complex choice.

[3]But no less important to discuss because of this, nor should they not be championed because developed nations command greater political leverage internationally

1.2.4 Shared responsibility based accounting: a literature survey

As previously mentioned, all middle ground approaches, which allocate responsibility to both producer and consumer, belong to the shared responsibility class of accounting methods denoted Shared Responsibility Based Accounting (SRBA).

The simplest SRBA possible would be the egalitarian scenario in which emissions embodied in trade are divided equally amongst trading partners: 50/50 between consumer and producer. This serves as a logical starting point since it is simple and transparent, as well as a good first approximation for any SRBA metric that can be used as a null hypothesis with which to test how much a given SRBA metric deviates from this simplest case. In any SRBA metric — including the 50/50 or what I refer to as Equal Allocation Based Accounting (EABA) — economic incentive to reduce emissions is therefore borne by both producer and consumer, thus achieving the main tenet of SRBA — sharing responsibility for emissions amongst both producer and consumer, thereby giving both actors incentive to mitigate[4]. Lenzen and colleagues[14] as well as Csutora and Mòzner[9] propose this as an acceptable SRBA solution although they refer to sharing emissions between actors along a supply chain rather than between countries engaging in trade on a bilateral basis[5]. This study aims to create a method in which emissions can be shared between countries. In addition to the novel equity-weighting metric to be developed here, a method to share emissions equally between importers and exporters in bilateral trade will also be presented and new NEIs presented using both accounting metrics.

It should now be evident that in order to respectfully address the issue of how accounting metrics imply responsibility for climate change and to propose an equitable solution to this aspect of burden sharing, SRBA should be employed. The remaining detail is how to formulate SRBA metrics methodologically. There have been multiple attempts to formulate an equitable and effective way to construct an SRBA accounting metric and the issue remains one of debate today. These methods to date are outlined in the following subsections.

[4]It should be noted that any SRBA metric that splits emissions amongst agents along a supply chain with fixed proportions will lessen the amount of emissions allocated to the final consumer as the supply chain grows

[5]Countries can be agents along a supply chain too. Here I treat all agents along the supply chain as a single actor when trade between them is intranational

This metric proposed in this study intends to answer this question in a novel way, one that includes fundamental notions of responsibility from normative ethics that have not yet been discussed.

1.2.5 Criteria for a legitimate and effective accounting metric

Before reviewing the suite of existing SRBA metrics, it is prudent to outline and define criteria for the design of any GHG accounting metric.

There are at least three conditions[6] underpinning any coherent accounting framework[7, 14, 27, 28]. If these criteria are not satisfied, a metric cannot be considered legitimate nor can it be used to inform national climate policy in an effective manner.

The three conditions are the following:

1. Additivity: The sum of all nations emissions must equal total global emissions
2. Monotonicity: Decreases in national carbon footprints must not lead to increases in global carbon emissions or vice versa
3. Sensitivity: Accounting should be responsive to factors that countries can influence and global emissions must also be able to be affected by changes in individual countries accounts

The first condition, Additivity, ensures that the account is fundamentally legitimate in a physical sense while the two other conditions listed are necessary for metrics to be able to used effectively in mitigation policy.

1.2.5.1 Additivity

Firstly, any accounting metric used to alter national emissions inventories (NEI), must not violate physical laws, namely conservation of mass of a physical object — conservation of emissions. This criteria is referred to as the first condition — Additivity, which states that any new metric

[6] Arguably there are six in the strictest sense[25] but according to Kander and colleagues, only three must be upheld for effective policy[26].

must have global emissions whose sum is equal to that of the sum of national emissions by territorial account.

1.2.5.2 Monotonicity

Monotonicity is another criteria necessary for effective policy — countries should not be able to change their emissions and it result in the opposite effect globally. For example, PBA does not satisfy monotonicity since decreasing national emissions often leads to a net increase in global emissions since the emissions reduction is a result of dislocating manufacturing to countries with higher emissions intensities of production. CBA also fails monotonicity for the converse scenario where it is possible for domestic emissions of one country to increase while global emissions decrease. This is of course not a favourable outcome since it would incentive countries experiencing this effect to resist emissions mitigation that would penalise or disadvantage them in international negotiations. An example of this occurring is shown in the supplementary materials of Kander *et al.*[7].

1.2.5.3 Sensitivity

Monotonicity indicated that countries may not influence global emissions in the opposite way that they influence their own. In contrast, Sensitivity dictates a weaker version of this: that countries must be able to have some effect on global emissions by changing their own account. Sensitivity must be satisfied otherwise countries will not have adequate feedback from changes to domestic emissions and will therefore be unable to construct meaningful mitigation policy.

1.2.6 Review of different accounting metrics

1.2.6.1 Metrics by Gallego and Lenzen

Gallego and Lenzen have developed a rigorous and robust way of allocating emissions responsibility all the way down a supply chain that can be adjusted parametrically to be weighted more towards consumer or producer sides and that preserves Additivity[28]. They propose a method to weight emissions along a supply chain equally between (i.e. split 50/50) each actor

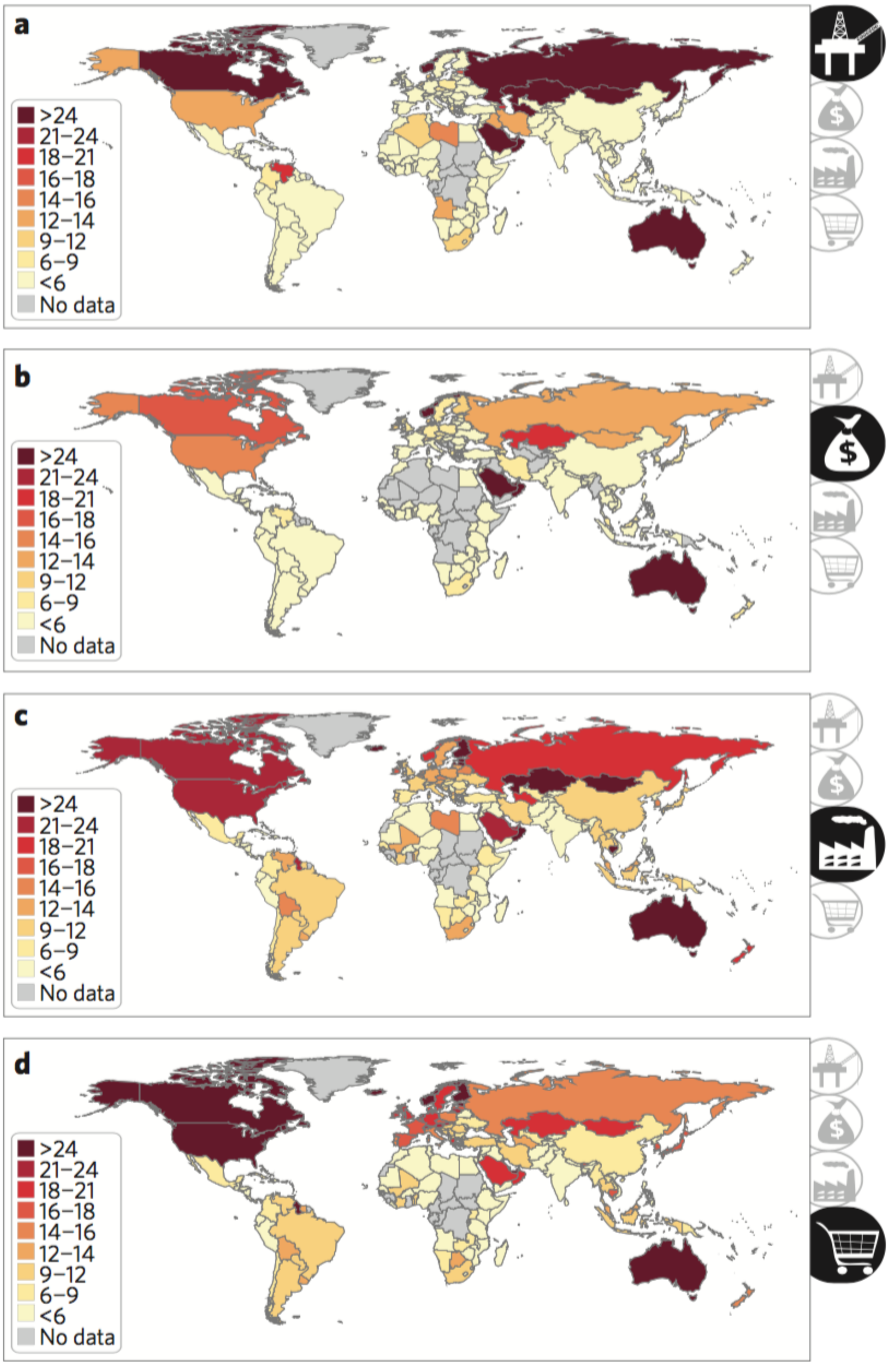

FIGURE 1.1: **Countries' emissions per capita according to different accounting principles (in the year 2011).** a-d, Panels show emissions, in tonnes CO_2 or CO_2 equivalent, according to: extraction-based accounting, reflecting the carbon content of fossil fuels extracted (a); income-based accounting, allocating emissions along the production chain based on the supply of factors of production (b); production-based accounting, assigning emissions to the country releasing the pollutant (c); and consumption- based accounting, attributing emissions to final users of goods and services produced (d). Note: panels a and b cover only CO_2 emissions from energy use (source: own calculations); c and d cover all GHG in tCO_2e (source: Eora database). See Supplementary Information for methodological and data information, and additional panels. Figure courtesy of Sabine Tschürtz . Reproduced directly from ref[12].

along a supply chain[14]. This leads to a problem where the longer the supply chain is, the less emissions burden is passed down to the final consumer. In order to remedy this, they propose a value added weighting conversion that preserves the share of emissions allocated to final consumers regardless of the supply chain length. It is noted that if this were not remedied, consumers could evade emissions responsibility by introducing more components along the supply chain before goods and services reach them. For example, adding an additional retailer between a vendor and consumer that does not add much embodied emissions but must assume 50% of the responsibility from the emissions from the embodied emissions from the previous actor on the supply chain, thereby removing 75% of emissions from the consumer allocation[7]. This phenomenon will provide an incentive to "de-merge" agents along a supply chain in reporting practises. Lenzen and colleagues[14] solve the problem of invariance when a supply chain is disaggregated by pegging the ratio passed on to a quantity independent of sector classification like value added. They propose changing the fixed 50/50 allocation ratio to the ratio of value added over the difference between gross output and intra-industry transactions (i.e. net output).

1.2.6.2 Carbon Emission Added approach

Bastianoni and colleagues put forward another method of SRBA, the Carbon Emission Added (CEA) approach that adopts the Embodied Energy-Emergy Analysis method[8].

Their approach is illustrated as such: starting from an arbitrary quantity of emissions, 100 units, and a fixed number of agents along a supply chain, 3 in their example denoted A, B, and C. In each of their respective activities, the three agents emit 50, 30, and 20 units of emissions respectively. Their method adds all emissions to an agent emitted by previous agents along the supply chain then normalises them by dividing the new emissions quantity for each agent by the new total emissions. In this example, this yields 50, 80, and 100 units divided by 230 and multiplied by 100 units, giving A, B, and C new emissions accounts of 22, 35, and 43 respectively (which add up to the original total of 100 units). Lenzen and colleagues[14] note that this method is not invariant of sectoral aggregation since it is also susceptible to the changes in the length of a supply chain. This can be easily shown by adding another agent to the supply chain who adds no value nor emissions. When CEA is applied, this last agent assumes partial

[7]it splits the remaining 50% 50/50 again with the consumer, therefore the consumer is only allotted 25% of emissions starting from the second last actor instead of 75% if that actor did not exist.

responsibility by shifting emissions off of the original three agents. Their invariant solution resolves this as discussed above in section 1.2.6.1.

The authors state a normative assertion in their conclusion — they feel that consumers should bear the majority of the responsibility and that producers should still be held accountable, but to a lesser extent so that they can be incentivised to improve their production efficiency and on the demand side, consumers will choose the optimal producer to save costs if carbon costs are embedded in the products through policy.

1.2.6.3 Technology-Adjusted Consumption-Based Accounting

Kander and colleagues provide a technically motivated rather than normative adjustment to CBA named Technology-Adjusted Consumption-Based Accounting (TCBA)[7]. They note the pitfalls of PBA and CBA practises. The former does not provide incentive against carbon leakage through trade and the latter does not provide direct incentive for exporters to decarbonise manufacturing processes, in addition to penalising certain types of trade that lower global net carbon emissions through aggregate reductions in carbon intensity. The authors aim to improve the CBA methodology by incorporating a weighting term that adjusts CBA by a factor of carbon intensity of production by domestically sector by the global average carbon intensity of the sector. In practice, they add emissions to exports that are above the global average carbon intensity or subtract emissions when under the average to the exporting country, giving the exporter a penalty (increase in emissions) or bonus (decrease in emissions) reflecting their production performance relative to the world average. The amount passed on to consumers is what is left after adding a penalty or deducting a bonus from the exporter — the emissions embodied in the imports if they were produced with the world average carbon intensity. It is shown that TCBA satisfies their three stipulated criteria for effective accounting metrics: Additivity, Monotonicity, and Sensitivity. A discussion of the metrics motivation and evaluation by remaining criteria can be found in correspondence between Domingos and colleagues and Kander and colleauges[25, 26].

Their proposition undoubtedly addresses the nuance of emissions intensity of production, and although it fails to directly consider the ethical implications and is inherently a valueless approach to remedying PBA, by assigning more responsibility to producers who source commodities from more emissions intensive manufacturers, they may address issues of equity indirectly since higher emissions intensities generally correlate with worse socio-environmental manufacturing standards. A major critique of TCBA is that although it claims to be an adjustment to CBA, it is in reality an adjustment to income-based accounting, since it propagates an effect downstream over producers rather than upstream over consumers, placing the onus to decarbonise more on the producer than consumer.

1.2.6.4 Beneficiary-based accounting

One of the most promising and easily understood proposed SRBA metric proposed thus far is a Beneficiary-Based Accounting (BBA) principle, as developed by Csutora and Mòzner[9]. In general, it is asserted that consumer and producer share responsibility for the embodied emissions in the commodity trade, or the emissions embodied in trade (EET), in a manner that reflects and is proportional to the economic benefit derived by each party in the transaction. They decide to allocate emissions embedded in the raw materials or throughput of a commodity are allocated to the consumer while those coupled to the value added processes are allocated to the producer. This generally results with more emissions, and by extension primary responsibility, falling upon the consumption side of trade. The authors state explicitly, but also *ex post* (i.e. after the fact), that their intention was to assign greater responsibility to the demand sign. In this sense they have designed an accounting metric with a normative basis. A major critique of their approach is that benefit relies entirely on monetary value as its measure. As discussed in section 1.1, this may be highly problematic.

1.2.6.5 Benefit principle and ecological deficit

Another definition of responsibility for climate change can be found in the work of Ferng[29]. She states that countries should be responsible for emissions that are in excess of their ecological capacity to absorb them, i.e. how much carbon emissions are not sequestered by a country's territorial share of the global carbon cycle uptake. These emissions are referred to as "over-emissions". National inventories are then constructed by taking the difference of CBA emissions and the country share of carbon cycle uptake as described above. She claims this is in adherence with the "benefit principle" and notion of "ecological deficit". The former describes in a similar way what is meant by who benefits from emissions as discussed by Csutora[9] and Marques[16], and the latter is very similar to the concept of ecological debt and has been discussed specifically in the context of climate change and quantified by Matthews[24] while being quantified for environmental impacts more generally by Srinivasan and colleagues[30].

Ferng recognises the conflation between accounting conventions and notions of responsibility: "As mentioned, in the context of globalization, the national direct CO_2 emission differs from the national responsible CO_2 emission in terms of the underlying principle of responsibility and the resulting estimates." Her metric attempts to reconcile this by taking the natural world to be annexed by nations and its carbon sequestering capability belonging to the nation whose territory it falls into. My main critique of this is that national sequestration ability measured by amount of forested area for example, unfairly benefits countries who are fortunate to be endowed with them and that their existence within national borders is arbitrary. Should Canadian forest be used to offset Canadian emissions? Or much like how the atmosphere is a global commons and receptacle for GHGs, perhaps the terrestrial biosphere should likewise be considered the commons for those carbon uptake? It is clear that countries with large forested areas will exploit this metric, as they already do with forestry credits in reporting emissions to the UNFCCC[8].

1.2.6.6 The "fair" way

Rodrigues and colleagues[27] derive an indicator that quantifies environmental responsibility (i.e. responsibility for environmental degradation related to human behaviour) that they assert is uniquely defined and intuitive to anyone. Furthermore, they assert that their method is the first "fair" manner of designating environmental responsibility and begins with a normative assumption, a claim not made explicitly by any other method proposed thus far. In this regard,

[8]Canada for example is able to offset much of its emissions growth in the oil and gas sector by counting forestry credits against it. Canada is home to 10% of the world's forests, which can be used to count approximately 63 Mt CO_2e against its territorial emissions according to Climate Action International (http://climateactiontracker.org/countries/canada.html)

their motivation is very similar to my own. They refer to their approach as "axiomatic" since it starts from intuitive and unquestionable premises, also much like I attempt in this thesis. Our methods diverge fundamentally when deciding what the axiomatic basis for responsibility is — they suggest that it be defined and quantified as the mean of upstream and downstream environmental pressures, i.e. the average of the damage coupled to the producer and consumer behaviour driving as quantified by environmental degradation (e.g. units of GHG emissions discharged) per monetary or physical unit transacted. They do not go as far as applying their indicator to reforming NEIs and instead cite some general examples of possible application. Additionally, the authors note a fourth criteria for an effective metric — Symmetry. Symmetry requires that the responsibility share for consumer and producer not change if roles are interchanged. This is not widely accepted in the literature. Lenzen and colleagues point out that the symmetry preserving condition is the exception to the rule rather than the rule itself[14].

1.2.6.7 Income-based accounting

Marques and colleagues argue that assigning all responsibility for emissions in production to the supply side would better render effective climate policy[16]. This goes against market-based intuition where most would support the converse argument, assigning all responsibility for emissions or other environmental externalities to the final consumer since it is reasoned that it is their demand that drives production. In practice, adding export emissions and subtracting import emissions from the countries direct (territorial) emissions yields income-based accounts. This serves as the opposite approach to consumption-based accounts where imports are added and exports subtracted from direct emissions. Marques *et al.*[16] assert that by assigning responsibility to producers rather than consumer, which they define as downstream rather than upstream accounting, will not penalise consumers who cannot afford to buy cleaner goods and instead push the full costs of clean production onto the producer. A simple example is to consider the difference in assigning responsibility to consumers of electricity produced during the combustion of coal or to the investor who profits from the operation of the coal plant. In this specific situation, it is evident that the investor is likely more responsible for the emissions since they profit more from the situation and arguably have more freedom to invest their capital into renewable energy, where under downstream responsibility, they would suffer less penalty. They define this approach as income-based responsibility since it targets income directly. In this regard, their metric would provide the basis for more progressive taxation rather than risk very regressive taxation when implementing consumption-based (upstream) accounting. I would argue that again, this approach although valid and very useful in concept, is yet another extreme and would not elicit fully equitable nor effective policy.

1.2.7 Ethics of climate change

Climate change is inherently an ethical problem. It is the embodiment and manifestation of inequity amongst humans and between humans and the nonhuman world since the dawn of the industrial age. It is no understatement to label climate change as a form of violence, directed from rich to poor, developed to developing; perpetrated perhaps unwittingly for many decades and now unambiguously with awareness of the nature of the problem. Many still live in denial of the situation, some implicitly — portrayed by apathy or mild concern — while others so vehemently so that they aim to discredit the science to sow doubt and prevent action by any means necessary. And this is for no surprising reason — climate change calls into question the very nature of human civilisation and threatens to upend every existing aspect in how humans conduct themselves on Earth from our economic paradigm to geopolitical relationships. Primary opponents to action are those whose profits and positions of power are most immediately under existential threat — fossil fuel corporations and anyone who profits from them. Many others still see this in a negative light, as a danger to our present way of life, while others as an opportunity to build a better world. Whether this story ends triumphantly or plunges the world into a state of disarray from which humans may never recover is perhaps the greatest challenge faced by any generation. It is with this in mind that many must ask themselves fundamental questions about the nature of our species and how we relate to each other and the world around us. All these questions are coloured with ethics. What is "right" and what is "wrong"? Who is responsible? How must they act? How will we share what is left of the atmospheric capacity for absorbing carbon without risking devastating climate destabilisation? As an individual, will you be able to look back on your life and feel you have done what you could? What is the individual's role? How can progress be best elicited?

1.2.7.1 Responsibility for climate change

Responsibility for climate change may be as complex a concept as the physics of climate change itself. For our purposes, it can be defined as the culpability for causing human-induced (or "anthropogenic") climate change including but not limited to global warming (e.g. causing heat waves that harm human health and damage crops), changes in precipitation (e.g. which are also detrimental to food systems and human infrastructure when flooding occurs), rising sea levels (e.g. which can inundate coastal or low-lying inhabited areas or salinate the drinking and irrigation water sources of these areas), etc. How blame is assigned is an open question for anyone interested in climate justice[9].

To take a step back for a moment, what does one mean when referring to justice, regardless of the context? Garvey provides a relevant discussion concerning justice and a lengthy discussion about its implication within the context of inequity and climate change[31]: "justice means that burdens and benefits should be distributed among people equally". To paraphrase, justice can be thought of simply as an egalitarian distribution of benefits and associated burdens or any harm attributed to the enjoyment of these benefits.

There are many different ways to frame responsibility for climate change. Some are more technical in nature while others can be understood more intuitively. Fundamentally, climate change demands moral obligations from both individuals and nations.

The effects of climate change are spatially and temporally isolated from their causes. This of course makes the problem more abstract than other human crimes that are more easily isolated in space and time, and therefore blame is less easily assigned and justice (be it distributive or corrective) less clearly administered. Another impediment to achieving climate justice is the nature of the inequity in climate change itself — actors who have benefited most from causing it, have reaped the most wealth and political power, and have the least incentive to address the issue since they are also least vulnerable to its negative impacts.

It is important to be able to distinguish explicit discussions of responsibility from those that are implied. As mentioned in section 1.1, responsibility for climate change has been mistakenly conflated with accounting conventions used in national emissions inventories (NEI). Some

[9] the offshoot of environmental justice dealing specifically with addressing inequities stemming from and due to climate change.

researchers have avoided making statements regarding responsibility by keeping work clearly defined as being independent of responsibility, e.g. by using "contributions" to climate change, rather than responsibility for climate change (as done by Matthews and colleagues[21]), one can define a quantitative measure of how much countries have exacerbated climate change given certain conditions (here most importantly/sensitivity, the chosen accounting convention).

Füssel has shown, using a variety vulnerability indicators, that those most vulnerable to impacts of climate change are least responsible for it[32]. More recently, Althor and colleagues show that climate change inequity is closely coupled to economic output, i.e. countries that benefit the most economically from fossil fuel usage are the ones who suffer the least from climate change impacts[33]. Figure 1.2 shows their findings.

The most straightforward accounting of responsibility can be quantified as contributions to climate change. There have been many attempts using differing methodology to compute the climate impacts of historic national emissions[21–23], often quoted in a temperature change (degrees warming or cooling) due to each country's historic GHG and aerosol emissions combined with land use change.

Contributions to climate change as discussed above can be further applied. Combining national contributions to climate change with the concept of ecological debt yields the notion of carbon and climate debts (and conversely, credits). This provides another way to think about responsibility for climate change that is also quantifiable and scientifically rigorous. Matthews has provided a quantifiable definition and comprehensive assessment of both national carbon and climate debts and credits using the climate response to historic emissions[24]. The main figure from this study is included as figure 1.3.

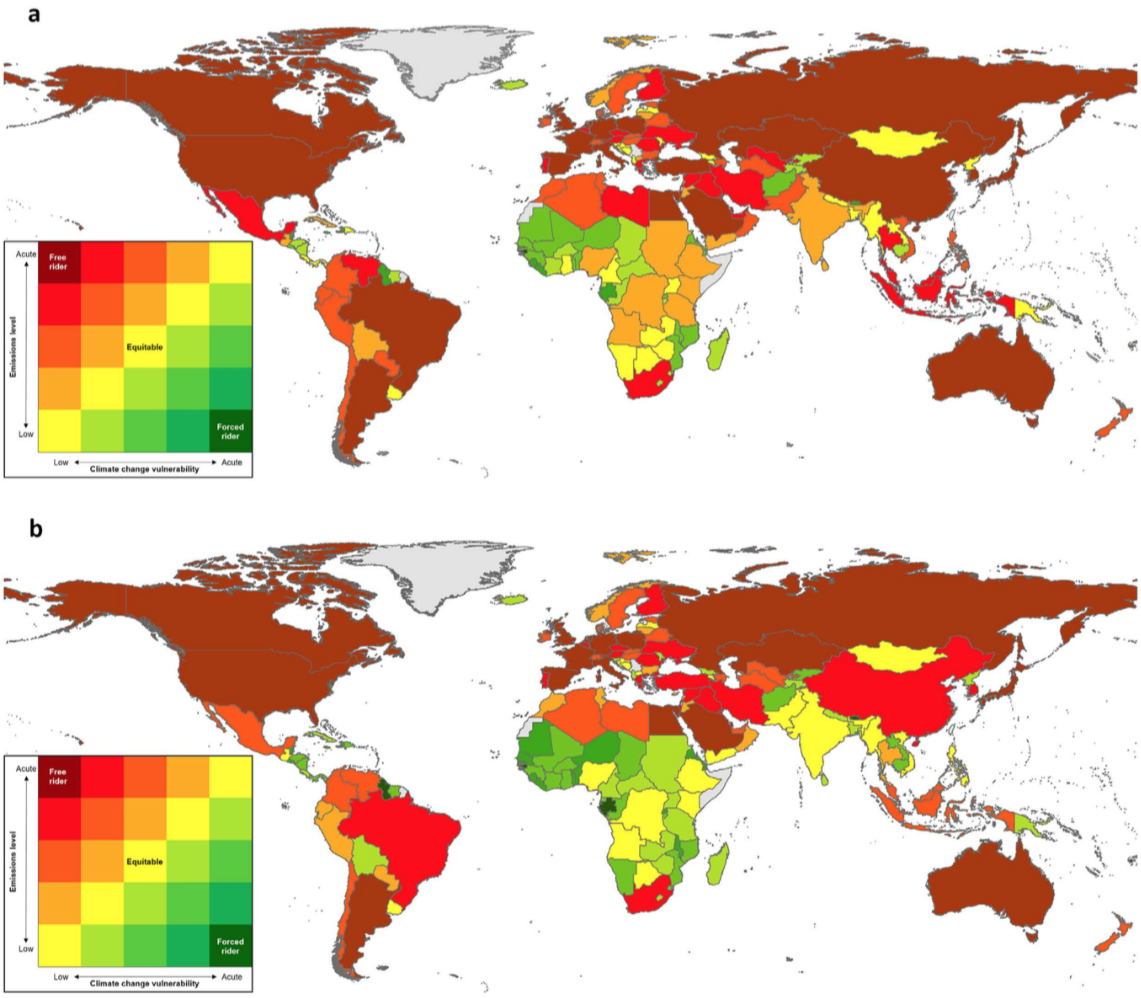

FIGURE 1.2: **Global mismatch between greenhouse gas emissions and the burden of climate change.** Global inequity in the responsibility for climate change and the burden of its impacts. (a) Climate change equity for 2010. (b) Climate change equity for 2030. Countries with emissions in the highest quintile and vulnerability in the lowest quintile are shown in dark red (the climate free riders), and those countries with emissions in the lowest quintile and vulnerability in the highest quintile are shown in dark green (the climate forced riders). Intermediate levels of equity are shown in graduating colours, with countries in yellow producing GHG emissions concomitant with their vulnerability to the resulting climate change. Data deficient countries are shown as grey. Maps generated using ESRI ArcGIS36. Reproduced directly from ref[33].

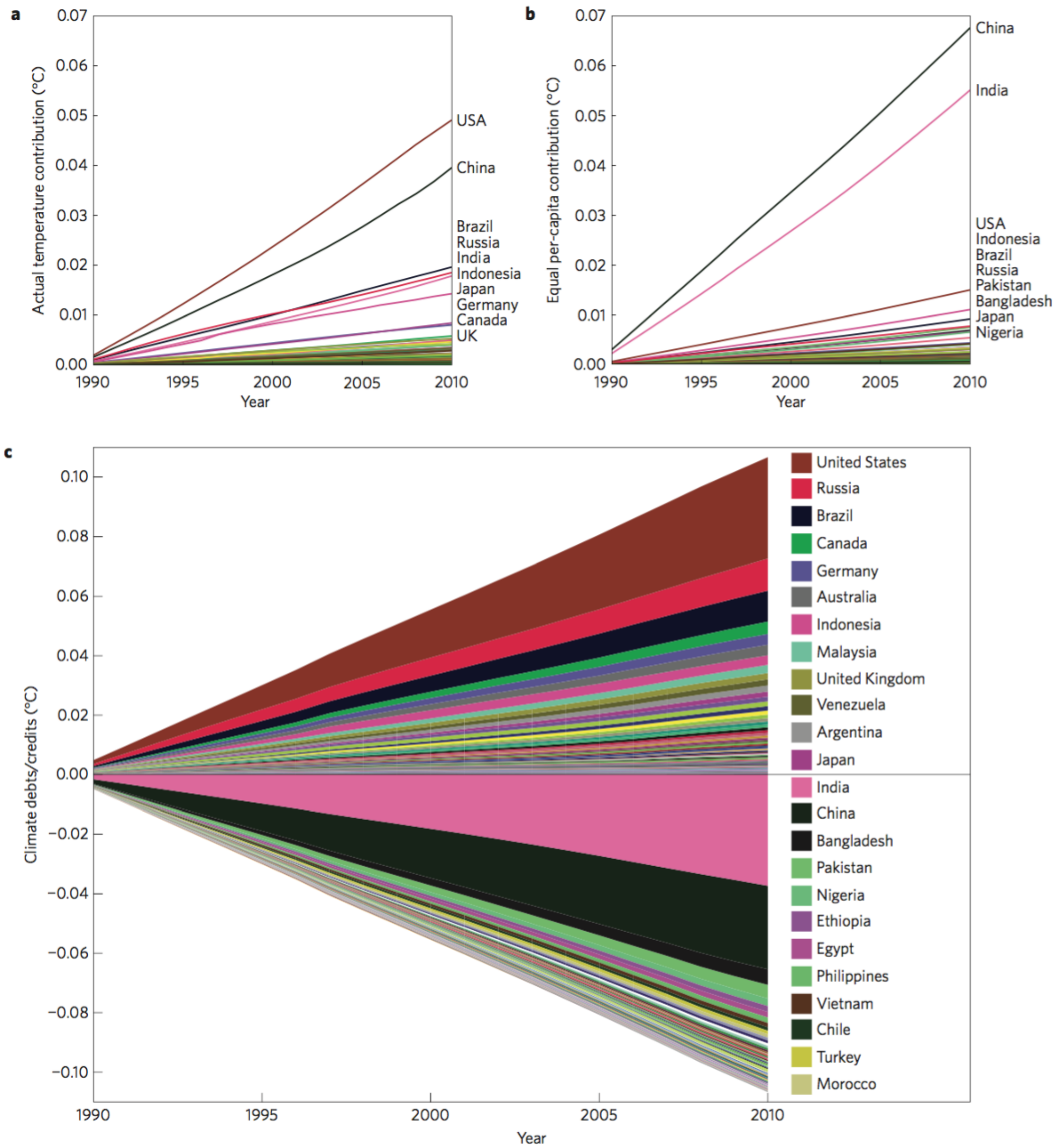

FIGURE 1.3: **National climate debts and credits.** (a) Actual national contributions to historical temperature changes. (b) Hypothetical equal per-capita national shares of historical temperature increases. (c) Climate debts and credits for each country, calculated according to equation (2) (see Methods) as the accumulated difference between a country's actual contribution to historical temperature changes (a) and its equal per-capita share of temperature increases (b). The climate debt/credit values are shown as a stacked area plot, whereby the width of each coloured area slice represents that country's accumulated climate debt or credit over time. All countries are included in each figure panel, with the top 12 debtor and creditor countries listed and identified by colour in the legend accompanying the lower panel. Reproduced directly from ref[24].

1.2.7.2 Subsistence and Luxury emissions: In search of an explicit and quantifiable definition

"Subsistence emissions" can be defined as the GHG emissions generated during the production of commodities deemed basic necessities vital to human life. Anything that is not part of this set of commodities can be defined in a complementary manner as "luxury emissions". Further discussion and differentiation of kinds of emissions is left for discussion in section **??**.

It has been argued that no emissions can be classified as subsistence emissions since humans were capable of providing adequately for themselves before the dawn of the fossil fuel age[34]. This extreme analysis suggests that their is a historical precedent for subsisting without fossil fuels, humans do not require using fossil fuels to feed and clothe themselves, and this is arguably correct in a historic context however for the needs of this enquiry, it is not relevant. We live in a period of history in which humanity is dependent on fossil fuels for subsistence, their usage being systemically ingrained in our daily lives. The argument may be made that fossil fuels are certainly necessary to feed and clothe humanity today given the sheer magnitude of the population now relative to the time before fossil fuels began being used, i.e. fossil fuels are instrumental in the energy and fertilisers used in all aspects of production, from textiles to industrial-scale agriculture. This expansion in population is of course largely owed to fossil fuels. Just because there may exist a zero-emission alternative, the fact remains that at present, the common practice in most material economic activity is using energy and material feedstock derived from fossil fuels. So I argue not that there are subsistence emissions by the strict definition noted above, but that there are, at least circumstantially, emissions that are coupled to more essential activities than others. Without going into more of a debate on the subject, one can accept that given there exist such a thing as subsistence emissions, there must also exist emissions that are not subsistence emissions, these being luxury emissions (and as alluded to later, things that may be neither subsistence nor luxury emissions).

Shue has discussed broadly what is implied by subsistence emissions and how they differ from luxury emissions[35], but does not go so far as to define the demarcation between the two explicitly, and by this limitation, also fails to define the categories and their criteria concretely. It is not immediately evident which commodities fall into either category.

The research presented here requires an explicit definition of what constitutes subsistence and non-subsistence or luxury emissions, or some set of emissions coupled to a hierarchy of commodities according to human need. This hierarchy can be analogous to a hierarchy of needs as constructed by Maslow[36] and those which are underpinned by Maslow, for example the hierarchy of human rights discussed by Brockett[37]. Furthermore, this study necessitates that this hierarchy of emissions to be not only ordinal, but cardinal (in the conventional mathematical sense), i.e. there must be a well-defined order between the levels in the hierarchy as well as the relative spacing on the scale the levels occupy.

1.3 Research Objectives

This study aims to:

1. Define a novel SRBA by weighting EET in an equitable manner based on intuitive and normative ethical premises
2. Compute national accounts using the novel metric to produce a new set of NEIs
3. Explicitly define and quantify subsistence and luxury emissions for the first time

Chapter 2

Methods

2.1 Data employed in the study

The study described in this thesis required data from multiple sources. EXIOBASE version 2.2.2 (http://www.exiobase.eu) is provided freely for academic use. EXIOBASE is a Environmentally-Extended MultiRegional Input Output (EE-MRIO) database that includes physical trade flows for 43 countries (accounting for 90% of global GDP) and 5 Rest of World (RoW) regions. The database also includes environmental impacts. Details regarding its construction can be found in references[38, 39]. This study uses the latest release available, containing data from the year 2007, and the product-by-product (pxp) configuration, which breaks the global economy into 200 product classifications. All GHG emissions data used in the study is also contained within the database.

Other sources of data include the Social Progress Index (SPI) by the Social Progress Imperative (http://www.socialprogressimperative.org/), a human welfare index, and population and Gross National Income (GNI) data from the World Bank (http://data.worldbank.org).

2.2 Defining the weighting convention

The goal of this thesis was to adopt an intuitive and normative ethical premise and quantify it as a weighted share of EET. This ethical premise is the following:

- *Those who engage in trade to satisfy basic needs for subsistence should be held relatively less accountable for the detrimental impacts of their consumption compared with those who engage in trade to satisfy less vital needs and wants.*

This differs from Csutora and Mózner's approach whereby they assert that emissions should be weighted according to economic benefit[9] or from that of Rodrigues and colleagues who use environmental pressure as the basis for quantifying responsibility[27]. Without delving deeply into a discussion of the pitfalls of using money or GDP as a measure of benefit, it can be said that economic benefits as measured by monetary value of raw materials and value added are suspect measures (as illustrated in section 1.1). It also differs greatly from the approach employed by Kander and colleagues[7] that as I previously argued, bypasses a value-based judgement involving ethical assertions entirely in favour of opting for a technologist approach. Their approach yields results that do not encapsulate measures of international equity but rather the question of whether trades made had higher embodied carbon intensity than the global average for a given sector or product. By avoiding an explicitly value-based assessment, they do not avoid making a framework with implications that have inherent values. Indeed, the scientist's decision to not engage with values is a value judgement in itself. Examining their results, the outcome of a TCBA account is intuitively unethical; for many wealthy countries, their accounts using this method are smaller than their consumption and even sometimes production based account (territorial emissions). All this to say is that the metric under development here is one motivated predominantly by ethical considerations. In the spirit of fairness, the basis of need is central to the metric. An egalitarian value of human lives should imply equal access to resources, and it follows that it is unjust for some to have access to luxuries when many do not have their basic needs met.

Consider the arbitrary trade:

- In a given bilateral trade, country i buys products from j, paying money in exchange
- Products are classified into three categories: subsistence commodities, non-subsistence and non-luxury commodities, and luxury commodities
- Each product classification has a specified use-value

- Money is received by the exporter and has a specified use-value dependent on the country income classification

- The emissions embodied in the imported products are weighted inversely to how useful[1] the trade is for each partner and split between them for each aggregate trade

This yields a weight that can be used to apportion emissions embodied in every individual bilateral trade. The explicit mathematical form is derived in section 2.3, after establishing quantifiable definitions for the use-value of income (section 2.2.1) and products (section 2.2.2).

2.2.1 Quantifying the use-value of income

Here I derive the functional form of the use-value curve for money from an empirical basis. I define the use-value of income as the increase in human welfare derived from a unit increase in income.

$$u_{income} = \frac{\Delta welfare}{\Delta income} \tag{2.1}$$

The functional form of the use-value of income (or wealth) can be rooted in observation. The recent advent of human welfare indices has made the study of the efficacy of wealth on human welfare possible. The most robust human welfare index is arguably the Social Progress Index (SPI) as proposed by the Social Progress Imperative[40]. To my knowledge it is unbeknown to these authors that through their enquiry into how well wealth translates into welfare, they have discovered an empirical relationship for the macroeconomic marginal use-value of money, in other words, the relation of human welfare to wealth. Here, I define the slope of this function — the change in human welfare for a unit change in wealth — the use-value of income[2], where SPI serves as a proxy for welfare and Gross National Income (GNI) per capita a proxy for wealth.

[1] "Need" here is substituted with usefulness. I assert that they are related in the sense that if one needs something more, it is more useful to them, and how useful it is can be characterised by its use-value.

[2] Use-value in this sense is an absolute measure while the relation itself (welfare versus income) is marginal use-value.

The Social Progress Index (SPI) is an index measuring social welfare of nations that incorporates metrics of welfare such as quality of education, crime rates, mortality and morbidity rates. More information on SPI can be found at their website: www.socialprogressimperative.org/.

The justification for SPI being the appropriate welfare index is twofold. Primarily, the criteria for selecting any welfare index to study the correlative effects of welfare and wealth is to pick a metric for welfare that is independent of wealth, i.e. a metric that does not have wealth (GDP or GNI per capita) as one of its input determinants of welfare. Unlike the Human Development Index (HDI), which is a much older welfare index that includes GDP/capita as one of the variables to assess welfare or development, SPI does not include wealth as an independent variable and therefore will not immediately auto-correlate with metrics of wealth.

Figure 2.1 shows a scatter plot of countries' SPI vs GNI/capita broken into four income classifications as defined by the World Bank. There is a strong correlation when fitted with a logarithmic function, with an R-squared value of 0.78. This relation shows a diminishing macroeconomic marginal use-value for income, i.e. as income increases, marginally less welfare is gained for an additional unit increase in income.

Figure 2.2 shows the linearised version of figure 2.1. The fit has a p-value of less than 2×10^{-16}, an R^2-value of 0.83, and a functional form of

$$SPI = 8.7ln(GNI/cap) - 11.3 \tag{2.2}$$

Equation 2.2 can be differentiated with respect to GNI/capita to obtain

$$u_{income} = \frac{d(SPI)}{d(GNI/cap)} = \frac{8.7}{GNI/cap} \tag{2.3}$$

Equation 2.3 shows that use-value of income for a given income per capita value is inversely proportional to income per capita.

These relationships can be interpreted as the mean marginal and absolute use-values of wealth for an inhabitant of a country with a given GNI per capita. The next assertion is as follows:

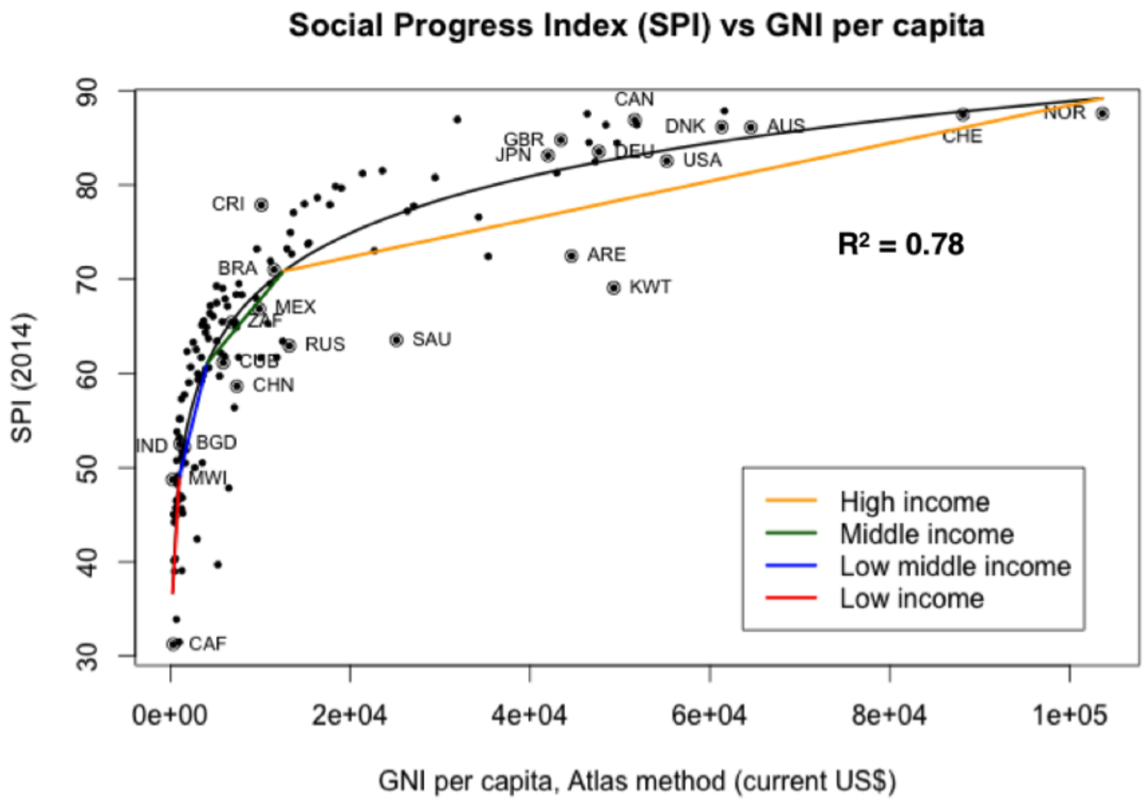

FIGURE 2.1: **Social Progress Index (SPI) versus Gross National Income (GNI) per capita in US dollars using the World Bank Atlas method (2014).** Country codes are as follows: CAF: Central African Republic, MWI: Malawi, IND: India, BGD: Bangladesh, CHN: China, CUB: Cuba, RUS: Russia, ZAF: South Africa, MEX: Mexico, BRA: Brazil, CRI: Costa Rica, SAU: Saudi Arabia, JPN: Japan, GBR: Great Britain, ARE: United Arab Emirates, KWT: Kuwait, DEU: Germany, CAN: Canada, USA: United States of America, DNK: Denmark, AUS: Australia, CHE: Switzerland, NOR: Norway.

the average individual inhabiting a country of a given GNI per capita will have a use-value for income that abides by this average trend.[3]

An incremental increase in welfare for those living in relatively wealthier countries than poorer ones will have a relatively smaller return for a unit increase in wealth. In other words, a unit increase wealth for someone with very little wealth will yield a much higher increase in welfare (using SPI as a proxy for welfare) compared to someone who has much higher wealth. This incremental increase, the change in welfare for a given change in wealth, i.e. the derivative of the

[3]This is a necessary approximation when studying countries as aggregate populations — the depth of this study does not allow for intranational analyses. See Chancel and Piketty for an in-depth report on the relationship between wealth distribution and emissions using intranational data[41].

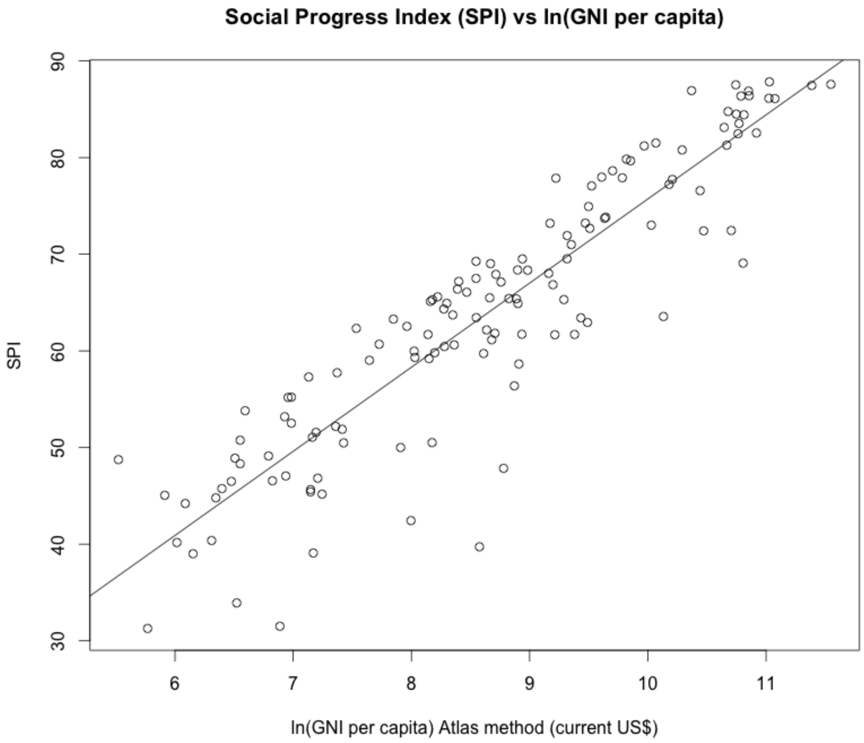

FIGURE 2.2: **Social Progress Index (SPI) versus natural logarithm of Gross National Income (GNI) per capita in US dollars using the World Bank Atlas method (2014).**

relationship depicted in figure 2.1, represents the absolute use-value of income for a person living in a country with a given GNI per capita. By a first order approximation, this relationship will serve as a measure for defining the use-value of income for a given country of a given income level. Income levels are taken from the World Bank definition for country classifications by income level.

In order to obtain a sensible range of values for the absolute use-value of income, countries of the same World Bank classification share the same use-value, derived from taking the mean slope of the income interval for each country classification (equivalent to the slope of the secant between the endpoints of each interval, shown in figure 2.1). Values are then scaled proportionally to fit on a scale where the maximum value is set to 100 units. Units for use-value are denoted *uval*, analogous to the hypothetical unit for classical utility *util*.

Country classifications can be found in table A.1 in appendix A. It should be noted that there are no low-income countries in the data set used in this study since low-income countries have all been aggregated into Rest of World (RoW) regions that when the weighted mean of income is computed, the RoW regions have a minimum mean income equivalent to that of a low-middle income country[4].

Table 2.1 shows the most recent World Bank country classifications by income and corresponding scaled use-values as derived in this section.

Use-value of income		
Country classification	Income [GNI/cap]	Use-value [$uval$]
Low	$1,025 or less	100
Low-middle	$1,026 - $4,035	25
Middle	$4,036 - $12,475	7
High	$12,476 or more	1

TABLE 2.1: Use-value of income for World Bank country classifications

[4]RoW income classifications are obtained by taking the population weighted mean of income for all countries included in the RoW region(maybe include this in previous section on use-value of income). Therefore, the data now only includes countries and regions of three income classifications: low-middle, middle, and high income.

2.2.2 Defining and quantifying use-values of products

Use-value (or functional value) can be defined in a Marxian sense as the value of a commodity in use to human beings. This value is a measure of the usefulness, in a functional sense to humans, which is inherent to the commodity, irrespective of preference and pleasure derived from the consumption of the commodity; this is therefore a different definition from that of utility as defined in classical economics (in a Benthamite or utilitarian sense) where utility is a measure of individual subjective consumption preferences. This inherent value should not be confused with intrinsic value. Intrinsic value can be said to be the value inherent in something regardless of its usefulness to humans. For example, animals have intrinsic value in the sense that they are living beings that have value in their own right of existence and certain animals are also perceived to have use-value to humans as food. Commodities, by definition are goods and services, usually fungible, for human consumption, and so do not necessarily have any value outside of their use-value for humans.

Here I use the term commodities to refer generally to all goods and services in the global economy. In practice, this study examines commodities as products to be bought and sold within and between countries[5]. From here on I will refer to the use-value of products as they are designated in the database used, however the terms products and commodities may be used interchangeably, commodities being a more general term for products.

The marginal use-value of income for countries of different income classifications (as by World Bank definition) has been defined and quantified above in section 2.2.1. Here I define the marginal use-value of products by calibration with that of income. More precisely, I attempt to define the use-value of products purchased with income of the average person living in a country of a given income classification. The products purchased by these people may have varying inherent use-values belonging to different categories of products, which I will define momentarily. In order to isolate the use-values of each product, I examine what kind of products are purchased with marginal income for individuals at each income level and map this income onto products purchased with said income.

[5]EXIOBASE has two classification schemes: by sector or by products, here it is more practical to examine trade as defined by products and so the product-by-product (pxp) table design is employed.

Use-value of products in this sense is therefore a measure of equivalent use-value to income rather than a direct measure of welfare derived from the consumption of a given product. An intuitive definition is the welfare gained through purchasing of a given product.

Here I have chosen to break up products into three categories that can be seen as simple intuitive classifications. Firstly, and most fundamentally, I define subsistence products. By defining subsistence products, I have implicitly defined the complement of the set — not subsistence products. I feel that this distinction (only having a two category classification system) is overly simplistic and insufficient to capture the nuances of the product hierarchy. I therefore seek to further distinguish between products that belong to the set of "not subsistence products" and split them further into two categories.

Emissions generated from the production and consumption of any of these categories are said to be embodied in the products themselves and can be categorised by the same distinction, i.e. emissions embodied in subsistence products are defined as subsistence emissions, and so on.

2.2.2.1 Defining the categories of products

As mentioned above, commodities are split into three categories. Before describing the three category classification system, consider the most obvious and robust division — "subsistence goods" and "not subsistence goods", where subsistence goods contain all necessities for physical well-being, like that of Maslow's description of basic physical needs pertaining to food, shelter, and clothing. Anything that is arguably in excess of what is needed to satisfy these basic physical requirements can be deemed not a subsistence good. Without making any great claims about cultural plurality and special individual considerations like extra needs for those with disabilities for example, it is fairly intuitive that this division is well-founded and I provide no additional justification for it here. Taking this very simplified division as a starting point provides a viable foundation for defining subsistence and non-subsistence on a commodity-by-commodity basis. If one is in agreement with this initial division, another division may be attempted — the subdivision of "non subsistence" commodities into "luxury" and "non-subsistence but non-luxury" commodities. The former represents goods and services that are clearly luxuries, that may satisfy subjective needs for self-actualisation, for example buying diamonds to assert one's wealth status. Something that is neither a luxury nor subsistence good falls into this more flexible latter category. It is not important to distinguish any further since I have no intention in this thesis to make claims regarding preferences and cultural or other more detailed considerations regarding use-value of commodities. As I argue in my underlying theory, the theoretical basis that allows the agreement on these three broad categories is sufficiently robust for use in a metric such as this. Further studies may delve deeper into arguments of finer categorical distinctions and will be discussed in the discussions section (including marginal use-value for goods as a function of goods per capita being the next refinement to the metric). Examples of commodities that are neither subsistence nor luxuries may include cars, poultry, etc.

Appendix A contains the table with the 200-product breakdown used and each of their use-value categories. Given that very few of the products available are unarguably luxuries, I erred on the conservative side, placing many that may be argued to be luxuries into the central — not subsistence, nor luxury — category.

2.2.2.2 Mapping use-value of income on products

As alluded to above, it is possible to derive a relationship between income and products. This relationship can be thought of as a functional mapping. This enables the derivation and calibration of the use-value of products starting from the empirical quantification of the use-value of income.

It is appropriate at this point to invoke Marx's description of commodities and the connection between their use-value and exchange-value:

"We have seen that when commodities are in the relation of exchange, their exchange-value manifests itself as something totally independent of their use-value. But if we abstract from their use-value, there remains their value, as has just been defined. The common factor in the exchange relation, or in the exchange-value of the commodity, is therefore its value."[42]

Marx recognises that the use-value, which is an inherent value of a commodity representative of its usefulness to humans, is distinct from its exchange-value, the value at which it is exchanged at, conventionally in modern society expressed by the price of a commodity when bought or sold. The "common factor" between exchange-value and use-value of a commodity, as he says, is something independent of both — the commodity's "value". Marx's definition of value is based predominantly on labour input. The specifics of how this inherent value of a commodity is defined are unimportant here. All that matters is that there exists some value that is common and bridges the use-value and exchange-value of a given commodity, the internal workings of it aside, all one has to accept is that such a conceptual characteristically trait of a commodity undoubtedly exists.

Here I argue that this inherent value can be used to calibrate the cardinal scale of use-value of a commodity and its exchange-value when purchased as a marginal product by an individual of a given income level.

The mapping is defined as follows: *marginal income is spent on marginal products*; therefore there is a functional mapping onto marginal goods for each income classification.

Now consider the following assertion that there is a mapping from each of the three income classifications onto each of the product designations/classifications as follows:

1. Low-income (or in this case, the lowest income being low-middle income) individuals (and likewise the average person in an aggregate body of individuals), must purchase "low-income products" so to speak. That means that people of low income generally have not met their subsistence needs and their marginal income is still being used to purchase subsistence products since they have not yet satisfied their need for them. I assert that it follows — owing to the mapping — that subsistence products share the same use-value as subsistence income, i.e. the marginal income of low-income individuals.

2. Middle-income individuals have met their subsistence needs and have the ability to buy products accessible to them but not low income individuals, that is to say they can buy "middle-income products", and these products are their marginal products. It may not be immediately clear whether these products map onto the middle category but for the moment, we accept this approximation.

3. High-income individuals have met their subsistence needs, have access to middle income products, and also have access to products only afforded to high income individuals "high-income products" these products are their marginal products, and since they are only

available to high income individuals (and not to individuals of income any lower than high income). I find this to be a satisfactory definition of luxury products. I map their income and associated use-values of their marginal income onto this set of products, and hence luxury products share the same use-value of that of high income marginal wealth.

Another way of thinking about the above distinction is as follows. The two extreme product classifications can be said to be subsistence and luxury products. These categories are associated with the two extreme income classifications: low (or in the case of this study, low-middle) and high income countries and regions. That which belongs in a grey area that is neither subsistence nor luxury goods falls into a category somewhere between these two extremes. It is more obvious that the extreme income classifications map neatly onto the extreme product classifications, however less clear if a precise mapping exists between the use-value of middle-income individuals and products that belong to neither extreme. From this point onwards products that do not belong to subsistence or to luxury categories will be referred to as "Non-Subsistence/Non-Luxury" (NS/NL) products[6].

2.2.2.3 Sensitivity analysis

Since there is some ambiguity regarding the mapping from middle-income use-value onto NS/NL products, sensitivity analysis should be performed by testing the resulting effect of shifting the use-value of NS/NL products over a range of values. The precise distribution and range of these values can be explored later on and this presently is left for future research. I would propose a random sampling using Monte Carlo analysis to test whether the metric outcome is sensitive to changes in the NS/NL use-value.

2.2.2.4 Classification of products into the three defined subsets

The matter remains of classifying each product used in the (EXIOBASE v2.2.2, product-by-product (pxp) format) MRIO database.

[6]The mapping does not make any assertions regarding quantity of each category of products consumed by individuals at different income levels. That is to say for example that high-income individuals may consume larger amounts of subsistence goods relative to a low-income individual in addition to consuming products inaccessible to low-come individuals. I expect that the amount of subsistence goods consumed by high-income individuals plateaus, increasing marginally less for increases in income, and therefore is not proportional to income.

Use-value of products		
Product classification	Income calibration	Use-value [*uval*]
Subsistence	Low-middle	25
NS/NL	Middle	7
Luxury	High	1

Table 2.2: Use-value of products for study product classifications

As a starting point, I invoked Maslow's hierarchy of needs[36] to help build a corresponding hierarchy of emissions associated with each level of needs.

In Maslow's hierarchy of needs or Brockett's hierarchy of human rights[37]: air, water, food, shelter, and sleep are to be found to be foundational since they are all of paramount importance to human existence; needs that without being met, no other fulfilment would be of any use. These foundational needs are fundamental and universal human requirements for sustained life. Cultural considerations hence only enter further up the hierarchy, the next positions held by requirements for safety, then the gratifications of love, esteem, and self-actualisation. Since not all these elements are tangible and commodifiable, Maslow's hierarchy is not totally analogous to the hierarchy of emissions I intended to create, which requires all its elements be physical commodities traded in the global economy with emissions associated with their production.

Maslow's description is therefore most useful for classifying subsistence products. It is fairly intuitive to apply what he calls primary physical needs as being fulfilled by the most essential subsistence products. These material needs are food, shelter, and clothing. Commodities purchased and traded in the global marketplace must be ranked according to their place in the hierarchy of needs. The challenge here is to find products in the database classification that correspond to components of goods and services that satisfy these needs and rank them accordingly. The following process should be considered *ad hoc* and open to further refinement. My classifications for this thesis are a first attempt and should be considered a starting point for further enquiry into this matter, as just the classification of goods and services into subsistence and other categories is a massive undertaking in itself.

Methodologically, I examined each product in the database individually and asked the following questions:

- Does this product satisfy a subsistence need?

- Does this product satisfy subsistence needs but in a way that is not in excess of another product that can satisfy the same need with less material or energy input or with less ecological or social burden? (e.g. Purchasing meat or processed food items when these nutritional needs can be met by simpler and less ecologically burdensome foods. Processed foods and meat would be considered non-essential, or non-subsistence food items and would therefore be classified as NS/NL or luxury products)
- What is the lowest income level individual able to reasonably afford this product?
- If this product is a raw material or intermediate product not designated for final consumption, what is its end use and what category of product would that be? When in doubt, side with the most conservative estimate (i.e. the closest category to subsistence). Then ask the previous questions again to which category it fall into.

The result of my classification is a hierarchy of products analogous to a simplified version of Maslow's hierarchy of needs. In practice this is a list of products, each classified as one of the three product categories defined above. This yields three sets of products and all their economic and environmental information. Using MRIO data, one can find how much of each country's economy is composed of each category of product and likewise how much emissions are generated by the production and consumption of each set of products within each country.

Here are a few examples of some classifications of certain commodities:

- Wheat: unprocessed staple food, therefore subsistence good
- Coal: energy for the majority of the global population; definitely not a luxury, but is coal entirely a subsistence good? Can the poorest afford energy derived from coal? At the moment, coal and other fuels for industrial electricity production are considered NS/NL products.
- Processed food or meat: non-subsistence food since nutritional needs can be satisfied by subsistence food with less environmental burden, can be purchased by individuals with middle or high incomes, arguably either NS/NL or luxury products depending on specific food. One may be tempted to make the argument that red meat is unambiguously a luxury

food (or an even more dramatic example being caviar) since it has a high environmental burden and many nutritional substitutes.

- Jet fuel, diamonds: only available to the wealthiest people, only purchased or used when all other needs are satisfied and are never indispensable or required to live a healthy life and are therefore categorised as luxuries.

In future research, it would be much more helpful to have a product breakdown by consumer-level goods rather than industrial outputs, which makes it very hard to determine what the end-use of many products are. For example it is unclear whether an ounce of pig iron is destined to become steel in the girder of rent-controlled apartments or the chassis of a luxury car. In this regard, since one is unable to differentiate, all pig iron must be considered the lowest common category — subsistence product.

2.2.2.5 Possible alternative methods to quantify subsistence and luxury emissions

Quantification of subsistence and luxury emissions that may result in similar results and could be used to test the results derived within this study could be derived from the distribution of intranational wealth and associated emissions as defined by the Greenhouse Development Rights (GDR) framework[7]. An alternative definition of subsistence emissions could be derived through the categorisation of all emissions generated in subsistence activities — consumption of subsistence goods and services of people living below the development threshold. The development threshold as defined by GDR is set at $7500 (PPP-adjusted)[44]. This quantification of subsistence emissions could be achieved most simply and readily by taking the complement of "Responsibility" emissions — the amount of emissions generated by those above the development threshold, which are used to quantify historic emissions that can be counted towards responsibility for climate change in the GDR framework. This is beyond the scope of this study and is left for future research.

One expected discrepancy between the method used in this study and this proposed alternative is that by including all commodities deemed to be necessary for subsistence in the calculation

[7]See technical report by Kemp-Benedict for a mathematical description of the GDR quantification of emissions "Responsibility" and financial "Capacity"[43]

of subsistence emissions, one includes basic consumption of those with wealth exceeding the development threshold, while when working backwards from only including that consumed by those living at or below the threshold, one exempts all basic consumption by those above the threshold. In other words, this means that subsistence emissions as defined by GDR only includes emissions coupled to activity by individuals living below the development threshold while this study's method of subsistence emissions will be greater as it includes emissions associated with subsistence activities from the entire population regardless of income. The reasoning used in GDR for only including emissions tied to wealth within the development regime is that only historical emissions generated in excess of providing for basic needs should be counted towards historic contributions to warming while wealth in excess of subsistence wealth should be included in a measure of financial capability for dealing with mitigation and adaptation defined as "Capacity". Emissions in excess of those tied to wealth below the development threshold, summed from a specified base year to present, are defined as "Responsibility", providing an additional quantifiable definition for responsibility for climate change as discussed in section 1.2.7.1. "Responsibility" as defined by GDR can be interpreted as the complement of subsistence emissions.

Notice that in figure 2.3, the three product classifications share use-values with the three lowest use-values for income (which correspond to the highest income classifications: low-middle, middle, and high) since there were no low income countries included explicitly in the study (low incomes countries, once aggregated into RoW regions became part of low-middle income regions). Since income maps onto products purchased, the range of use-values for products must span the same range as for incomes. If this were not true, all exchanges where subsistence products were sold would bias weights toward producer responsibility since consumers would have use-value of products associated with the exchange always much greater than the income level of the country receiving money in the transaction.

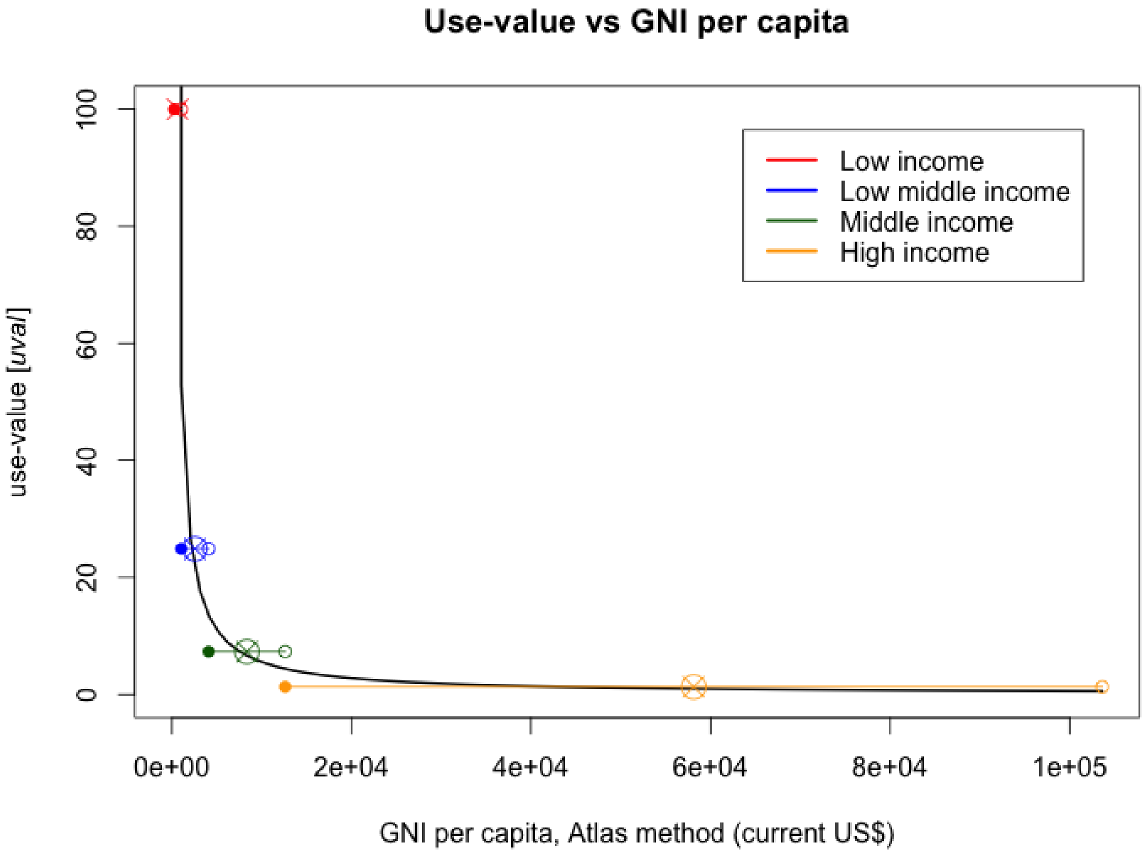

FIGURE 2.3: **Use-value of money and products for four income classifications and three product classifications.** Maximum use-value is set to 100 *uval* and relative values are scaled proportionally to the mean slope for each income classification from the curve fit in figure 2.1. use-value of income and products are shown as cross and circular markers respectively. Both are derived from the mean use-value for income classifications, depicted as the step function overlaid on the continuous inverse function. Step length depicts the interval of the income classification. use-values of products share values with the top three income classifications since income maps onto products purchased with said income and there are no low-income countries in the data set utilised.

2.2.3 Examples of transactions and the outcomes of emissions shared

Here are examples of transactions, only described qualitatively for the moment:

Example 1: USA (country i) buys diamonds from Côte d'Ivoire[8] (j). Côte d'Ivoire is very poor and desperately needs the income for subsistence, that income having very high use-value for them, while the diamonds are arguably much less essential for the livelihood of Americans purchasing them. USA should therefore take the brunt of the responsibility for the environmental impacts of the consumption and therefore the emissions linked with the diamond mining and processing.

Example 2: USA buys wheat from Canada. Wheat is a subsistence good since it is an unprocessed subsistence food while Canada is a high income country. USA therefore is assigned a relatively smaller amount of emissions embodied in the wheat purchased.

Example 3: USA buys televisions from China. Televisions are most definitely not a subsistence good since they do not satisfy basic physical requirements however they are not inaccessible enough to be deemed luxuries and being quite ubiquitous in any low-middle to middle income family, are classified as non-subsistence/non-luxury items. China receives money in exchange for their televisions and is a middle-income country. Since the use-value of the item and the money exchanged for both parties is roughly equivalent, they must share the embodied emissions approximately equally.

There is a caveat worth noting here: just because countries are the actors making these transactions and their citizens the consumers of the products being traded, money received as income does not necessarily go into the public purse. This of course depends on taxation. For instance in the first example, most revenue from sales of diamonds may even go to a Canadian multinational rather than the government and people of Côte d'Ivoire. The most egregious case of a failure to capture the profit dynamic would be if the company extracting labour or resources is from the same country buying the products, while operating in a country with little or no corporate tax.

[8] In the study, Côte d'Ivoire belongs to RoW Africa

2.3 Quantifying the weighting metric

As stated in section 2.2, the intention is to design a weighting metric that partitions EET inversely to a country's need to engage in a given trade. This is most simply quantified by using an inverse weighted sum where the sum of the reciprocal of use-values are normalised.

Shares for imported and exported emissions are denoted by W_{imp} and W_{exp}. Superscript notation denotes which countries are engaging in trade and the direction of that which is being traded. For imports, ij represents an import to i from j, and for exports the same order represents an export from i to j. In other words, the i^{th} country is the focal actor, i.e. the importer or exporter in any given import or export respectively, while the j^{th} country is the trading partner and fulfils the opposite role (exporter and importer, respectively).

The general form of trade interactions and associated weighting calculation for countries ij are as follows:

$$W_{imp}^{ij} = \frac{(u_{prod}^{j})^{-1}}{(u_{prod}^{j})^{-1} + (u_{inc}^{j})^{-1}} = \frac{(u_{prod}^{j})^{-1}}{(u_{prod}^{j})^{-1} + (u_{inc}^{j})^{-1}} \times \frac{u_{prod}^{j} u_{inc}^{j}}{u_{prod}^{j} u_{inc}^{j}} = \frac{u_{inc}^{j}}{u_{prod}^{j} + u_{inc}^{j}} \tag{2.4}$$

$$W_{exp}^{ij} = \frac{(u_{inc}^{i})^{-1}}{(u_{prod}^{i})^{-1} + (u_{inc}^{i})^{-1}} = \frac{(u_{inc}^{i})^{-1}}{(u_{prod}^{i})^{-1} + (u_{inc}^{i})^{-1}} \times \frac{u_{prod}^{i} u_{inc}^{i}}{u_{prod}^{i} u_{inc}^{i}} = \frac{u_{prod}^{i}}{u_{prod}^{i} + u_{inc}^{i}} \tag{2.5}$$

where u_{prod} and u_{inc} are the use-values for products and incomes respectively

Notice that in an import transaction between countries i and j, i receives products from j and j receives income from i. Since both the products and the income come from and are received by the same country (j), only use-values from j are required to compute weights. In exports, the reverse is true — only i's use-values are needed since i sell the products and receives the income.

Weighted shares of import or export emissions are calculated by multiplying the EET in a particular trade with its associated weight value.

Now we are prepared to calculate weights and can illustrate the outcome of the previous example in 2.2.3.

Example 1: USA receives diamonds $\rightarrow$ luxury product $\rightarrow$ $u_{product} = 1$ *uval*

RoW Africa receives income $\rightarrow$ low-middle income region $\rightarrow$ $u_{income} = 25$ *uval*

$\therefore \qquad W_{USA} = \frac{25}{25+1} = \frac{25}{26} = 0.96 \qquad \& \qquad W_{RoWAfrica} = \frac{1}{26} = 0.04$

Example 2: USA receives wheat $\rightarrow$ subsistence product $\rightarrow$ $u_{product} = 25$ *uval*

Canada receives income $\rightarrow$ high-income country $\rightarrow$ $u_{income} = 1$ *uval*

$\therefore \qquad W_{USA} = \frac{1}{25+1} = \frac{1}{26} = 0.04 \qquad \& \qquad W_{Canada} = \frac{25}{26} = 0.96$

Example 3: USA receives televisions $\rightarrow$ NS/NL product $\rightarrow$ $u_{product} = 7$ *uval*

China receives income $\rightarrow$ middle-income country $\rightarrow$ $u_{income} = 7$ *uval*

$\therefore \qquad W_{USA} = W_{China} = \frac{7}{14} = 0.5$

Other possible weight combinations include $\frac{1}{8}, \frac{7}{8}$ and $\frac{7}{32}, \frac{25}{32}$.

Therefore the possible weight values range from $\frac{1}{26} = 0.04$ to $\frac{25}{26} = 0.96$.

2.4 Theoretical framework: Sharing EET between countries

Figure 2.4 shows a simple arbitrary bilateral trade between country 1 (C^1) and two other countries (country 2 and 3; C^2 and C^3). The country that is at the centre of a trade is denoted the focal country and the others engaging in trade are the trading countries. Focal countries occupy the i^{th} (first superscript) position in the notation while traders occupy the j^{th} (second superscript) position.

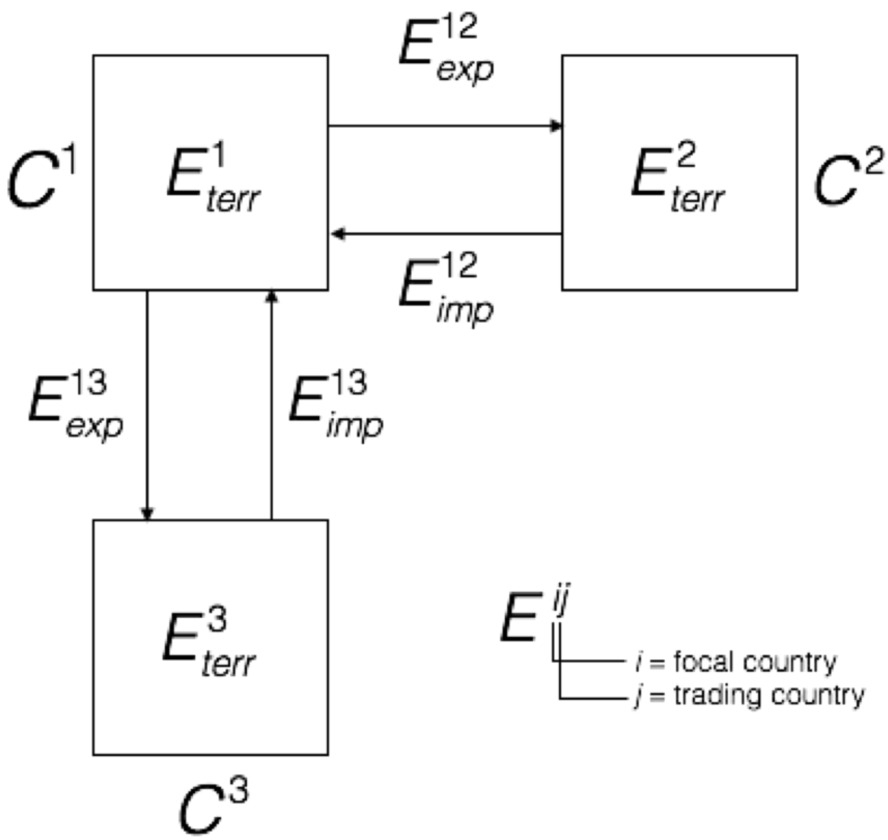

FIGURE 2.4: **Three country world with one country engaging in bilateral trade with others.** C denotes country and E denotes emissions. Territorial (terr) emissions are intrinsic to each country — comprising of emissions generated within a country's borderss — and trade flows are only shown with country 1 (C^1) trading with others from its point of view.

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The following section shows a worked arbitrary two-country (bilateral trade) for a single sector (for an aggregate transaction of one year) case to illustrate the simplest scenario. After showing the weighting method for a bilateral transaction, the method will be generalised for a world with n countries and m sectors.

2.4.1 Bilateral trade

To begin, only the bilateral interactions between countries 1 and 2 are examined. For the C^{12} interaction: C^1 imports E^{12}_{imp} emissions in goods or services (from now on, only goods will be mentioned for brevity) from C^2, i.e. C^1 receives goods and C^2 receives money. Hence the weight is as follows:

$$W^{12}_{imp} = \frac{(u^2_g)^{-1}}{(u^2_g)^{-1} + (u^2_m)^{-1}} = \frac{u^2_m}{u^2_g + u^2_m} \tag{2.6}$$

where u^2_g and u^2_m denote the use-values of goods coming from C^2 and money being received by C^2 respectively.

Note that both indices for the use-values are for country 2. Although country 1 receives the goods, they originate from country 2 and likewise are determined by country 2's output.

When reading the MRIO table, output comes from row entries and flows into column entries. In practice, one must look up the use-values for money and goods from the same country, which simplifies the construction of the weighting matrix greatly (see section 2.6 below).

The other flow from the perspective of C^1 is its exports to C^2. C^1 receives money and C^2 receives goods from C^1. Hence the weight is calculated as follows:

$$W^{12}_{exp} = \frac{(u^1_m)^{-1}}{(u^1_g)^{-1} + (u^1_m)^{-1}} = \frac{u^1_g}{u^1_g + u^1_m} \tag{2.7}$$

Similarly to W^{12}_{imp} shown in equation 2.6, only use-values from the country of origin of goods is needed since they it is their goods that are transacted and are also on the receiving end of the money being exchanged.

Also, every bilateral trade has two arbitrary points of view that are equivalent. Figure 2.5 shows imports and exports between two countries from both countries' points of view.

Before incorporating weights into the manipulation of EET, let us review the two country world case for computing CBA emissions. Generally, CBA emissions (i.e. a consumption-based account of emissions, also referred to as footprint emissions), are obtained by adding

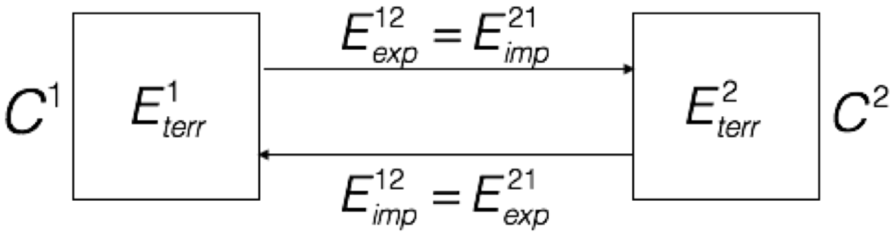

FIGURE 2.5: **A closer look at bilateral trades.** C denotes country and E denotes emissions. Territorial (terr) emissions are intrinsic to each country and trade flows are only shown with country 1 (C^1) trading with country 2 (C^2) and vice versa.

emissions embodied in imports and subtracting emissions embodied in exports from a country's territorial emissions. CBA emissions represent the total emissions embodied in all goods and services consumed by the population of a country. The difference of emissions embodied in imports E_{imp} and emissions embodied in exports E_{exp} is known as the trade balance $\Delta EET = E_{imp} - E_{exp}$. If it is negative (i.e. $E_{imp} < E_{exp}$), a country is a net exporter, and when positive (i.e. $E_{imp} > E_{exp}$), a net importer.

$$E^1_{CBA} = E^1_{terr} + E^{12}_{imp} - E^{12}_{exp} = E^1_{terr} + E^{21}_{exp} - E^{21}_{imp} \tag{2.8}$$

$$E^2_{CBA} = E^2_{terr} + E^{21}_{imp} - E^{21}_{exp} = E^2_{terr} + E^{12}_{exp} - E^{12}_{imp} \tag{2.9}$$

Additivity is preserved and can be shown by adding the first relation in equation 2.8 with the second in equation 2.9:

$$E^1_{CBA} + E^2_{CBA} = E^1_{terr} + E^{12}_{imp} - E^{12}_{exp} + (E^2_{terr} + E^{12}_{exp} - E^{12}_{imp}) = E^1_{terr} + E^2_{terr} \quad \square \tag{2.10}$$

As for the weighting and its preservation of Additivity, let us examine the four weights for import and export emissions between each country:

$$W^{12}_{imp} = \frac{u^2_m}{u^2_g + u^2_m} \tag{2.11}$$

$$W^{12}_{exp} = \frac{u^1_g}{u^1_g + u^1_m} \tag{2.12}$$

$$W^{21}_{imp} = \frac{(u^1_g)^{-1}}{(u^1_g)^{-1} + (u^1_m)^{-1}} = \frac{u^1_m}{u^1_g + u^1_m} \tag{2.13}$$

$$W^{21}_{exp} = \frac{(u^2_m)^{-1}}{(u^2_g)^{-1} + (u^2_m)^{-1}} = \frac{u^2_g}{u^2_g + u^2_m} \tag{2.14}$$

By inspection, one can see that W^{12}_{imp} and W^{21}_{exp} are complementary (i.e. they are algebraic complements of each other — equation 2.11 and 2.14 sum to unity). Likewise, W^{12}_{exp} and W^{21}_{imp} are also complements, shown by adding 2.12 and 2.13.

$$W^{12}_{imp} + W^{21}_{exp} = 1 \therefore W^{12}_{imp} = \tilde{W}^{21}_{exp} \ \& \ \tilde{W}^{12}_{imp} = W^{21}_{exp} \tag{2.15}$$

$$W^{12}_{exp} + W^{21}_{imp} = 1 \therefore W^{12}_{exp} = \tilde{W}^{21}_{imp} \ \& \ \tilde{W}^{12}_{exp} = W^{21}_{imp} \tag{2.16}$$

where $\tilde{}$ denotes the complement

Now to apply these weights to a bilateral trade — firstly for export emissions:

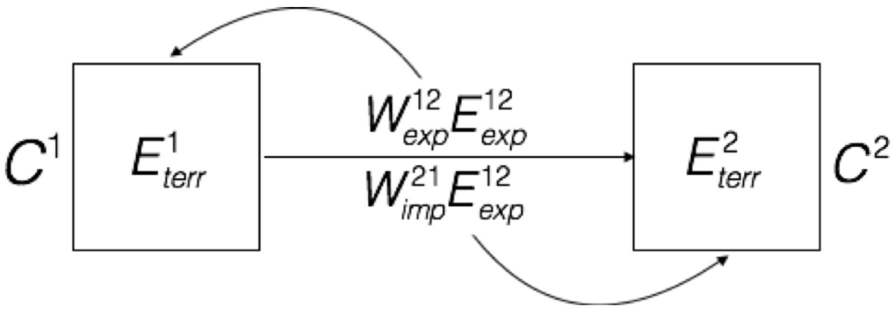

FIGURE 2.6: **Sharing emissions embodied in exports from C^1 to C^2.** C denotes country and E denotes emissions. Territorial (terr) emissions are intrinsic to each country and trade flows are only shown with country 1 (C^1) exporting to country 2 (C^2).

Let us show Additivity holds for the partitioning of C^1's export emissions, E^{12}_{exp}:

$$W^{12}_{exp}E^{12}_{exp} + W^{21}_{imp}E^{12}_{exp} = (W^{12}_{exp} + W^{21}_{imp})E^{12}_{exp} = 1 \times E^{12}_{exp} = E^{12}_{exp} \quad \square \tag{2.17}$$

Now for import emissions:

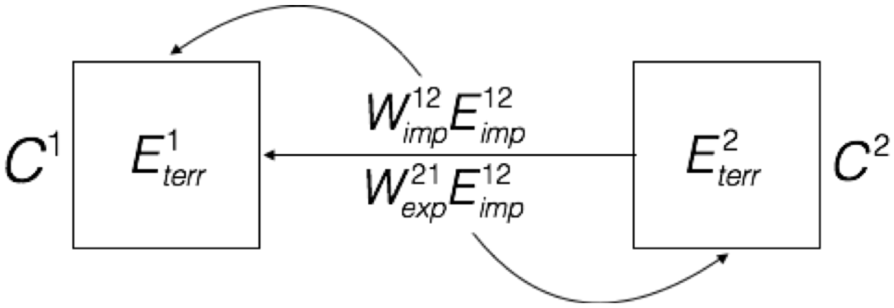

FIGURE 2.7: **Sharing emissions embodied in imports from $\mathbf{C^2}$ to $\mathbf{C^1}$.** C denotes country and E denotes emissions. Territorial (terr) emissions are intrinsic to each country and trade flows are only shown with country 1 (C^1) importing from country 2 (C^2).

$$W^{12}_{imp}E^{12}_{imp} + W^{21}_{exp}E^{12}_{imp} = (W^{12}_{imp} + W^{21}_{exp})E^{12}_{imp} = 1 \times E^{12}_{imp} = E^{12}_{imp} \quad \square \tag{2.18}$$

Now to derive a shared responsibility metric using weights of one's choosing. Equity-weighting will be used in this study however any Shared Responsibility-Based Accounting (SRBA) weighting metric can be applied to this arbitrary framework. SRBA emissions using the following weighting scheme is obtained in a similar way as with CBA, except with one modification — EET are weighted before being allocated and emissions embodied in imports and exports end up being partitioned between trading partners, i.e. the SRBA emissions for a country are obtained by adding the weighted import emissions and subtracting the complement of the weighted export emissions from its territorial emissions. The complement of export emissions are subtracted because the specified country *keeps* its weight of export emissions, while the remainder (i.e. the complement) is allocated to the importing country and hence removed from the exporter. This is illustrated in figure 2.6. Note that adding the weighted export emissions would result in double counting since they are already included in a country's territorial emissions. Therefore, subtracting the complement is instead the correct procedure.

For a two country world, the SRBA for C^1 will be as follows:

$$
\begin{aligned}
E^1_{SRBA} &= E^1_{terr} + W^{12}_{imp}E^{12}_{imp} - E^{12}_{exp} + W^{12}_{exp}E^{12}_{exp} \\
&= E^1_{terr} + W^{12}_{imp}E^{12}_{imp} - (1 - W^{12}_{exp})E^{12}_{exp} \\
&= E^1_{terr} + W^{12}_{imp}E^{12}_{imp} - (\tilde{W}^{12}_{exp})E^{12}_{exp} \\
&= E^1_{terr} + W^{12}_{imp}E^{12}_{imp} - (W^{21}_{imp})E^{12}_{exp}
\end{aligned}
\tag{2.19}
$$

and similarly for C^2:

$$
\begin{aligned}
E^2_{SRBA} &= E^2_{terr} + W^{21}_{imp}E^{21}_{imp} - E^{21}_{exp} + W^{21}_{exp}E^{21}_{exp} \\
&= E^2_{terr} + W^{21}_{imp}E^{21}_{imp} - (1 - W^{21}_{exp})E^{21}_{exp} \\
&= E^2_{terr} + W^{21}_{imp}E^{21}_{imp} - (\tilde{W}^{21}_{exp})E^{21}_{exp} \\
&= E^2_{terr} + W^{21}_{imp}E^{21}_{imp} - (W^{12}_{imp})E^{21}_{exp}
\end{aligned}
\tag{2.20}
$$

2.4.2 Extending theory to world with fixed finite number of countries and sectors

One can see that the case of trade between two countries is relatively straightforward. It requires little additional work to show that this base case can be extended to model the split allocation of EET for a world of any number of countries or regions. Each pair of countries or regions engages in bilateral trade amongst themselves and so the bilateral trade case holds true for all interactions when examining trade on an individual basis.

It is now necessary to introduce matrix notation to describe emissions flows of imports and exports, and their corresponding weighting values. Begin by considering matrices comprising either the flow of products, or their embodied emissions.

Notice that the information contained in the matrix containing all flows of import emissions is equivalent to that contained in the analogous export matrix (it is indeed important that they both be complete representations of global import or export flows). This should be fairly intuitive and has been illustrated for the two-country case. One only need to recall that one country's imports are another country's exports. Therefore the set of all imports must be the same as the set of all exports, with directions of low reversed. This is expressed in linear algebra with two matrices that are the transpose of one another.

By convention in MRIO analysis, commodities measured in physical quantities or their monetary value, or the corresponding environmental extensions (of inputs — e.g. water, or outputs — e.g. emissions), flow from the i^{th} (row index) country-sector pair, to the j^{th} (column index) country-sector pair. In other words, when wanting to know the total amount of inputs for a unit output of a given commodity (or unit output of a sector) manufactured in a given country, one sums down the column of the table who's index corresponds to the product (or sector) and country in question.

In the n country, m sector world, one must simply note that trades should not be double counted nor should trades within countries be weighted. The former is accomplished by using consistent convention for notation to organise imports and exports so that equivalent transactions are not double-counted. The latter is simply a matter of excluding operations with equal country indices. This is accomplished either by directly removing intranational trade for all sectors of each country or by weighting intranational transactions to zero during the weighting step[9] This will be discussed explicitly in greater detail in section 2.7.

In order to perform weights on all bilateral transactions simultaneously, a weighting matrix comprised of all the needed weights is required. Consider a matrix W_{imp} where the ij^{th} entry represents the weight for the import of good from the i^{th} country-product pair to the j^{th}. As illustrated above, only values that belong to the i^{th} country and sector (from the rows) are needed to calculate the weight for the import trade since goods originate from country i and money is destined for i as well. So it follows that imports to all sectors in each country (counting along the columns of the import matrix) of each product (or from each sector) from each country (counting along the rows), will populate a matrix that represents all the weights for all the imports between every pair of countries or regions in the world (excluding the block diagonal of course since it represents intranational flows).

[9]In practice, by setting the block diagonal of the transaction matrix or weighting matrix to zero

It follows that element-wise matrix multiplication of matrices containing appropriate weights and emissions will be a concise and sufficient means to perform calculations of emissions accounts for all countries simultaneously.

The explicit composition of the weighting, import and export emissions matrices will be discussed in chapter **??**.

Note that only the weighting matrix is required since like the relation between import and export matrices, both weighting matrices for imports and exports are directly related. This will be elaborated upon in section 2.6.

2.5 "Diagonalisation" and other manipulations in the context of this study

Before continuing, it is important to clarify the definitions of mathematical definitions for manipulations used in input-output computations that differ from conventional linear algebra though in instances share the same name or have ambiguous meaning unless contextualised and made explicit.

The ambiguous operations are as follows:

1. Diagonalise
2. Block-diagonalise
3. Element-wise

Firstly, notice that diagonalisation — or specifically, to "diagonalise" a vector — in this context differs from the conventional mathematical definition. Rather than taking a square matrix and performing an operation to yield another square matrix with only entries along the diagonal with equivalent information, here the term is used to describe taking a vector (dimension n) and placing each of its entries along the diagonal of a square ($n \times n$) matrix. Doing this allows matrix computation as needed in IO manipulations.

Lastly, $\boldsymbol{Z}\hat{\boldsymbol{x}}^{-1}$ is also known as the matrix of coefficients $\boldsymbol{A}$ whose elements represent the amount of input required from each i^{th} sector to produce one unit of output in the j^{th} sector. It is equivalent to dividing each column element-wise in the transaction matrix $\boldsymbol{Z}$ by the output vector $\vec{x}$. "Element-wise" refers to algebraic computations where corresponding entries of matrices (ij^{th} entries) of matrices, or in the case of a matrix and a vector as in the computation of A, each i^{th} entry in the j^{th} column in Z is divided by the i^{th} entry in $\vec{x}$, i.e. $A_{ij} = Z_{ij}/x_i$.

2.6 Constructing the weighting matrix

In order to construct the weighting matrices for imported and exported emissions, first consider the scenario for country i importing commodities from country j, depicted in figure 2.8. In this single bilateral trade, a particular good or service — the quantity of which is aggregated over a calendar year — is sold from j to i, and so i receives the good or service while j receives money in the aggregate transaction. The goods or services sold, imported into i, contains emissions of E^{ij}_{imp}, which is equivalent to the E^{ji}_{exp} for the same goods or services being conversely exported from j to i.

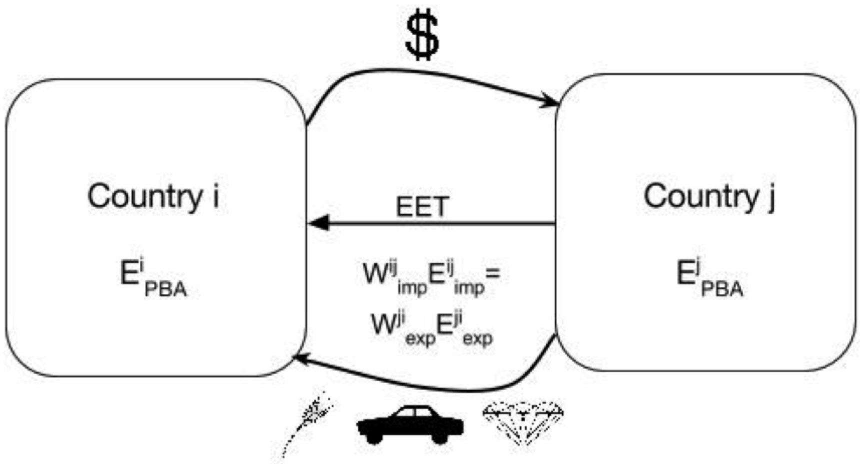

FIGURE 2.8: **Weighting Emissions Embodied in Trade (EET) between countries i and j.**

It follows that since emissions — being physical quantities — are conserved, that the emissions weight for imported emissions W^{ij}_{imp} and the emissions weighted to remain in the exporting country or export emissions from j to i, W^{ji}_{exp}, are complementary, i.e. they sum to unity. This must be true for every trade in order to preserve the Additivity of the metric, Additivity referring to the formalism in accounting showing conservation of physical quantities, in this case the mass of greenhouse gas emission. Additivity will be discussed in further detail in section 1.2.5.1.

Here the quantity W^{ij}_{imp} and W^{ji}_{exp} represent weights for individual aggregate annual transactions between two countries and sectors. Lower case may be used conventionally for entries in a matrix while upper case is used for the matrix itself but this convention is not used since i and j are not referring directly to entries but instead to the countries participating in the transaction. Each weight actually denotes whether goods are being imported or exported, going from country or region i to j, and from sector or product k to l. A more complete notation could be the following:

$$^{imp}W_{kl}^{ij} \quad and \quad ^{exp}W_{kl}^{ij} \tag{2.21}$$

However this is not employed here for the sake of brevity.

These quantities can be used as entries in a matrix that contains the weights for transactions between every country and sector ordered the same as the multiregional input-output table being used to calculate trade flows and associated environmental impacts.

One can infer certain conditions from the above arbitrary scenario depicted in figure 2.8:

$$W_{imp}^{ij} + W_{exp}^{ji} = 1 \quad \therefore \quad W_{imp}^{ij} = \tilde{W}_{exp}^{ji} \;\&\; \tilde{W}_{imp}^{ij} = W_{exp}^{ji} \tag{2.22}$$

$$\tilde{\boldsymbol{W}}_{exp} = \boldsymbol{J} - \boldsymbol{W}_{exp} = \boldsymbol{W}_{imp}^{\intercal} \quad \because \quad W_{imp}^{ij} = 1 - W_{exp}^{ji} \tag{2.23}$$

where:

$W_{imp/exp}^{ij}$ = weight for imports/exports of given product being imported to/exported from i from/to j

$\boldsymbol{W}_{imp/exp}$ = matrix of weights for each aggregate annual transaction between each country and sector

i, j denote row and column — and corresponding country and sector or product pair — of the weighting matrix $\boldsymbol{W}$

$\tilde{}$ denotes the complement

$^{\intercal}$ denotes the transpose

$\boldsymbol{J}$ is a square matrix of ones the dimension of $\boldsymbol{W}$

Equation 2.22 is simply an arbitrary version of equation 2.15 derived for a two country world. Equation 2.23 shows the relationship between W_{imp} and W_{exp}. where the transpose of W_{imp} is equivalent to the complement of W_{exp}. This provides an advantage to calculating weights and accounts as it simplifies the computations required by only needing to directly compute one of the weighting matrices.

2.6.1 Coding in python using open source script

It is worth bringing attention to the choice of programming language and coding resources used in this study.

Open source code, like the scientific computing code written in python3 used in this study, helps ensure equal access to information and resources, improves transparency and reproducibility, and helps to expedite research by through sharing tools broadly and freely amongst the scientific community. It is in this spirit that Konstantin Stadler of Norwegian University of Science and Technology in the Industrial Ecology Programme shares his code with whoever wishes to use it. The reader can find the source code online on GitHub at the following repository, the package called pymrio
(https://github.com/konstantinstadler/pymrio). During the process of learning and altering the pymrio, I was able to help debug and improve aspects of the program. A new release of pymrio was recently made available in part because of my contributions.

2.6.2 Constructing $\mathbf{W_{imp}}$

It was found that the most computationally efficient way to construct the weighting matrices was to first construct $\boldsymbol{W}_{imp}$ and use the relation found in equation 2.23 to determine $\tilde{\boldsymbol{W}}_{exp}$ (and $\boldsymbol{W}_{exp}$ however it is not needed in the calculations as can be seen from equations 2.36 and 2.37 below that apply weightings).

Rather than looping through each index and calling a dictionary to assign a use value for goods and money to populate the weighting matrix, it was found to be five orders of magnitude faster[10] to populate vectors for each use value, repeat them to span the dimensions of the weighting matrix, then perform element-wise multiplication between the use-value matrices to yield the weighting matrix.

[10] From 4.5 hours to 0.4 seconds

The use value vector for goods, using the numpy (np) python package for manipulation of large data arrays in an efficient manner, is calculated as follows:

```
u_product_vec = np.tile(product_values, len(income_db))
```

Where the tile function takes the 200 use values of each product in the product-by-product (pxp) version of EXIOBASE 2.2.2 and tiles them 48 times to yield a vector 9600 entries long.

$$\vec{u}_{prod} = \begin{bmatrix} u^1_{prod} \\ \vdots \\ u^{200}_{prod} \\ \vdots \\ u^1_{prod} \\ \vdots \\ u^{200}_{prod} \end{bmatrix} \tag{2.24}$$

For the use value vector for incomes:

```
u_income_vec = np.repeat(income_values, len(product_db))
```

Whereas the repeat function takes each income use value and repeats it 200 times to yield a row vector that has each 48 income use values repeated in place 200 times to form another vector 9600 entries long.

$$\vec{u}_{inc} = \begin{bmatrix} u_{inc}^{1} \\ \vdots \\ u_{inc}^{1} \\ \vdots \\ u_{inc}^{i} \\ \vdots \\ u_{inc}^{i} \\ \vdots \\ u_{inc}^{48} \\ \vdots \\ u_{inc}^{48} \end{bmatrix} \tag{2.25}$$

Operations above are element-wise. Algebraically, the code can be expressed as:

$$\vec{W}_{imp} = \vec{u}_{inc} \# (\vec{u}_{inc} + \vec{u}_{prod})^{-1} \tag{2.26}$$

Where # denotes element-wise multiplication. Each entry in $\vec{W}_{imp}$ can be written as:

$$W_{imp}^{ij} = \frac{u_{inc}^{j}}{u_{inc}^{j} + u_{prod}^{j}} \tag{2.27}$$

The final import matrix is the import weight vector $\vec{W}_{imp}$ repeated as a column vector 9600 times:

$$\begin{aligned} \boldsymbol{W_{imp}} = \begin{bmatrix} \vec{W}_{imp} & \cdots & \vec{W}_{imp} \end{bmatrix} &= \begin{pmatrix} w_{imp}^{1} & \cdots & w_{imp}^{1} \\ \vdots & \cdots & \vdots \\ w_{imp}^{9600} & \cdots & w_{imp}^{9600} \end{pmatrix} \\ &= \begin{pmatrix} w_{imp}^{1,1} & \cdots & w_{imp}^{1,9600} \\ \vdots & \ddots & \vdots \\ w_{imp}^{9600,1} & \cdots & w_{imp}^{9600,9600} \end{pmatrix} \end{aligned} \tag{2.28}$$

In order to perform the weighting, alterations were made to the diagonalised output matrix by weighting the individual entries. This was accomplished through element-wise multiplication of the weighting matrices and the block diagonalised output matrix $\hat{\boldsymbol{x}}$. The diagonalised output matrix is the dot product of the Leontief inverse L and the block-diagonalised final demand matrix $\hat{\boldsymbol{Y}}$.

$\hat{\boldsymbol{Y}}$ is created by block-diagonalising each country the aggregated final demand matrix $\boldsymbol{Y}_{agg}$ (9600 rows by 48 columns, each row representing the demand by each sector or for each product for each country or region along the columns) into 200-by-200 blocks (block size equal to the number of sectors or products).

$$\hat{\boldsymbol{Y}} = \begin{bmatrix} Y_{agg}^{1,1} & 0 & 0 & & Y_{agg}^{1,48} & 0 & 0 \\ 0 & \ddots & 0 & \cdots & 0 & \ddots & 0 \\ 0 & 0 & Y_{agg}^{200,1} & & 0 & 0 & Y_{agg}^{200,48} \\ & \vdots & & & & \vdots & \\ Y_{agg}^{9200,1} & 0 & 0 & & Y_{agg}^{9200,48} & 0 & 0 \\ 0 & \ddots & 0 & \cdots & 0 & \ddots & 0 \\ 0 & 0 & Y_{agg}^{9600,1} & & 0 & 0 & Y_{agg}^{9600,48} \end{bmatrix} \tag{2.29}$$

Where $\hat{\boldsymbol{Y}}_{ij}$ represents the final demand from country j for a product from the i^{th} country-product pair

The Leontief inverse $\boldsymbol{L}$ is computed for the traditional demand-driven Input-Output model:

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{Z}\hat{\boldsymbol{x}}^{-1})^{-1} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \tag{2.30}$$

$\boldsymbol{L}$ can be expressed as a Taylor expanded polynomial that converges to zero, i.e. it represents the contributions from each actor along a finite supply chain for the production of a single unit of a given product in a given country (again, where flows go from row to column entries).

$$\boldsymbol{L} = \boldsymbol{I} + \boldsymbol{A} + \boldsymbol{A}^2 + \boldsymbol{A}^3 + \dots \tag{2.31}$$

and the final output diagonalised matrix $\hat{\boldsymbol{x}}$ and vector $\vec{x}$ are then be computed as follows:

$$\hat{\boldsymbol{x}} = \boldsymbol{L} \times \hat{\boldsymbol{Y}} \tag{2.32}$$

Where $\hat{\boldsymbol{x}}_{ij}$ represents how many units of the i^{th} country-product pair are needed to satisfy final demand in the j^{th}

$$\vec{x} = \sum_{i} \hat{\boldsymbol{x}} \tag{2.33}$$

Which yields a column vector from the row sum of $\hat{\boldsymbol{x}}$ representing the total amount of the *ith* product used globally to satisfy demand for the *ith* product-country pair.

where:
$\times$ denotes matrix multiplication
$\hat{}$ denotes a diagonalised matrix version of the corresponding vector
$\boldsymbol{Z}$ is the inter-industry flow matrix representing all trade flows between countries and sectors or products
$\boldsymbol{I}$ is the identity matrix of same dimension as $\boldsymbol{Z}$
$\hat{\boldsymbol{x}}^{-1}$ is the matrix inverse of the block diagonalised output vector $\hat{\boldsymbol{x}}$

It should be noted that $\hat{\boldsymbol{x}}$ is used to compute the footprint (CBA) emissions, while the total output vector is $\vec{x}$ is required to compute territorial (PBA) emissions.

2.7 Calculating EET, weighted EET, and SRBA emissions

In order to calculate import and export emissions in isolation — needed for their own inspection as well as to calculate any form of SRBA emissions — a diagonalised output matrix that captures trade in isolation is required. This matrix, denoted $\hat{\boldsymbol{x}}_{trade}$, is obtained by removing (i.e. setting to zero) the block diagonal (derived in the same way as $\hat{\boldsymbol{Y}}$), which removes all intranational transactions since the block diagonal contains all intranational flows.

For import and export weighting, the diagonalised output trade matrix, $\hat{\boldsymbol{x}}_{trade}$, was multiplied element-wise by the $\boldsymbol{W_{imp}}$ and $\tilde{\boldsymbol{W}}_{exp}$ matrices respectively. These weighted trade output matrices where then used in the standard calculations to yield weighted import and export emissions used in SRBA calculations.

The accounts for territorial (PBA), footprint (CBA), any SRBA emissions, and an equal allocation account (EABA) where EET is split 50/50 between traders (denoted as half), are displayed below in equations 2.34 through 2.37. Note that equation 2.36 may be applied generally using any weighting scheme however here it is only used for the equity-weighting metric developed in this study.

$$\vec{E}_{PBA} = \vec{S} \# \vec{x} \tag{2.34}$$

$$\vec{E}_{CBA} = \vec{E}_{PBA} + \vec{E}_{imp} - \vec{E}_{exp} = \vec{S} \times \hat{\boldsymbol{x}} = \vec{S} \times (\boldsymbol{L} \times \hat{\boldsymbol{Y}}) \tag{2.35}$$

$$\vec{E}_{SRBA} = \vec{E}_{PBA} + \vec{E}^{w}_{imp} - \tilde{\vec{E}}^{w}_{exp} = \vec{E}_{PBA} + \vec{E}^{w}_{imp} - \vec{E}_{exp} + \vec{E}^{w}_{exp} \tag{2.36}$$

$$\vec{E}_{half} = \vec{E}_{PBA} + \frac{1}{2}\vec{E}_{imp} - \frac{1}{2}\vec{E}_{exp} = \frac{1}{2}(\vec{E}_{PBA} + \vec{E}_{CBA}) \tag{2.37}$$

The relation in equation 2.37 can be easily proven by expanding $\vec{E}_{CBA}$ using equation 2.35:

$$\begin{aligned} \vec{E}_{half} &= \frac{1}{2}(\vec{E}_{PBA} + \vec{E}_{CBA}) \\ &= \frac{1}{2}(2 \times \vec{E}_{PBA} + \vec{E}_{imp} - \vec{E}_{exp}) \\ &= \vec{E}_{PBA} + \frac{1}{2}\vec{E}_{imp} - \frac{1}{2}\vec{E}_{exp} \end{aligned} \tag{2.38}$$

The components used in equations 2.34 to 2.37 are shown in equations 2.39 to 2.42. These are the major alterations to the code in the pymrio package for its basic calculations that allows weighted accounting. In principle, this weighting step can be used to generate any shared responsibility based account (SRBA). The only aspect that is entirely specific to EWBA is the specific weighting matrix used and the framework it is derived from. Future studies could use similar methodology to generate their own weighting frameworks and metrics, and use the same matrix weighting procedure.

Note that in equation 2.36, SRBA emissions are derived by subtracting the complement of the weighted export emissions — not the weighted export emissions themselves. This is expanded in the second term of the equation, illustrating that the correct calculation starts from a consumption-based account for export emissions then adds back the weighted proportion for the specified country. To make calculations more efficient, only the complementary weighted emissions are calculated and the first term in the equation used to derive SRBA emissions.

$$\vec{E}_{imp} = \vec{S} \times \boldsymbol{\hat{x}}_{trade} \tag{2.39}$$

$$\vec{E}_{exp} = \vec{S} \# \vec{x}_{exp} = \vec{S} \# \sum_{j} \boldsymbol{\hat{x}}_{trade} \tag{2.40}$$

$$\vec{E}^{w}_{imp} = \vec{S} \times (\boldsymbol{W_{imp}} \# \boldsymbol{\hat{x}}_{trade}) \tag{2.41}$$

$$\vec{\tilde{E}}^{w}_{exp} = \vec{S} \# (\sum_{j} \boldsymbol{\tilde{W}_{exp}} \# \boldsymbol{\hat{x}}_{trade}) = \vec{S} \# (\sum_{i} \boldsymbol{W}^{\intercal}_{\boldsymbol{imp}} \# \boldsymbol{\hat{x}}_{trade}) \tag{2.42}$$

Chapter 3

Results and Discussion

The main results presented here pertain to the revision of national emissions inventories (NEI) for the year 2007 using the equity-weighting metric outlined in sections 2.3. In order to achieve this, weighting quantities had to be derived exogenously, which is above and beyond what is normally drawn from — all other shared responsibility metrics do not stray outside of input-output data and their environmental extensions, using metrics such as value added and emissions intensities to derive their weights[1].

By contrast, the weighting quantities used here were computed from the use-value of incomes for nations of different income classifications and commodities[2]. These use-values were derived especially for this study and can be considered novel results in and of themselves.

In addition to quantifying use-values of goods and income for nations, the following results aim to explicitly define and directly quantify subsistence and luxury emissions. A third category comprises emissions that are linked to activities that are not quite considered to fulfilling subsistence needs nor luxury wants — non-subsistence/non-luxury (NS/NL) commodities (as described in 2.2.2 for deriving the use-value of commodities). A breakdown by country and region of these categories of emissions is shown in figure 3.1. The results for these categorisations must be considered hypothetical and the following preliminary quantification a first estimate

[1]Recall that the only other attempt at a "fair" Shared Responsibility Based Accounting (SRBA) framework used consumption and production footprint data derived from a MultiRegional Input Output (MRIO) database[27].

[2]Future versions could include marginal use-value dependent on quantity owned by nations

in a recursive process. In other words, by investigating the results of the chosen commodity classification in terms of their associated emissions, we can examine whether our choices for each commodity are sensible and revise ones that are questionable. Additionally, in future research, product breakdown in the employed MRIO database should be reworked to list end-use products rather than their industrial inputs to better facilitate their classification.

3.1 Emissions breakdown by country and region

The subsistence category is defined as the set of all products that are very likely to be used to fulfil subsistence needs, for example as defined by Maslow to be requirements to satisfy basic physical needs of food, shelter, and clothing. The luxury category is defined as the set of all products that are very likely to only be needed to satisfy luxury wants, for example goods and services that are only accessible to the wealthiest of people that are unarguably not essential for human welfare. The NS/NL category serves as the middle bin and at present contains many products for whom arguments for their placement were not immediately clear. This set is therefore likely larger than necessary and revising the chosen products in NS/NL will potentially yield some products being placed in the two extreme categories.

Figure 3.1 depicts the breakdown of emissions into the three categories as defined in section 2.2.2. Intuitively, luxury emissions forms a relatively small proportion of emissions for all countries and regions. The largest proportion of luxury emissions belongs unsurprisingly to more affluent countries including the United Kingdom (GB), Scandinavian countries (e.g. Sweden (SE), Norway (NO)). On the other hand, countries with relatively large proportions of subsistence emissions are also intuitively endowed to countries with large segments of the population living in poverty up to the development threshold. Countries displaying the largest proportions of subsistence emissions are most notably China (CN), India (IN), and Indonesia (ID).

3.2 New national inventory results

Here I present the results for the new SRBA metric designed in this study, named Equity-Weighted Based Accounting (EWBA). Equal-Allocation Based Accounting (EABA), where

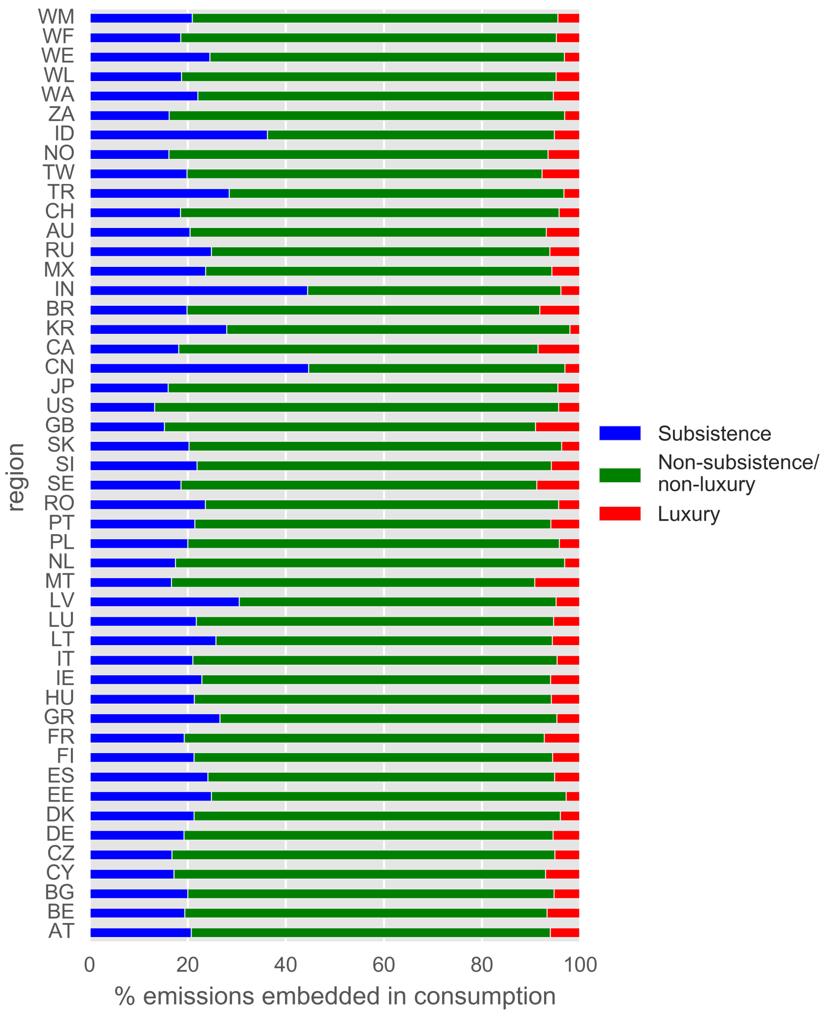

FIGURE 3.1: **Breakdown of emissions by hierarchical type.**

Emissions Embodied in Trade (EET) are divided equally (i.e. 50/50) between trading partners, is also depicted in the following figures as both a first order approximation for any SRBA and also a null hypothesis which to measure the results of EWBA against. EABA should be considered a plausible policy solution and will be discussed in section 3.4 to check its validity alongside EWBA as a policy ready and relevant accounting metric. It should be regarded attractive in its simplicity and transparency of calculation and is therefore possibly the most immediately viable alternative to PBA while being a compromise from full CBA.

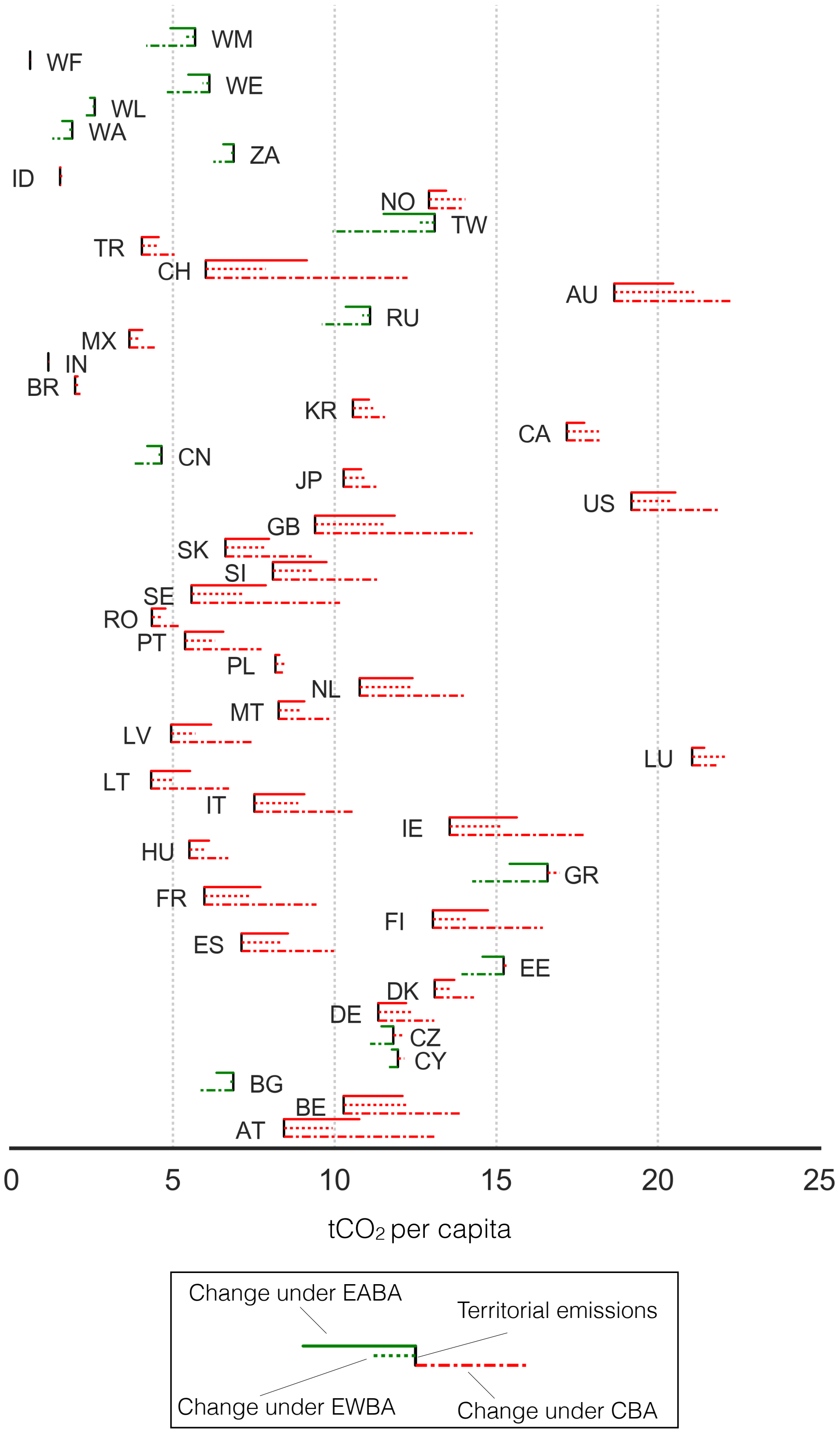

FIGURE 3.2: **Change from territorial emissions (PBA) to CBA, EABA, and EWBA accounting for 2007.** For many countries, EWBA accounting suggests different abatement responsibility (carbon footprint) than do CBA or PBA.

Figure 3.2 shows per capita territorial emissions as calculated with PBA methods using EXIOBASE version 2.2.2. as the central point, depicted with a black dash. Deviations from territorial emissions are depicted by lines: solid (top) line for change under EABA, dotted (middle) line for change under EWBA, and dash-dotted (bottom) line for change under CBA. Red denotes an emissions increase under the specified accounting metric from territorial emissions while green denotes a decrease.

Figure 3.3 shows the same data except with deviations relative to EABA. The solid (top) line shows now change under PBA, the dotted (middle) line shows change under EWBA, and the dash-dotted (bottom) line shows change under CBA.

National emissions are shown on a choropleth map in figure 3.4.

Percent deviation of EWBA emissions from territorial emissions is depicted in figure 3.5 also on a choropleth map. See appendix B for a table of values in increasing order. It is noteworthy that the highest deviation of 30.7% above PBA emissions, is that of Switzerland (CH) who is a large importer of NS/NL and luxury goods by CBA, associated emissions (as depicted in figure 3.1).

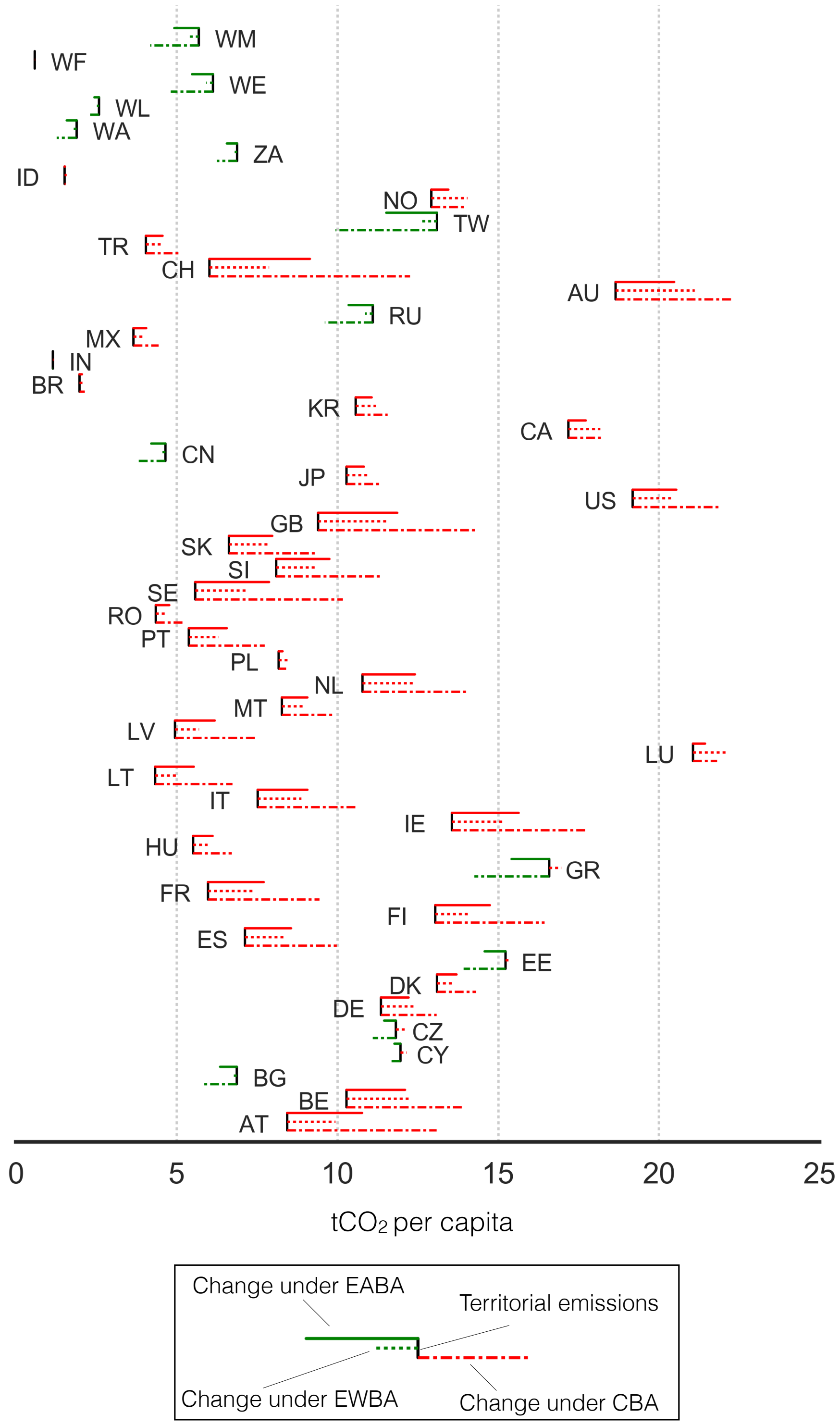

FIGURE 3.3: **Change from equal allocation emissions to PBA, CBA, and EWBA accounting for 2007.** For many countries, EWBA accounting suggests different abatement responsibility (carbon footprint) than do CBA or PBA.

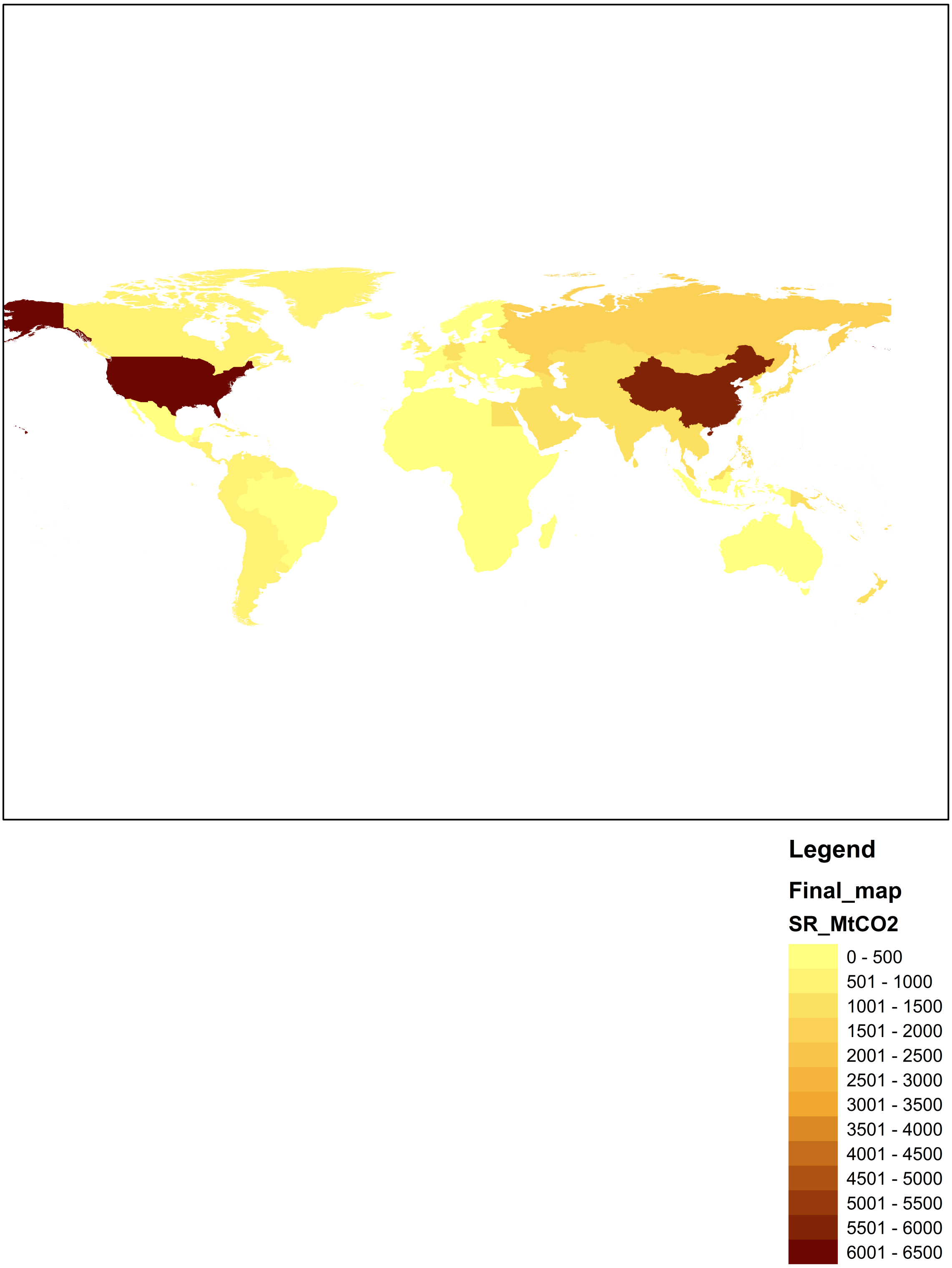

FIGURE 3.4: **EWBA national emissions for 2007**. Rest of World regions display aggregate emissions.

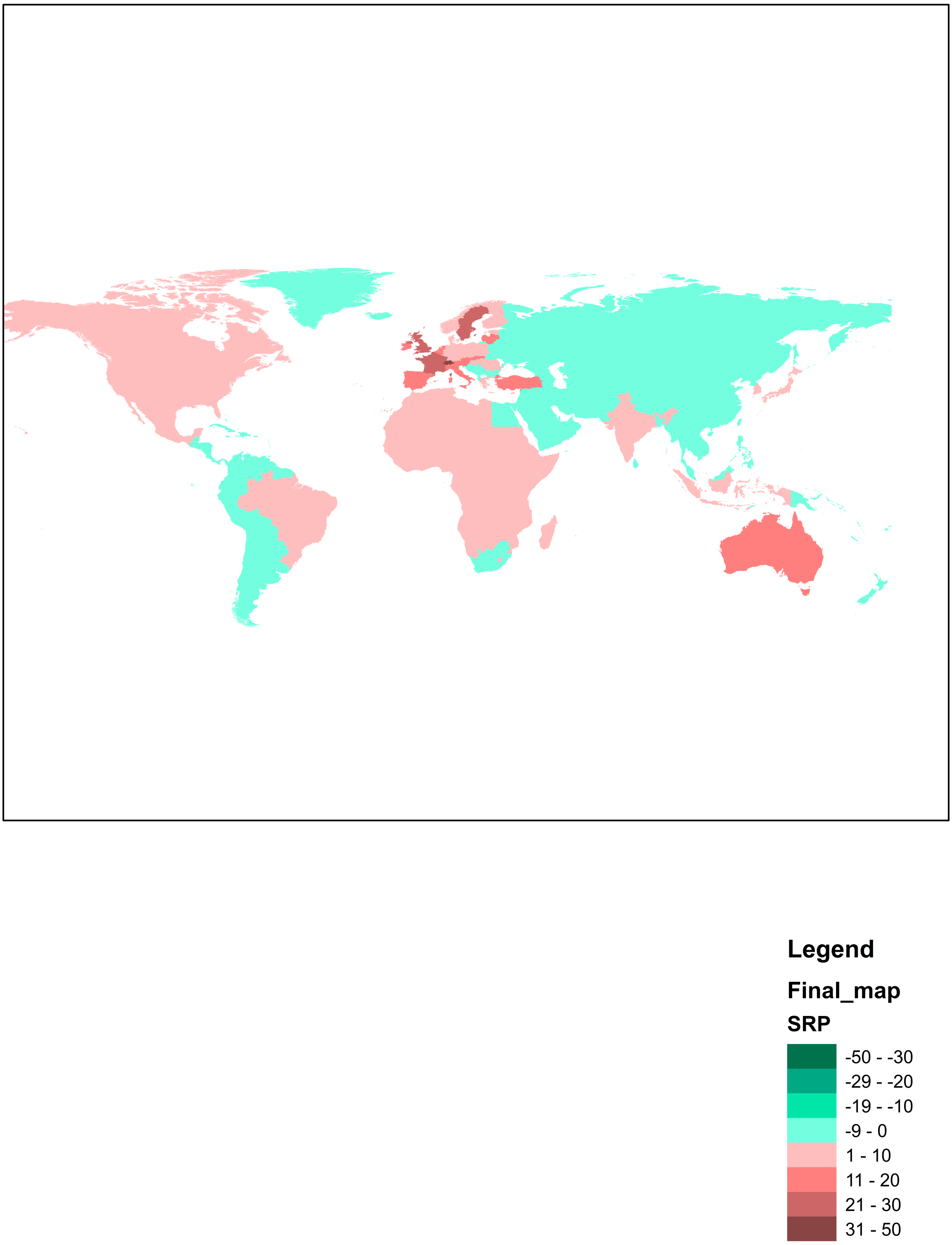

FIGURE 3.5: **Percent change of EWBA from PBA for 2007**

	Income classification				
Ordinal ranking	# low-middle	# middle	# high	Total	Representative country/ region
C <EA <EW <P	0	5	2	7	South Africa
C <EA ≈ EW <P	1	1	0	2	RoW Asia
all ≈	3	1	1	5	India
P <EA ≈ EW <C	0	3	12	15	USA
P <EA <EW <C	0	0	1	1	Australia
P <EW <EA <C	0	0	11	11	Austria
P <EA <EW ≈ C	0	0	1	1	Canada
P <EA <C <EW	0	0	2	2	Norway
C <EA <P <EW	0	0	4	4	Greece

TABLE 3.1: **Metric effects on emissions accounts.** CBA, EABA, EWBA, and PBA are abbreviated as C, EA, EW, and P respectively.

3.2.1 Distribution of countries by accounting metric

Figures 3.6 and 3.7 show the distribution of countries according to national accounts computed by each metric.

It is clear that accounting metrics, although they can have profound and important effects on the individual inventories and abatement responsibility of individual countries or regions, does not heavily impact the distribution of countries by emissions. National emissions by any account results in very similar distribution of emissions — figure 3.6 shows that most countries and regions have very low emissions (between 0 and 1000 MtCO_2) while there are a small handful of countries with much higher emissions (between 4500 and 6500 MtCO_2).

Looking at emissions scaled down by population yields a more notable distinction between the effect of metrics on global emissions distribution. Figure 3.7 shows the distribution of per capita emissions. PBA emissions are most skewed to the low end while CBA yields the furthest right skewed distribution. As with the effect of the metric on individual accounts, EWBA gives a distribution closer to PBA while EABA relatively closer to the CBA extreme. EABA and EWBA distributions are very similar when examining per capita emissions.

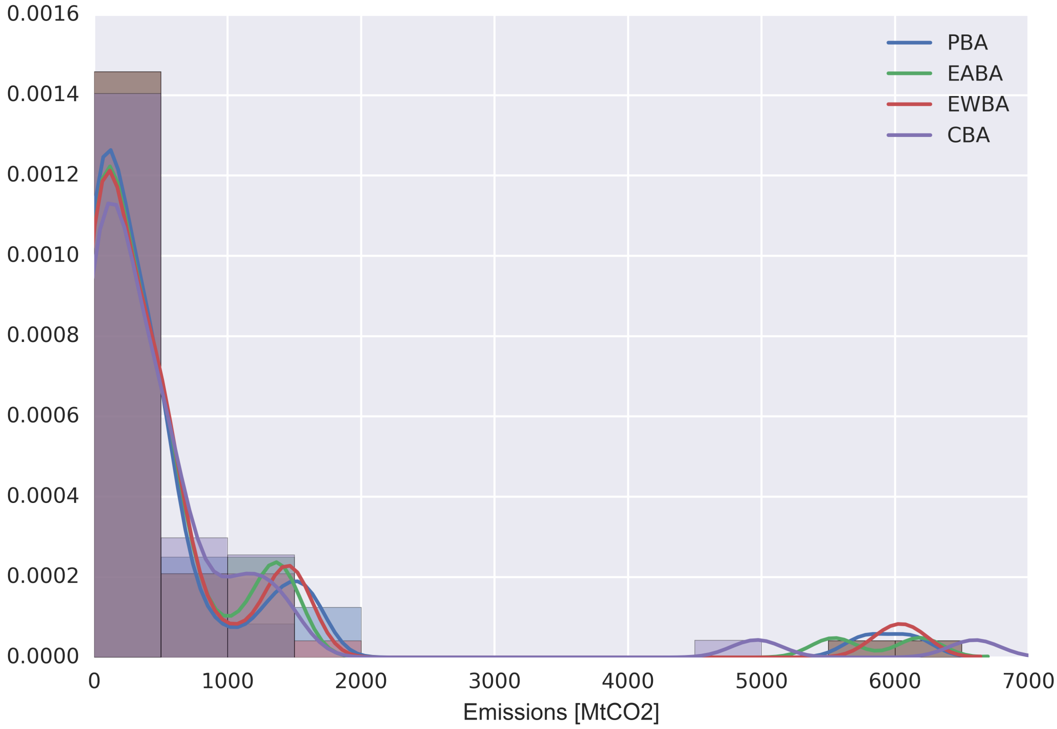

FIGURE 3.6: **Distribution of countries by regional emissions for the year 2007.**

3.3 Emission responsibilities according to different accounting metrics

It is clear that EWBA as well as EABA yield very different national accounts of emissions and if adopted as a convention internationally, NEIs would be would be drastically different for many countries. To go a step further, revised NEIs imply revised abatement responsibility. Here I intend to make the case that it is best through revisions to accounting metrics that responsibility to mitigate at the national level be expressed in a way that is both equitable and effective.

Figures 4.3 and 4.4 (and other figures showing non-CO_2 gases in Appendix B) show the differences in NEIs under different accounting metrics. Common features that have already been illustrated in other studies of CBA are that most developed countries are net importers of emissions and therefore have larger footprint emissions than territorial.

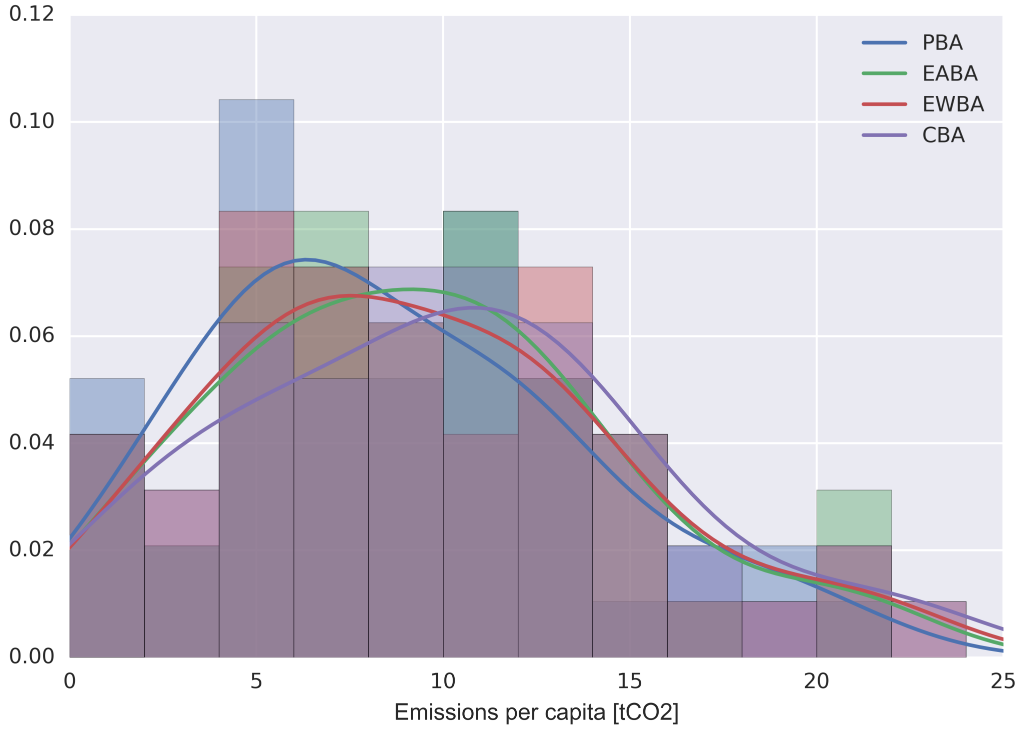

FIGURE 3.7: **Distribution of countries by per capita emissions for the year 2007.**

3.3.1 Effects of accounting metrics on national emissions

Table 3.1 summarises the results of the study, showing the effects on NEIs of adding the two novel metrics EABA and EWBA (abbreviated as EA and EW respectively).

3.3.1.1 Net exporters of emissions

Countries and regions with CBA emissions less than PBA emissions — net exporters of emissions — mostly exhibited higher EW than EA emissions and belonged to the World Bank middle-income classification. Among them, RoW Asia exhibited approximately equal EA and EW emissions.

3.3.1.2 Net-zero trade balance countries

Countries that exhibited emissions that were approximately equal by all accounts included mostly low income countries and regions, including RoW Africa and India. These countries necessarily have balanced trade flows (since their have equal CBA and PBA emissions) and very low emissions per capita.

3.3.1.3 Net importers of emissions

Countries with PBA less than CBA emissions can be divided into three categories. Firstly, countries with approximately equal EA and EW emissions are mostly high income countries, USA being among them. Secondly, countries with EA<EW include only Australia. Thirdly, countries with EW<EA are numerous and only contain high income countries, Austria being an example of the category. This shows that most wealthy countries who are net importers of emissions will have abatement responsibility prescribed by EWBA less than that of EABA but greater than PBA. In simple terms, this means these countries would be held responsible for less than half of their net imported emissions (their emissions trade balance) but still more responsible than only for their territorial emissions. Their partial responsibility for net imported emissions being less than half according to EWBA is presumably due to the practice of importing mostly subsistence and NS/NL goods from middle-income countries like China. Recall that in the case NS/NL imports, USA and China split emissions equally since the use-value of the imported goods is equivalent to that of the money paid to China. For subsistence imports, USA receives a smaller proportion of emissions than that which remains in China's account (more examples can be found in section 2.2.3).

3.3.1.4 Canadian abatement responsibility according to EWBA

Canada stands alone as the only country to have approximately equal CBA and EW emissions that are in excess of EA and PBA emissions accounts. This suggests emissions embodied in Canadian exports largely remain in Canada's ledger under EWBA. To speculate, Canada predominately exports carbon intensive raw materials like bitumen and timber. Raw materials and fuels are considered subsistence nad NS/NL goods respectively. Canada being a high income country, always has the lowest relative use-value for money received in trades and therefore highest shares of its export emissions. Canada also largely imports NS/NL and luxury goods and has relatively high responsibility for import emissions. These effects in tandem are a likely explanation for why Canada's emissions by EWBA are similar to CBA emissions.

3.3.1.5 Peculiarities of EWBA

More peculiar effects of EWBA are exhibited by the last two ranking categories. EW emissions fall outside the range between PBA and CBA emissions for these two categories — net importers and exporters respectively. Although this may be counter-intuitive, EWBA is not bound by PBA and CBA and this occurrence is therefore allowed.Notice that only high income countries exhibit this effect. Norway for example is a large importer of emissions and high income country, while their main export is oil. Norway's oil exports, currently classified as a NS/NL good, will always result in Norway bearing at least half of the emissions responsibility.

3.4 Checking the metric

In order to ensure that the metric is legitimate and effective, it must abide by certain conditions. First and foremost, in order to work at all, it must not violate conservation of physical quantities. The condition for satisfying this clause is referred to as Additivity (see section 1.2.5.1). Recall that in the case of GHG emissions, Additivity simply means that the sum of emissions by any metric must equal global emissions (by any other established metric).

The two other conditions that must be upheld are Monotonicity (see section 1.2.5.2) and Sensitivity (see section 1.2.5.3). They are not necessary for a metric to make sense physically however they are arguably needed if a metric, if employed in policy, be effective to encourage national governments to mitigate effectively through policy. Recall that Monotonicity is respected if domestic emissions reductions do not cause net global rise in emissions. PBA for example does not satisfy monotonicity since emissions reductions domestically may cause increases globally since countries will simply import goods they cease producing domestically from countries with higher carbon intensities in the specified manufacturing sector. Also, recall that Sensitivity more generally refers to the metric abilities for countries to formulate policy that causes emissions reductions globally. If emissions reduced domestically are offset by increases abroad, global emissions are insensitive to the metric.

3.4.1 Additivity: Practical problems

Global emissions are a physical quantity and should therefore be conserved as such regardless of the accounting metric used to allocate national emissions. It is found that the sum of emissions by PBA is equal precisely to that by CBA and EABA. Here I examine the output of the data rather than the theoretical formulation of EWBA itself which is left for discussion in section 3.4.5.

There is a small error in Additivity for EWBA emissions. The sum of global emissions by the EWBA accounting metric is 3% (849 Mt CO_2) larger than that by other accounts where global emissions for the year 2007 for CO_2 only are approximately 30 Gt CO_2. This can likely be attributed to a rounding error when applying the weights. This will be checked for by redoing accounts so that weights are kept as whole numbers and ratios only applied at the final step in calculation. To check that this was not due to the definition used for SRBA figures as described in equation 2.36, EABA calculated in the same way is equivalent to the shorthand way averaging PBA and CBA figures (equation 2.37), and the sum of EABA emissions conserves emissions computed by both means. Therefore EABA preserves Additivity (in practice, as well as in theory).

The underlying cause of the sum of emissions by EWBA being 3% larger than by other metrics reported in this study is likely due aggregation error caused by multiplying many emissions figures or transactions by small weight values. Weight values ranged approximately from 0.02 (2%) to 0.98 (98%). When using the low end weights, even though stored with highest allowed precision (as full length floats in memory), when applied to many values — here being 9600 values per country or region for each output profile — precision may have been lost in aggregation compared to using larger, more precise weights like in the EABA metric.

It is a common problem in MRIO, error may be propagated and exhibited when multiplying many numbers in a large data set (of any kind, not necessarily limited to MRIO) by small numbers (i.e. numbers close to zero)[3].

A possible solution to this discrepancy would be to normalise EWBA data to other metrics post hoc by multiplying all EWBA values by the ratio of global emissions by PBA to global emissions by EWBA. Normalising the data so that the sum of EWBA emissions equals that by other accounts implicitly assumes that the error is proportionally distributed over the data set (all countries and sectors). If the issue is one of double counting, it is likely that the double counting occurs in concentrated areas within the global economy (in areas of higher trade activity) and is therefore not evenly distributed. In this case, normalising as such would diminish some errors while amplifying others. I opt for leaving the results as is and for discussing this error as this seems to be the common practice in Input-Output experiments.

[3]This was discussed over correspondence with Thomas Wiedmann of the School of Civil and Environmental Engineering at the University of New South Wales. Dr. Wiedmann has experience in aggregation error in MRIO and has coauthored several studies included in this thesis, for example reference [7].

3.4.2 Mathematical proofs for EWBA satisfaction of the three conditions

3.4.2.1 Sensitivity

Recall that Sensitivity requires that countries must be able to influence global emissions by changes in their behaviour (e.g. energy system choices, trade patterns, domestic consumption levels) and this be reflected in their national account.

Sensitivity is not necessarily preserved but it should be noted that it is not possible, by design, to preserve Additivity and Sensitivity (see supplementary material of reference [7]).

Kander and colleagues state a restriction that must be met in order to test whether an accounting metric upholds Sensitivity: changes in territorial emissions in countries other than the one in question (s maintaining their notation in the supplementary material) are directly or indirectly due to changes in trade flows related to s.

They supply two assumptions that can be used to impose this restriction.
Let F denote direct emissions
x_i^{sr} is the output from sector i in country s that is consumed finally (directly or indirectly) by country r
q denotes the Leontief emissions multiplier: the direct plus indirect emissions linked to 1 unit of production in sector i in country r
# denotes element-wise multiplication
Δ denotes change

$$\sum_{r \neq s, t \neq s} \Delta x_i^{rt} = -\Delta x_i^{st} \tag{3.1}$$

$$\sum_{r \neq s} \Delta F_i^r = \sum_{r \neq s} q_i^r \# \Delta x_i^{rs} + \sum_{r,t \neq s} q_i^r \# \Delta x_i^{rt} \tag{3.2}$$

Equation 3.1 states that if there is a change in the quantity of sector i exported from country s, there will be a change of equal magnitude but opposite sign compensating from another country or countries in the corresponding sector.

Equation 3.2 states that if there is a change in emissions anywhere excluding s, it is directly related to a change in the amount of emissions imported or exported from or to s. The first term on the right hand side of the equation is the change in territorial emissions outside of s attributed to changes in exports to s and the second term is for changes in imports from s.

These two conditions (articulated in equations 3.1 and 3.2) ensure that any change in global emissions can be attributed to factors that s can influence.

Let $G = \sum_{i,s} F_i^s$ be total global anthropogenic emissions and E^s the total emissions attributed to country s by any specified accounting method.

Now we can finally state the Sensitivity condition formally, given conditions in equations 3.1 and 3.2,

$$if \quad \Delta E^s \neq 0 \quad then \quad \Delta G \neq 0 \tag{3.3}$$

3.4.3 Monotonicity

Recall that the second condition that must be met is that a country's emissions account must not be able to increase when the country contributes to lowering emissions globally, or vice versa. It should be intuitive, much like with Sensitivity, why Monotonicity is a critical criteria for any effective accounting metric. If an a country's actions can unjustly penalise or reward it for making reductions or growing their emissions, there would be no incentive or useful information derived from the employment of a given metric. This happens with both PBA and CBA (CBA is less obvious but is illustrated by Kander and colleagues in the supplementary material of reference [7]). Monotonicity can be thought of as a stricter version of Sensitivity, and if satisfied, Sensitivity should therefore necessarily also be satisfied.

Monotonicity can be formalised mathematically as follows:

$$if \quad \Delta E^s \geq 0 \quad then \quad \Delta G \geq 0 \quad or \quad if \quad \Delta E^s \leq 0 \quad then \quad \Delta G \leq 0 \tag{3.4}$$

3.4.4 Additivity

Recall that in order for an account to be physically legitimate, it must not violate conservation of emissions and so the sum of emissions by any account must equal global emissions.

Formally, Additivity demands:

$$\sum_{s} E^{s} = G = \sum_{i,s} F_{i}^{s} \tag{3.5}$$

When using today's MRIO best practises, PBA and CBA satisfy Additivity. CBA did not used to satisfy Additivity since emissions intensities were approximated using global averages but now accurate estimates are available for all countries individually. Note that in the case of PBA under UNFCCC guidelines, international aviation and shipping emissions are excluded and so PBA fails by the strict definition of Additivity, however our usage of the condition can be made to exclude the same emissions and then Additivity can be defined as agreement with an established metric.

3.4.5 Does EWBA satisfy the three criteria?

EWBA emissions can be stated explicitly using equations 2.36, 2.41, and 2.42:

$$\begin{gathered} E_{EWBA} = \vec{E}_{terr} + \vec{E}^{w}_{imp} - \vec{\bar{E}}^{w}_{exp} = \\ E_{terr} + \vec{S} \times (\boldsymbol{W}_{imp} \# \hat{\boldsymbol{x}}_{trade}) - \vec{S} \# (\sum_{j} \boldsymbol{W}^{\intercal}_{imp} \# \hat{\boldsymbol{x}}_{trade}) \end{gathered} \tag{3.6}$$

Note that q and $\vec{S}$ both contain the same kind of value, $\vec{S}$ being the vector of all emissions intensities for final output for each country and sector, while Kander *et al.* employ q to with implied vector notation instead. From here on, for consistency with their conventions, I adopt their notation. I also drop the *trade* subscript from the diagonalised trade output matrix in favour of their notation for countries and sectors, i.e. $\hat{x}_{trade}$ becomes $\hat{x}_{i}^{sr}$ where i is the sector and s the country of origin for exports or destination for imports and r the trading partner.

It follows that for an individual country, EWBA emissions can be written as:

$$E^s_{EWBA} = \sum_i F^s_i + \sum_{i,r\neq s} [q^r_i \#(w^{rs}_i \hat{x}^{rs}_i) - q^s_i \#(w^{sr}_i \hat{x}^{sr}_i)] \tag{3.7}$$

Where s the the specified country and i any sector within it, and w^s_i denotes the weight in $\boldsymbol{W}_{imp}$ for a product from country s and sector i. The first summation on the right hand side of equation 3.7 is the territorial emissions of country s where F denotes the direct emissions and i the sector of origin. The first term in the second summation represents the weighted import emissions and the second term is the complement of export emissions, both imputed to the account of country s. For example, the import term, for each index, equals the product of the emissions intensity from sector i in country r, the weight for products and the amount of products from sector i going from country r to s respectively.

This shows that EWBA satisfies Additivity since:

$$\sum_{i,r\neq s} q^r_i \#(w^{rs}_i \hat{x}^{rs}_i) = \sum_{i,r\neq s} q^s_i \#(w^{sr}_i \hat{x}^{sr}_i) \tag{3.8}$$

Where the sum of the weights are equal since they come from identical weighting matrices (N.B. transposing does not affect the information contained within a matrix), and recall that all imports are also exports and that the set of all imports globally contains the equivalent to the set of all exports. Therefore the second term in equation 3.7 will sum to zero for the sum of all EET globally.

As in Kander *et al.*[7](supplementary materials), to prove that EWBA satisfies Sensitivity and Monotonicity conditions, we require the assumptions laid out in equations 3.1 and 3.2, as well as one additional assumption that a change in export from country s will be substituted by another country in the global market. Now we can say with certainty that any change in global emissions is due to changes in emissions made by country s by EWBA accounts.

It can be shown, given the assumptions in equations 3.1 and 3.2:

$$\Delta G = \Delta E^s_{EWBA} \tag{3.9}$$

The proof is as follows:

Here the world is divided into two groups: country s and all other countries, i.e. global change in emissions are equal to the sum of the change in emissions over all sectors for country s and all other countries.

Given 3.1 and 3.2, the change in global emissions ΔG can be written as:

$$\begin{aligned}\Delta G &= \sum_i \Delta F_i^s + \sum_{i,r\neq s} \Delta F_i^r \\ &= \sum_i \Delta F_i^s + \sum_{i,(r\neq s),t} q_i^r \# \Delta x_i^{rt} \\ &= \sum_i \Delta F_i^s + \sum_{i,(r,t\neq s)} q_i^r \# (\Delta x_i^{rs} + \Delta x_i^{rt}) \\ &= \sum_i \Delta F_i^s + \sum_{i,r\neq s} [q_i^r \# \Delta x_i^{rs} - q_i^s \# \Delta x_i^{sr}]\end{aligned} \tag{3.10}$$

While changes in emissions for country s are given by altering equation 3.7:

$$\Delta E_{EWBA}^s = \sum_i \Delta F_i^s + \sum_{i,r\neq s} [q_i^r \# (w_i^{rs} \Delta \hat{x}_i^{rs}) - q_i^s \# (w_i^{sr} \Delta \hat{x}_i^{sr})] \tag{3.11}$$

By inspection of the second term in equation 3.11 and substituting in equation 3.8 altered for changes in output to yield equation 3.12, one can see that $\Delta E_{EWBA}^s = \Delta G$:

$$\sum_{i,r\neq s} q_i^r \# (w_i^{rs} \Delta \hat{x}_i^{rs}) = \sum_{i,r\neq s} q_i^s \# (w_i^{sr} \Delta \hat{x}_i^{sr}) \tag{3.12}$$

$$\begin{aligned} &\sum_{i,r\neq s} [q_i^r \# (w_i^{rs} \Delta \hat{x}_i^{rs}) - q_i^s \# (w_i^{sr} \Delta \hat{x}_i^{sr})] \\ &\sum_{i,r\neq s} q_i^r \# (w_i^{rs} \Delta \hat{x}_i^{rs}) - \sum_{i,r\neq s} q_i^s \# (w_i^{sr} \Delta \hat{x}_i^{sr}) \\ &= \sum_{i,r\neq s} q_i^r \# (w_i^{rs} \Delta \hat{x}_i^{rs}) - \sum_{i,r\neq s} q_i^r \# (w_i^{rs} \Delta \hat{x}_i^{rs}) \\ &= 0\end{aligned} \tag{3.13}$$

The second term on the right hand side of equation 3.10 shows that ΔG (when expanded to represent CBA), also sums to zero for the same Additivity preserving reason that the sum of imports is equivalent to the sum of exports (and their emissions) globally.

Therefore, $\Delta E^{s}_{EWBA} = \Delta G$, which means EWBA satisfies Monotonicity as well as Sensitivity. *QED*.

3.5 Successful experiment?

Here I make a small recap of what my end goals where for this metric (research objective 1.) and whether I've accomplished them. My other two objectives have been accomplished and results already presented.

3.5.1 EWBA yield significantly different from null hypothesis (EABA)?

This is a good time to take a moment to reflect on the outcomes of this study, the final product of which is a new account of national emissions aimed at distributing emissions embodied in trade equitably among participatory nations. Do the NEIs using EWBA vary significantly from those using EABA? If so, we reject the "null hypothesis" that EWBA would not vary significantly from EABA emissions. EABA is used as both a standalone metric for independent consideration and as a first order approximation for any SRBA metric by splitting EET equally (i.e. 50/50) between trading partners for each bilateral trade. EWBA emissions generally fell between EABA and PBA emissions, and for many countries was markedly different from EABA emissions. EWBA therefore provides a novel account in theory, derived from novel principles, and yields results that differ greatly from other established metrics as well as from EABA. It is in these regards that EWBA can be considered a successful metric and I am happy to regard it as significantly different in both theory and practice from EABA.

3.5.2 Are EWBA results more equitable?

Has EWBA yielded a more equitable NEI for all countries and regions in this study? Examining the newly derived national accounts of CO_2 *ex-post*, I determine that the results show an intuitive improvement to equity considerations as dictated by the metric construction. And so, this shows that there is an effective translation of intuitive ethical first principles into quantified accounts of environmental impacts, GHGs specifically in the case of this study though the methodology outlined here can be applied to impact. I assert that through the reform of GHG accounting metrics, responsibility for climate change can be reconciled with national emissions reporting. NEIs now take into consideration the relative need of countries to engage in trade and minimise responsibility for those trades that are more vital for human subsistence than not while maximising responsibility for trades that are relatively unnecessary. That said, the metric in its present form tends to bias weights for EET shares towards exporters (producers, i.e. downstream bias) since many products have been classified as subsistence and NS/NL items since their nature and end-use was ambiguous and the most conservative classification was opted for by convention. In future versions of the metric, using more robust product classification by means of revision to classifications in MRIO databases to final user products or by other means of defining the emissions hierarchy, this bias should be eliminated and one would expect results to be closer to EABA (and CBA for that matter) emissions. In any case, the current results represent an improvement in equity captured in accounts from PBA. Are these improvements vastly better than PBA? I argue that any divergence from PBA is a vast improvement, especially one motivated by the distribution of goods on the basis of need rather than purchasing power and egalitarian values of fair and equal access to — at the very least — necessities for human subsistence.

3.5.3 Will EWBA results yield more effective and equitable policy if employed?

Based on principles for an effective accounting metric specified by Kander and colleagues[7] for example, EWBA satisfies all three criteria for a legitimate and effective accounting metric — Additivity, Sensitivity, and Monotonicity. It provides an equity-based SRBA framework for sharing emissions between producers and consumers, which will incentivise mitigation of emissions by both up and downstream actors.

I argue that in addition to rendering more effective international policy, it will engender more equitable policy, since the basis of need is reflected in accounting, and over time, countries will align their behaviour, most notably and deliberately (hypothetically) in their choices of consumption, so that they minimise their penalty in emissions burden by avoiding importation of luxury goods, or alternatively, assume larger — in certain cases, virtually the full — responsibility for emissions associated with these imports. Revised accounts will also yield new abatement responsibilities and adaptation fund contributions more commensurate with responsibility as defined in this study.

It should also be noted that in a manner of speaking, effective policy begets equitable policy in the sense that the more successful we are at mitigating climate change, the less poor and vulnerable people will suffer. The means at least partly justify the ends in this sense, but as I have shown in the derivation of my metric, the means too are important and ideally both the method and the outcome should be carried out in the most equitable manner allowed.

3.6 Future research

3.6.1 Rigorous derivation of subsistence and luxury emissions

In future research, it would be prescient to ascertain the amount of emissions associated with what people in a nation need to subsist and how much emissions are in excess of that in a more methodical way than that used in this study. The limitations of the study did not allow for a more rigorous undertaking of the quantification of subsistence emissions and my method can be considered an *ad hoc* approach to gain a rough preliminary assessment of subsistence emissions. Alternative methods alluded to earlier comprise either:

1. Modifications to product classifications in MRIO databases using life-cycle analysis to build new IO tables using end-use consumer goods rather than their industrial inputs, and

2. Direct quantification of subsistence and luxury emissions using GDR framework math as outlined in reference [43].

3.6.2 Modulation of use-value of products

In the study presented, the use-value of products was fixed for all items and therefore invariant of the identity of the consumer. One major improvement would be an additional level of complexity here to make the use-value of products dependant on the consumer (in the case of national climate policy, necessarily the country as a whole).

One manner in which this could be achieved would be to have an initial product use-value for each of the three categories — sharing the same quantity as the present use-value for instance — that would be the maximum use-value for each product. the value would decrease as a function of wealth of a country or number of units of the specified product already owned (per capita) in the consumer country. The function could match the form and parametrisation of the use-value of income, and so use-value of products would start at their initial value and decrease inversely to either quantity stated above. For example, say Canada imports cars, and has 662 cars per 1000 people, while India only has 18[4]. At present, cars for both countries are regarded as having the same use-value regardless of which country imports them. With this revision to the metric, India would hold much higher use-value for an additional car compared to Canada who already has many cars per person and hence each additional car yields much less value. This would then translate into the inverse effect of emissions responsibility and Canada would receive a much larger share than India in a *ceteris paribus*, i.e. trade with any fixed country say Japan for example. This application of the concept of marginal use-value to products should formidably enhance the equity implications of the metric.

[4]Source: List of countries by vehicles per capita, Wikipedia. Accessed August 19, 2016

Chapter 4

Conclusion

In this thesis, I have shown that starting from an intuitive ethical assertion, one can empirically derive and quantify responsibility for emissions embodied in international trade. Weighted shares of EET are allocated and national emissions inventories are recalculated. Equal Allocation-Based Accounting (EABA) splits EET equally between trading partners and is included for reference. Shared responsibility-based accounting (SRBA) — like the equity-based weighting metric I have developed here, referred to as Equity-Weighted Based Accounting (EWBA) — provides a more nuanced alternative to Consumption-Based Accounting (CBA) that may be more politically tractable and more equitable. EABA can also be offered as a standalone alternative SRBA metric. Regardless of the choice of alternative metric employed, without reforms to the current production-based accounting metric, increasing international trade will amplify "carbon leakage". This will further undermine international mitigation efforts, and continue to disadvantage countries with large manufacturing sectors while favouring rich countries who increasingly import goods from developing countries while not imposing limits on consumption or using CBA to independently monitor their emissions footprints. There must be an effort to at least take consumption-based emissions into consideration lest policy will continue to be ineffective at both national and international levels. I argued that it would be ideal for national accounts to reflect responsibility for climate change, and any framework put forward should be rooted primarily in ethical considerations. I offer EWBA as a solution that if employed could accomplish just that. I show that EWBA offers a compromise between PBA and CBA emissions and by association, their impact and abatement responsibilities. EWBA in its present form yields emissions figures that fall closer to PBA then CBA for most affluent countries. I expect further refinements to the metric to yield results closer to CBA emissions than the results presented here do. Additivity is not preserved in practice due to aggregate rounding error however in theory it, as well as the two other obligatory criteria for effective accounting metrics — Sensitivity and Monotonicity — are satisfied. Future research will comprise further refinements to the metric and potentially research surrounding its implementation into international climate policy.

Additionally, inventories derived with EWBA are largely similar to those by EABA. EABA therefore provides a useful first-order approximation for EWBA. It is far more simple in design and hence a more transparent metric. For these reasons, I advocate EABA be adopted as a revised accounting metric for international climate policy. It is policy-ready when using the best available CBA inventories and easily calculated as the mean of PBA and CBA emissions. If implemented, it would accomplish the main goals of EWBA — or any SRBA metric — by sharing the burden of emissions abatement between both producers and consumers, thereby incentivising efforts from actors on both supply and demand sides and better reflecting responsibility for climate change. To reiterate, I feel it imperative that accounting be revised to meet these criteria, since otherwise, effective climate policy may continue to be out of reach.

Appendix A

Country and Product Tables

Product	**Classification**
Paddy rice	0
Wheat	0
Cereal grains nec	0
Vegetables, fruit, nuts	0
Oil seeds	0
Sugar cane, sugar beet	0
Plant-based fibers	0
Crops nec	0
Cattle	2
Pigs	2
Poultry	2
Meat animals nec	2
Animal products nec	2
Raw milk	1
Wool, silk-worm cocoons	0
Manure (conventional treatment)	0
Manure (biogas treatment)	0
Products of forestry, logging and related services	0

Fish and other fishing products; services incidental of fishing	1	
Anthracite	1	
Coking Coal	1	
Other Bituminous Coal	1	
Sub-Bituminous Coal	1	
Patent Fuel	1	
Lignite/Brown Coal	1	
BKB/Peat Briquettes	1	
Peat	1	
Crude petroleum and services related to crude oil extraction, excluding surveying	1	
Natural gas and services related to natural gas extraction, excluding surveying	1	
Natural Gas Liquids	1	
Other Hydrocarbons	1	
Uranium and thorium ores	1	
Iron ores	1	
Copper ores and concentrates	1	
Nickel ores and concentrates	1	
Aluminium ores and concentrates	1	
Precious metal ores and concentrates	2	
Lead, zinc and tin ores and concentrates	1	
Other non-ferrous metal ores and concentrates	1	
Stone	0	
Sand and clay	0	
Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.	0	
Products of meat cattle	2	
Products of meat pigs	2	
Products of meat poultry	2	

Meat products nec	2
products of Vegetable oils and fats	0
Dairy products	1
Processed rice	0
Sugar	0
Food products nec	0
Beverages	1
Fish products	2
Tobacco products	1
Textiles	0
Wearing apparel; furs	1
Leather and leather products	1
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials	0
Wood material for treatment, Re-processing of secondary wood material into new wood material	0
Pulp	1
Secondary paper for treatment, Re-processing of secondary paper into new pulp	0
Paper and paper products	1
Printed matter and recorded media	1
Coke Oven Coke	1
Gas Coke	1
Coal Tar	1
Motor Gasoline	1
Aviation Gasoline	2
Gasoline Type Jet Fuel	2
Kerosene Type Jet Fuel	2
Kerosene	1

Gas/Diesel Oil	1
Heavy Fuel Oil	1
Refinery Gas	1
Liquefied Petroleum Gases (LPG)	1
Refinery Feedstocks	1
Ethane	1
Naphtha	1
White Spirit & SBP	1
Lubricants	1
Bitumen	1
Paraffin Waxes	1
Petroleum Coke	1
Non-specified Petroleum Products	1
Nuclear fuel	1
Plastics, basic	1
Secondary plastic for treatment, Re-processing of secondary plastic into new plastic	0
N-fertiliser	0
P- and other fertiliser	0
Chemicals nec	1
Charcoal	1
Additives/Blending Components	1
Biogasoline	1
Biodiesels	1
Other Liquid Biofuels	1
Rubber and plastic products	0
Glass and glass products	0
Secondary glass for treatment, Re-processing of secondary glass into new glass	0
Ceramic goods	0

Bricks, tiles and construction products, in baked clay	0	
Cement, lime and plaster	0	
Ash for treatment, Re-processing of ash into clinker	0	
Other non-metallic mineral products	0	
Basic iron and steel and of ferro-alloys and first products thereof	0	
Secondary steel for treatment, Re-processing of secondary steel into new steel	0	
Precious metals	2	
Secondary precious metals for treatment, Re-processing of secondary precious metals into new precious metals	2	
Aluminium and aluminium products	0	
Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium	0	
Lead, zinc and tin and products thereof	0	
Secondary lead for treatment, Re-processing of secondary lead into new lead	0	
Copper products	0	
Secondary copper for treatment, Re-processing of secondary copper into new copper	0	
Other non-ferrous metal products	0	
Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	0	
Foundry work services	0	
Fabricated metal products, except machinery and equipment	0	

Machinery and equipment n.e.c.	1
Office machinery and computers	1
Electrical machinery and apparatus n.e.c.	1
Radio, television and communication equipment and apparatus	1
Medical, precision and optical instruments, watches and clocks	1
Motor vehicles, trailers and semi-trailers	1
Other transport equipment	1
Furniture; other manufactured goods n.e.c.	1
Secondary raw materials	0
Bottles for treatment, Recycling of bottles by direct reuse	0
Electricity by coal	1
Electricity by gas	1
Electricity by nuclear	1
Electricity by hydro	1
Electricity by wind	1
Electricity by petroleum and other oil derivatives	1
Electricity by biomass and waste	1
Electricity by solar photovoltaic	1
Electricity by solar thermal	1
Electricity by tide, wave, ocean	1
Electricity by Geothermal	1
Electricity nec	1
Transmission services of electricity	1
Distribution and trade services of electricity	1
Coke oven gas	1
Blast Furnace Gas	1
Oxygen Steel Furnace Gas	1
Gas Works Gas	1

Biogas	1	
Distribution services of gaseous fuels through mains	1	
Steam and hot water supply services	1	
Collected and purified water, distribution services of water	0	
Construction work	0	
Secondary construction material for treatment, Re-processing of secondary construction material into aggregates	1	
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	1	
Retail trade services of motor fuel	1	
Wholesale trade and commission trade services, except of motor vehicles and motorcycles	1	
Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods	1	
Hotel and restaurant services	1	
Railway transportation services	1	
Other land transportation services	1	
Transportation services via pipelines	1	
Sea and coastal water transportation services	1	
Inland water transportation services	1	
Air transport services	2	
Supporting and auxiliary transport services; travel agency services	2	
Post and telecommunication services	1	
Financial intermediation services, except insurance and pension funding services	1	

Insurance and pension funding services, except compulsory social security services	1	
Services auxiliary to financial intermediation	1	
Real estate services	1	
Renting services of machinery and equipment without operator and of personal and household goods	1	
Computer and related services	1	
Research and development services	1	
Other business services	1	
Public administration and defence services; compulsory social security services	1	
Education services	1	
Health and social work services	1	
Food waste for treatment: incineration	1	
Paper waste for treatment: incineration	1	
Plastic waste for treatment: incineration	1	
Intert/metal waste for treatment: incineration	1	
Textiles waste for treatment: incineration	1	
Wood waste for treatment: incineration	1	
Oil/hazardous waste for treatment: incineration	1	
Food waste for treatment: biogasification and land application	1	
Paper waste for treatment: biogasification and land application	1	
Sewage sludge for treatment: biogasification and land application	1	
Food waste for treatment: composting and land application	1	
Paper and wood waste for treatment: composting and land application	1	

Food waste for treatment: waste water treatment	1
Other waste for treatment: waste water treatment	1
Food waste for treatment: landfill	1
Paper for treatment: landfill	1
Plastic waste for treatment: landfill	1
Inert/metal/hazardous waste for treatment: landfill	1
Textiles waste for treatment: landfill	1
Wood waste for treatment: landfill	1
Membership organisation services n.e.c.	1
Recreational, cultural and sporting services	1
Other services	1
Private households with employed persons	1
Extra-territorial organizations and bodies	1

Table A.2: **Products and their classifications**. Levels 0, 1, and 2 denote subsistence, non-subsistence/non-luxury (NS/NL), and luxury product classifications respectively.

Country Code	Country Name	Country Group Name	Income
AT	Austria	European Union	3
BE	Belgium	European Union	3
BG	Bulgaria	European Union	2
CY	Cyprus	European Union	3
CZ	Czech Republic	European Union	3
DE	Germany	European Union	3
DK	Denmark	European Union	3
EE	Estonia	European Union	3
ES	Spain	European Union	3
FI	Finland	European Union	3
FR	France	European Union	3
GB	United Kingdom	European Union	3
GR	Greece	European Union	3
HU	Hungary	European Union	3
IE	Ireland	European Union	3
IT	Italy	European Union	3
LT	Lithuania	European Union	3
LU	Luxembourg	European Union	3
LV	Latvia	European Union	3
MT	Malta	European Union	3
NL	Netherlands	European Union	3
PL	Poland	European Union	3
PT	Portugal	European Union	3
RO	Romania	European Union	2
SE	Sweden	European Union	3
SI	Slovenia	European Union	3
SK	Slovak Republic	European Union	3
CA	Canada	North America	3
US	United States	North America	3
CN	China	Asia	2
ID	Indonesia	Asia	1
IN	India	Asia	1
JP	Japan	Asia	3
KR	South Korea	Asia	3
TW	Taiwan	Asia	3
BR	Brazil	South America	2
MX	Mexico	South America	2
RU	Russian Federation	Russia	3
AU	Australia	Australia	3
CH	Switzerland	Switzerland	3
TR	Turkey	Turkey	2
NO	Norway	Norway	3
ZA	South Africa	Africa	2
WA	RoW Asia and Pacific	Rest of World	1
WE	RoW Europe	Rest of World	2
WF	RoW Africa	Rest of World	1
WL	RoW America	Rest of World	2
WM	RoW Middle East	Rest of World	2

TABLE A.1: **Country codes and income classifications**. For incomes, levels 1, 2, and 3 denote low-middle, middle, and high income classifications respectively.

Appendix B

Additional Figures

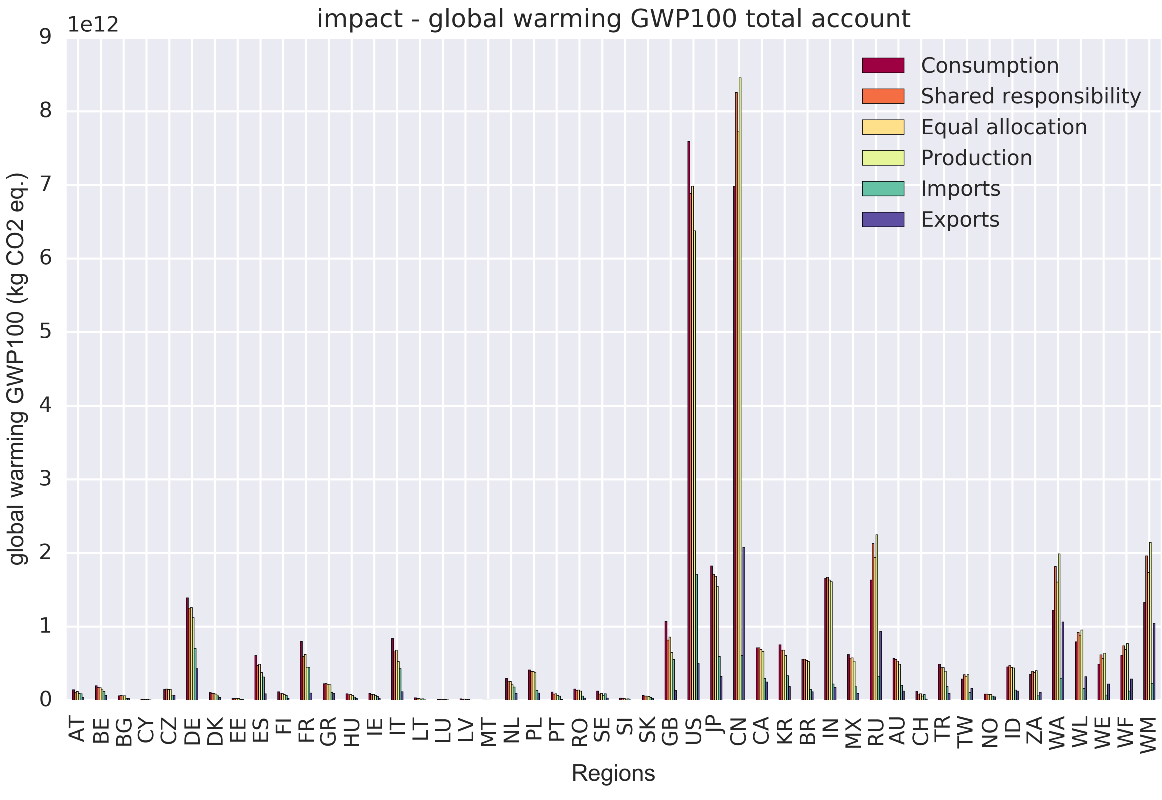

Figure B.1: **Global warming potential with 100 year time horizon (GWP100) [CO_2-eq] national emissions for 2007**

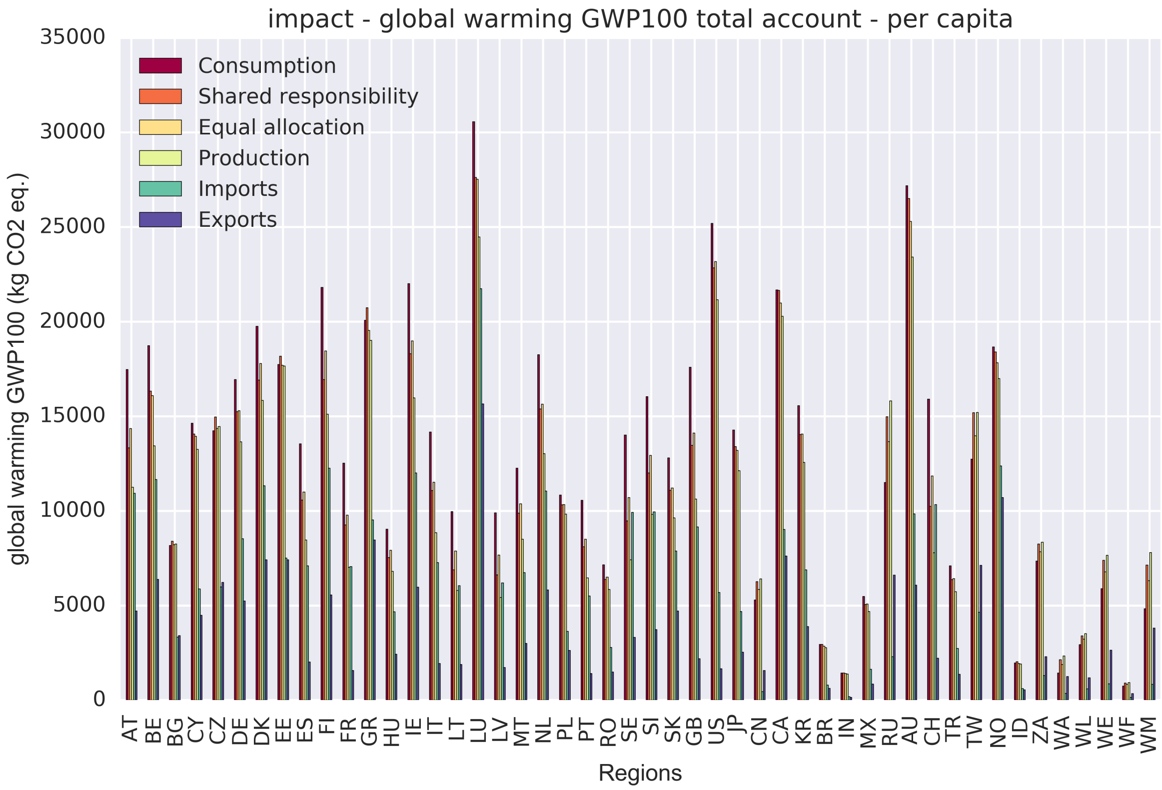

FIGURE B.2: **Global warming potential with 100 year time horizon (GWP100) [CO_2-eq] per capita emissions for 2007**

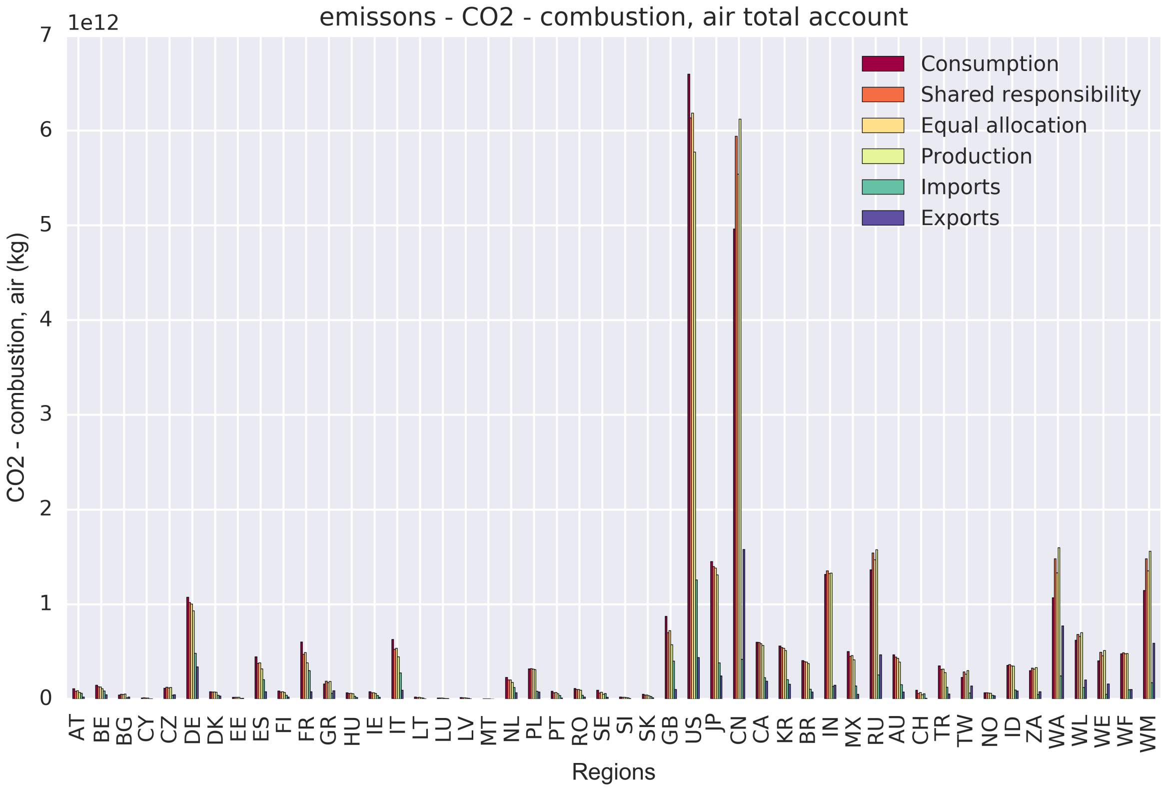

FIGURE B.3: **Carbon dioxide national emissions for 2007**

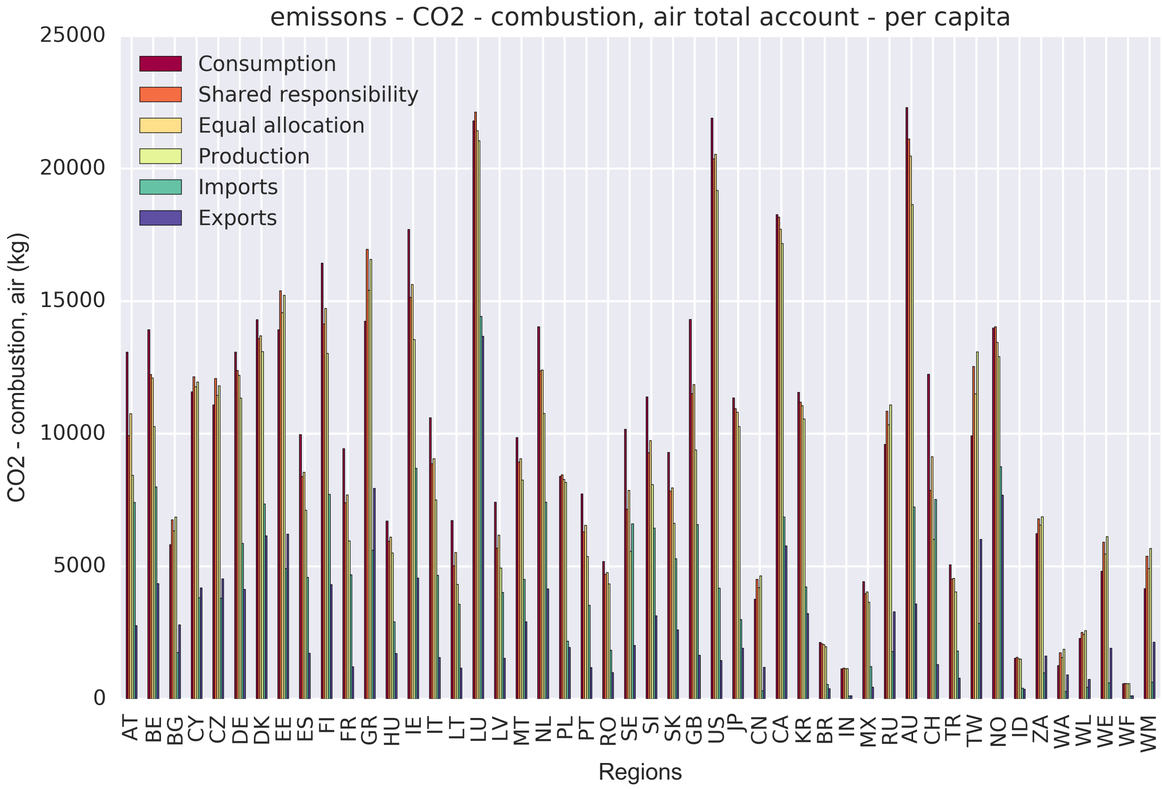

FIGURE B.4: **Carbon dioxide per capita emissions for 2007**

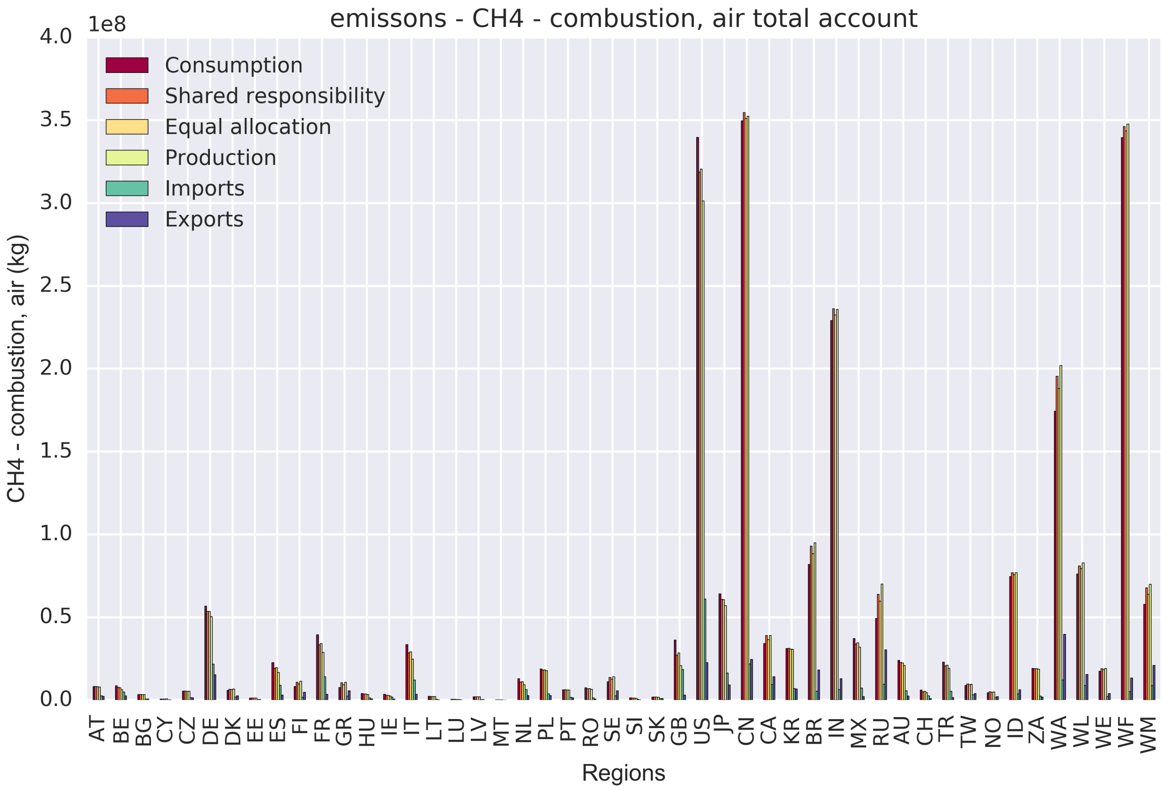

FIGURE B.5: **Methane national emissions for 2007**

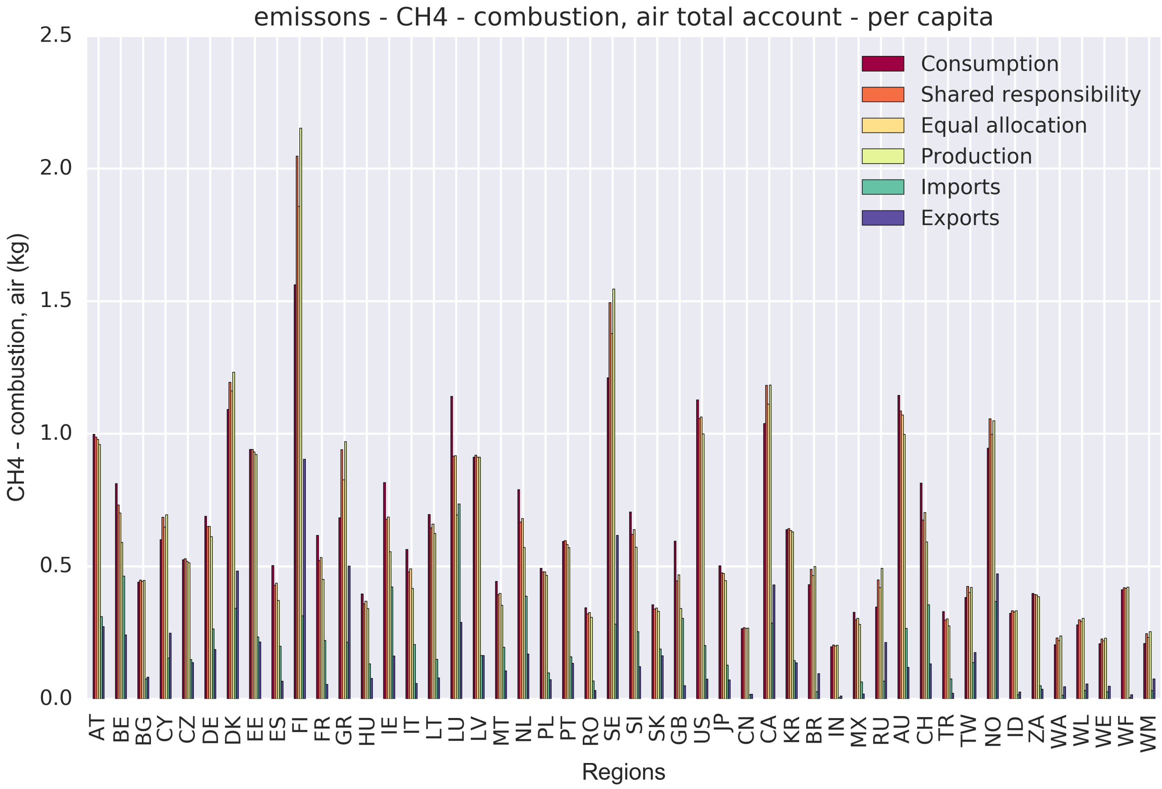

FIGURE B.6: **Methane per capita emissions for 2007**

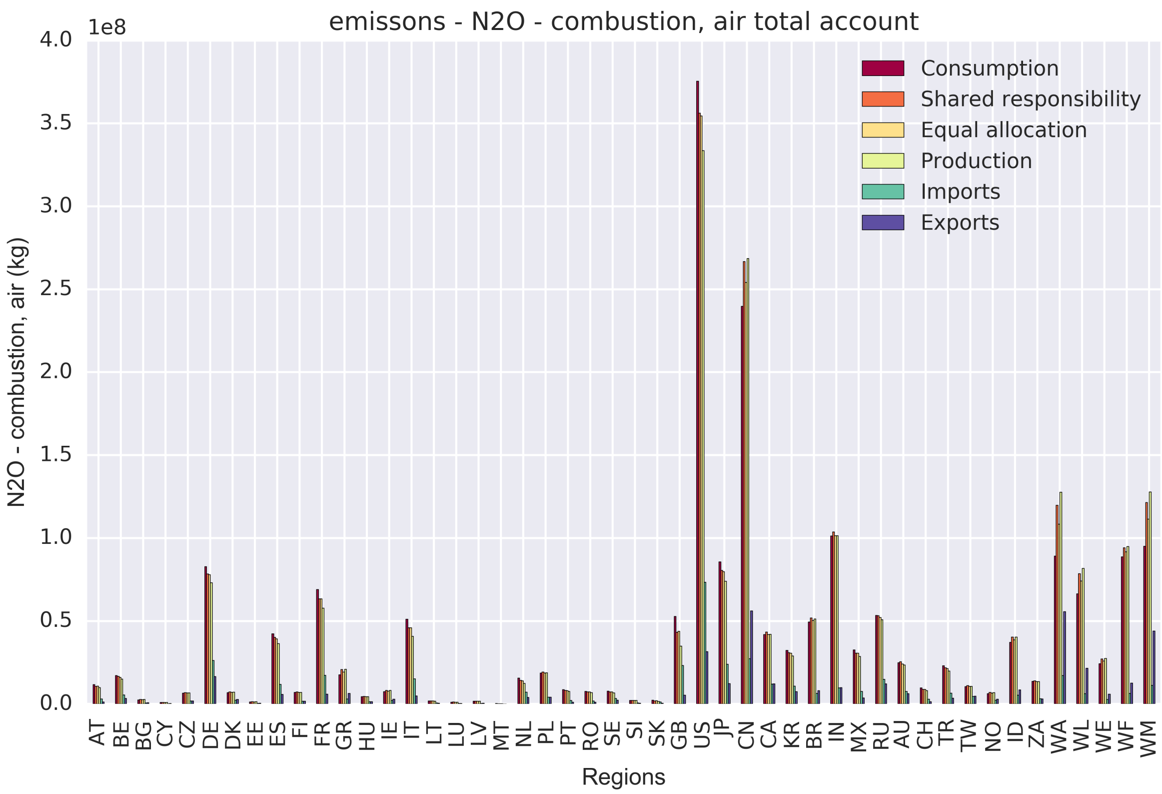

FIGURE B.7: **Nitrous oxide national emissions for 2007**

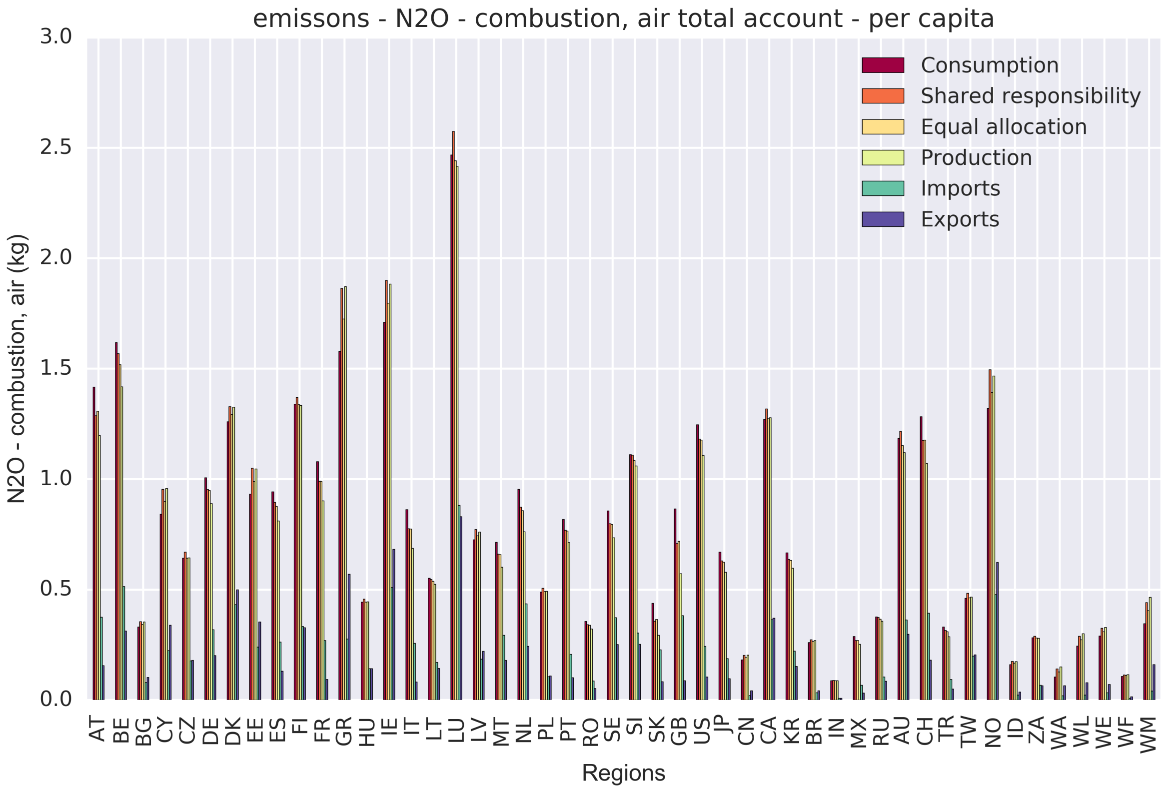

FIGURE B.8: **Nitrous oxide per capita emissions for 2007**

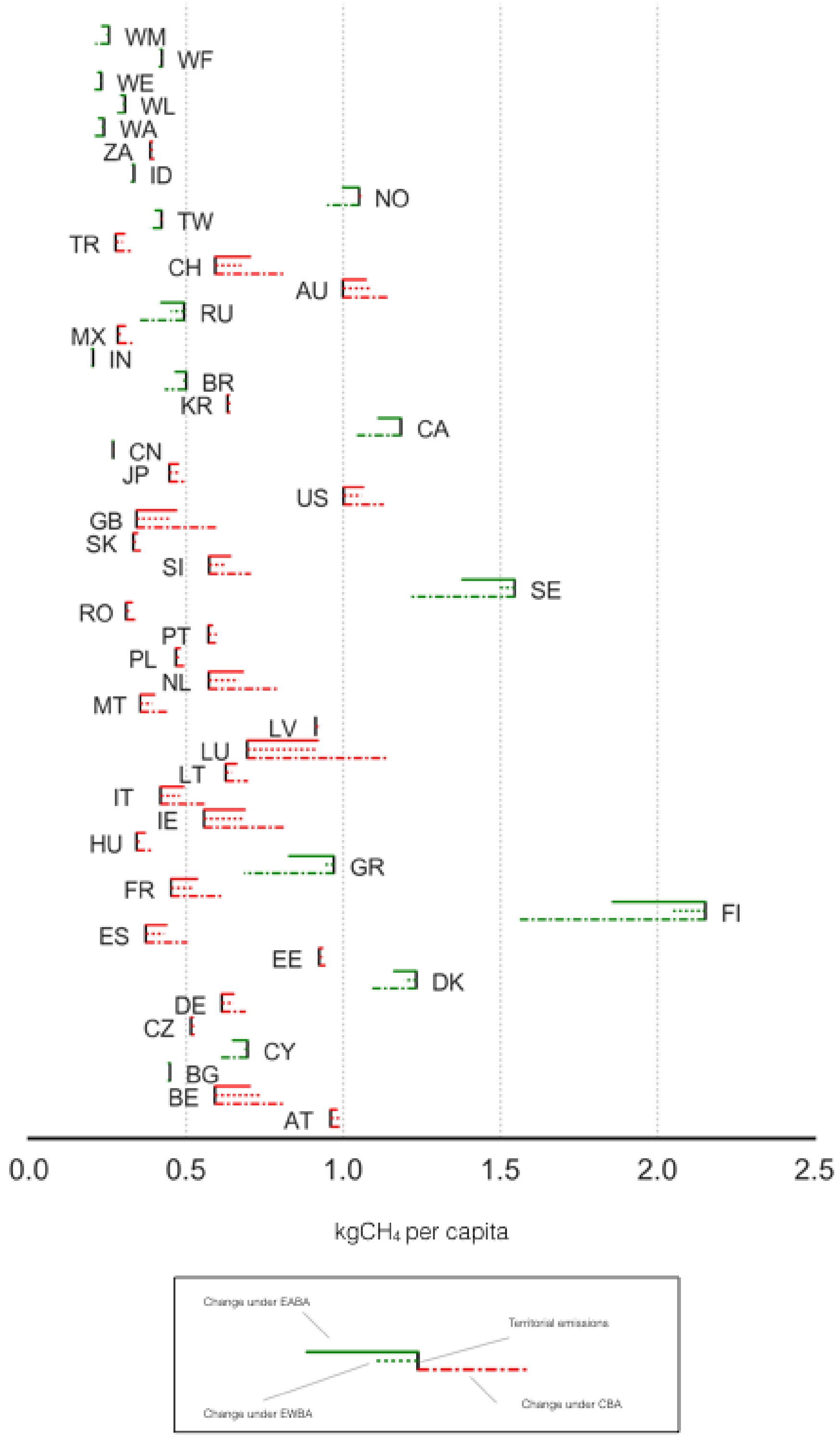

FIGURE B.9: **CH_4 change from territorial emissions (PBA) to CBA, EABA, and EWBA accounting for 2007.** For many countries, EWBA accounting suggests different abatement responsibility (carbon footprint) than do CBA or PBA.

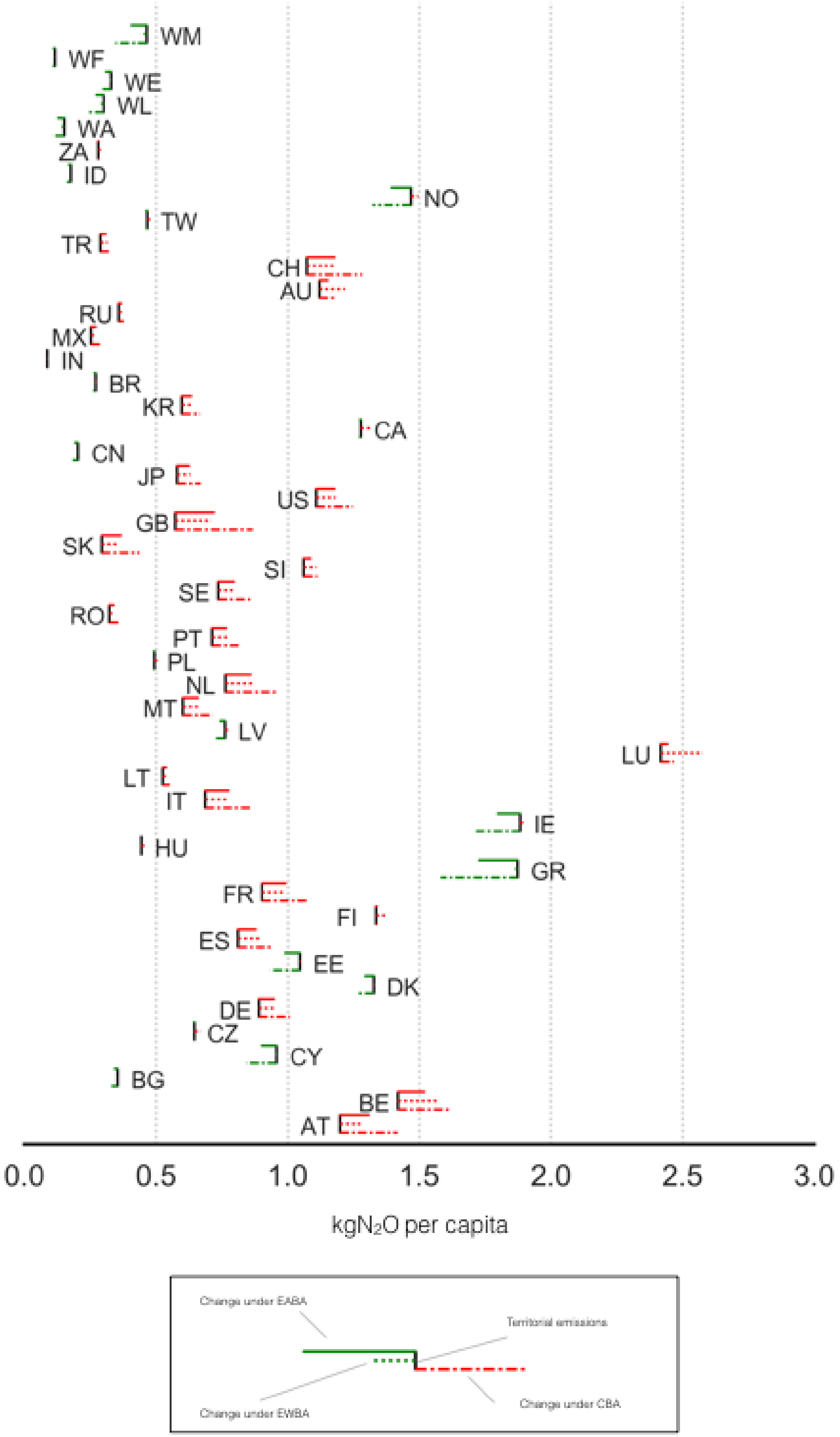

FIGURE B.10: **N_2O change from territorial emissions (PBA) to CBA, EABA, and EWBA accounting for 2007.** For many countries, EWBA accounting suggests different abatement responsibility (carbon footprint) than do CBA or PBA.

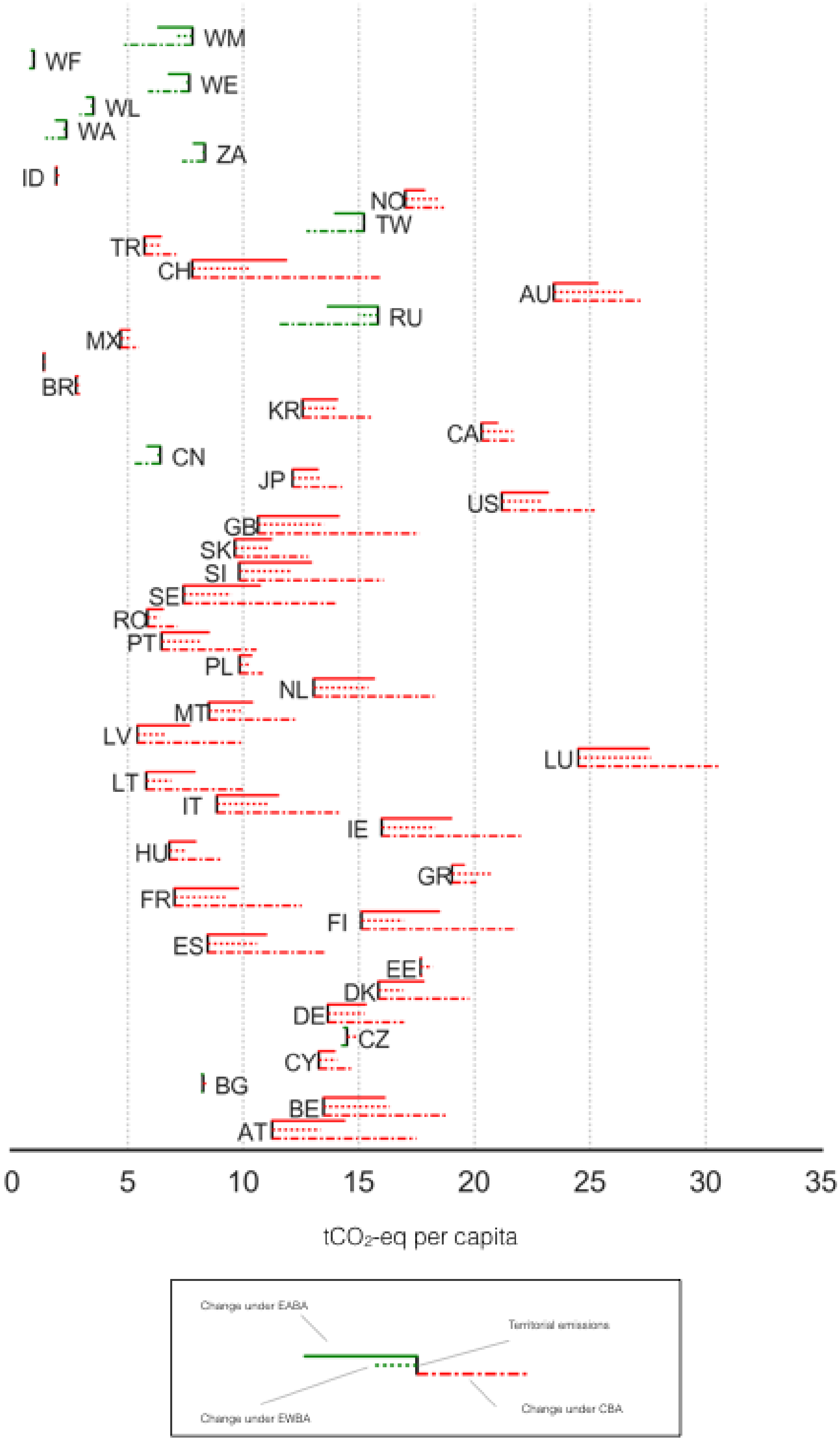

FIGURE B.11: **CO_2-eq change from territorial emissions (PBA) to CBA, EABA, and EWBA accounting for 2007.** CO_2-eq do not suggest drastically different abatement responsibility when compared with CO_2 alone

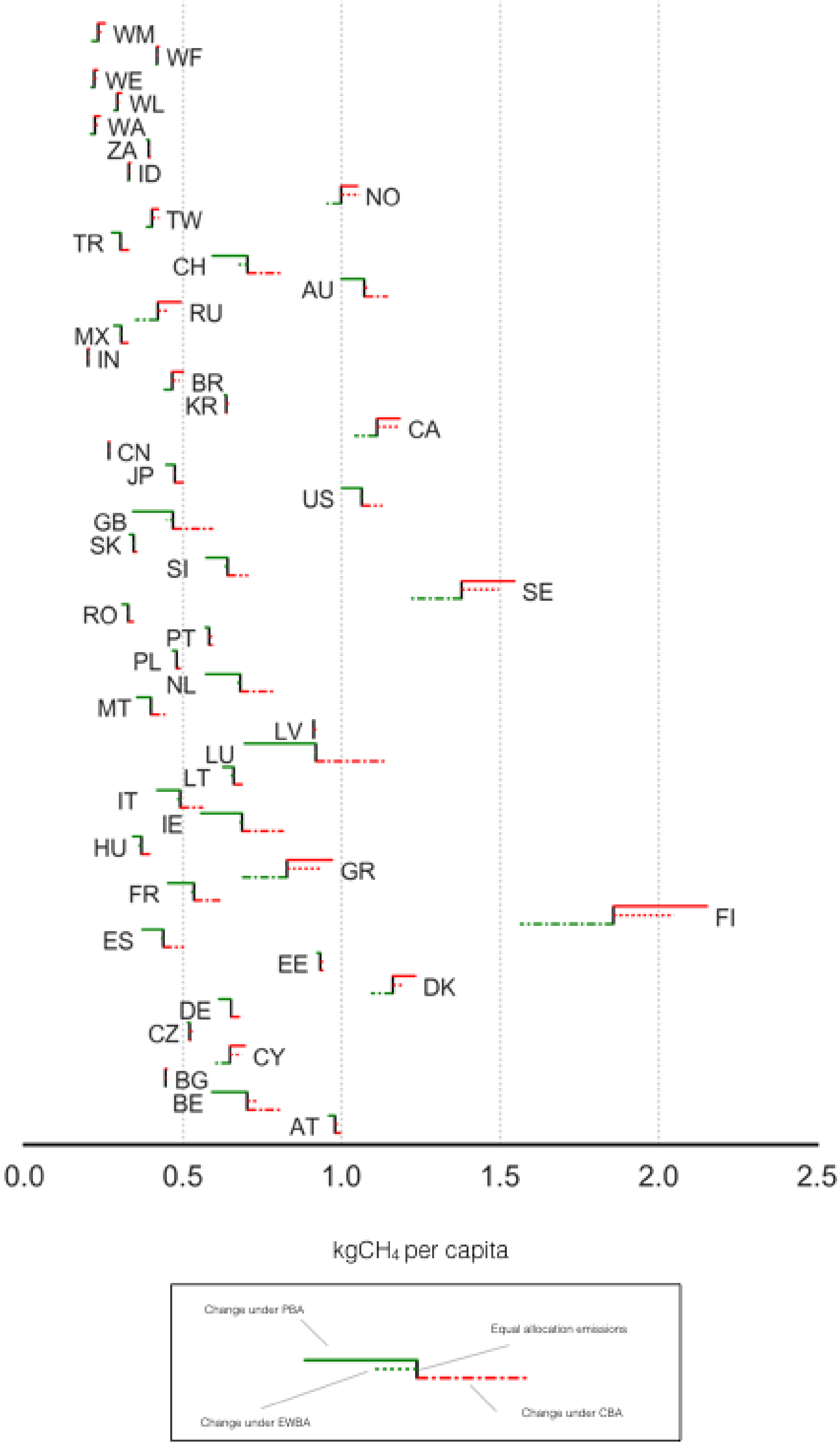

FIGURE B.12: **CH_4 change from equal allocation emissions to PBA, CBA, and EWBA accounting for 2007.** For many countries, EWBA accounting suggests different abatement responsibility (carbon footprint) than do CBA or PBA.

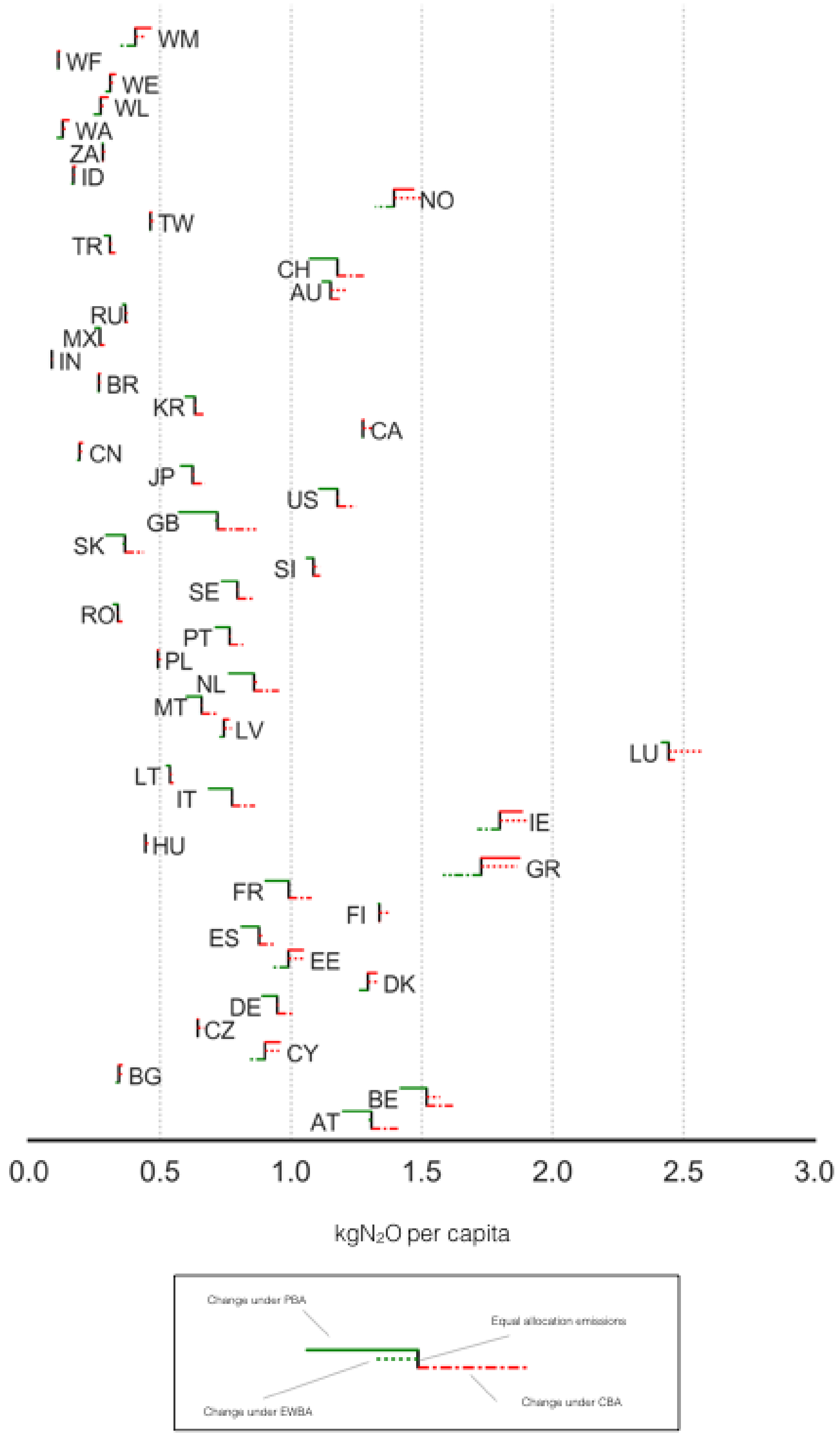

FIGURE B.13: **N_2O change from equal allocation emissions to PBA, CBA, and EWBA accounting for 2007.** For many countries, EWBA accounting suggests different abatement responsibility (carbon footprint) than do CBA or PBA.

Change from PBA to EWBA	
Region	%
WA	-7.3
WM	-5.2
TW	-4.3
WE	-3.4
CN	-2.9
WL	-2.4
RU	-2.2
BG	-1.6
ZA	-1.1
EE	1.1
CY	1.6
IN	1.8
WF	1.9
GR	2.3
CZ	2.3
PL	3.5
DK	3.8
ID	4.9
LU	5.1
CA	5.8
KR	6.0
BR	6.1
US	6.2
JP	6.6
HU	8.1
RO	8.2
MT	8.3
FI	8.5
MX	8.6
NO	8.7
DE	9.2
IE	11.7
TR	12.1
AU	13.3
SI	14.8
NL	15.0
LV	15.1
LT	16.2
PT	17.2
AT	17.8
ES	17.8
IT	18.2
SK	18.4
BE	19.1
GB	22.6
FR	24.0
SE	28.3
CH	30.7

Table B.1: Change from PBA to EWBA

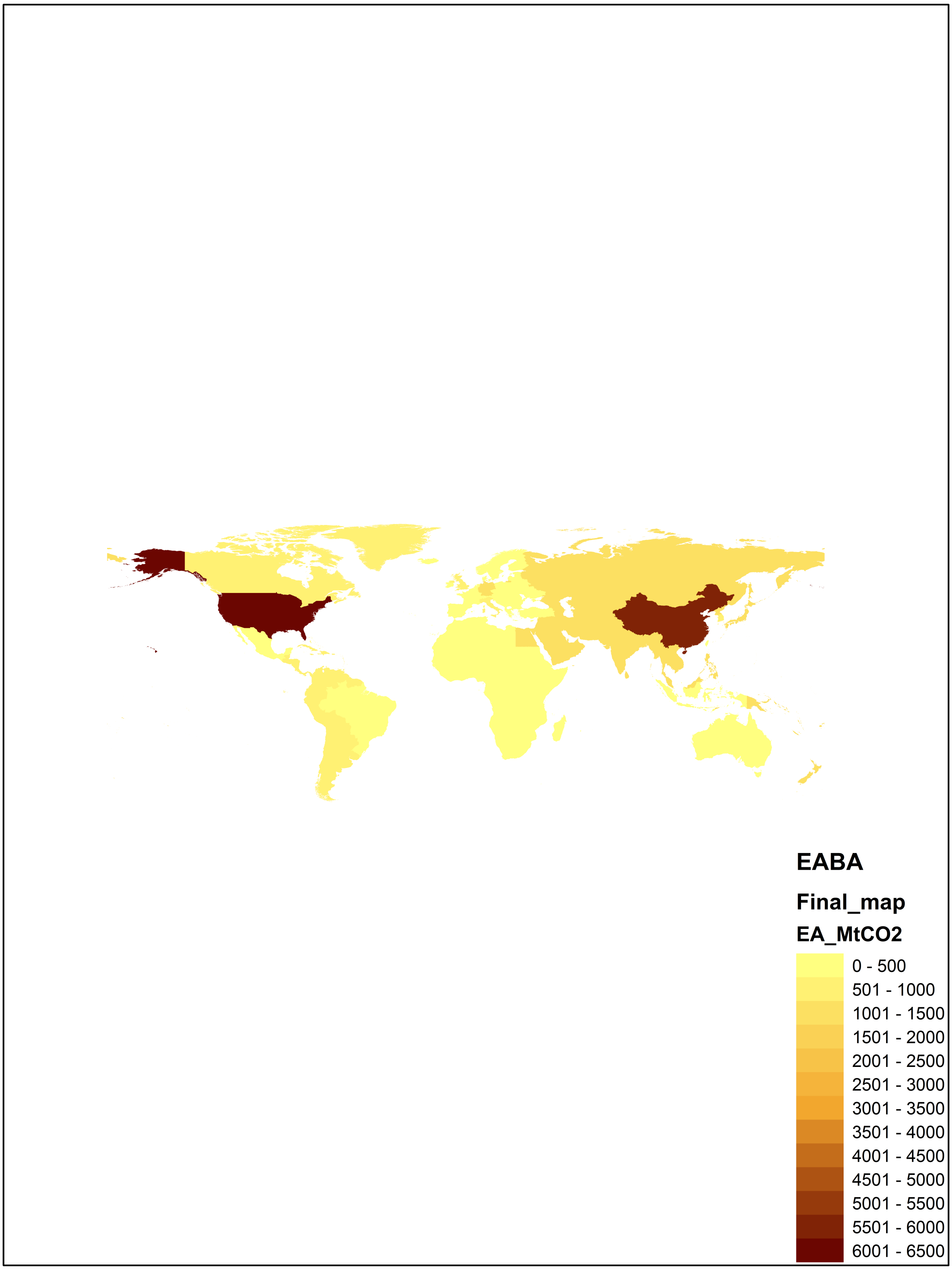

FIGURE B.14: **EABA national emissions for 2007**. Rest of World regions display aggregate emissions.

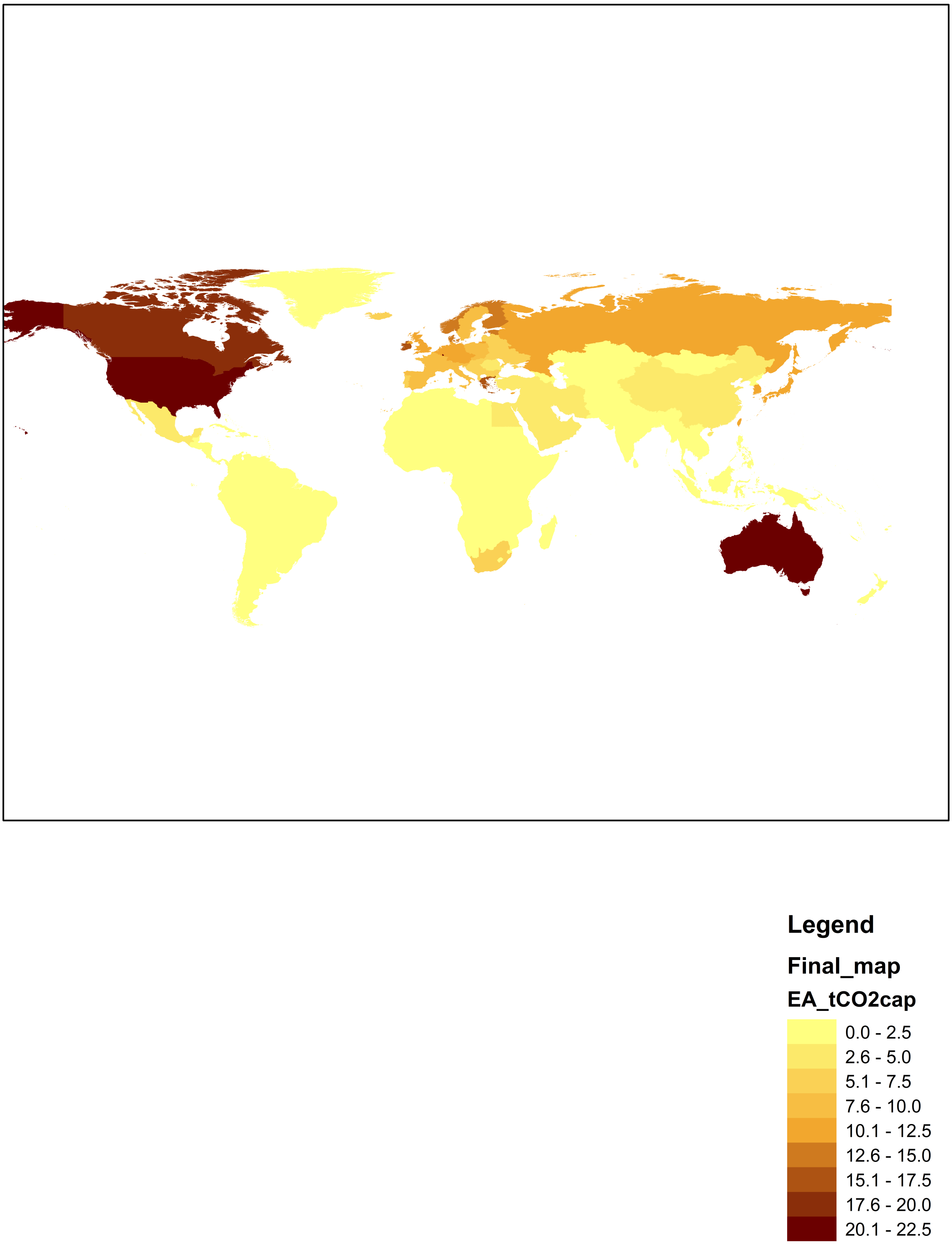

FIGURE B.15: **EABA per capita emissions for 2007**. Rest of World regions display aggregate emissions.

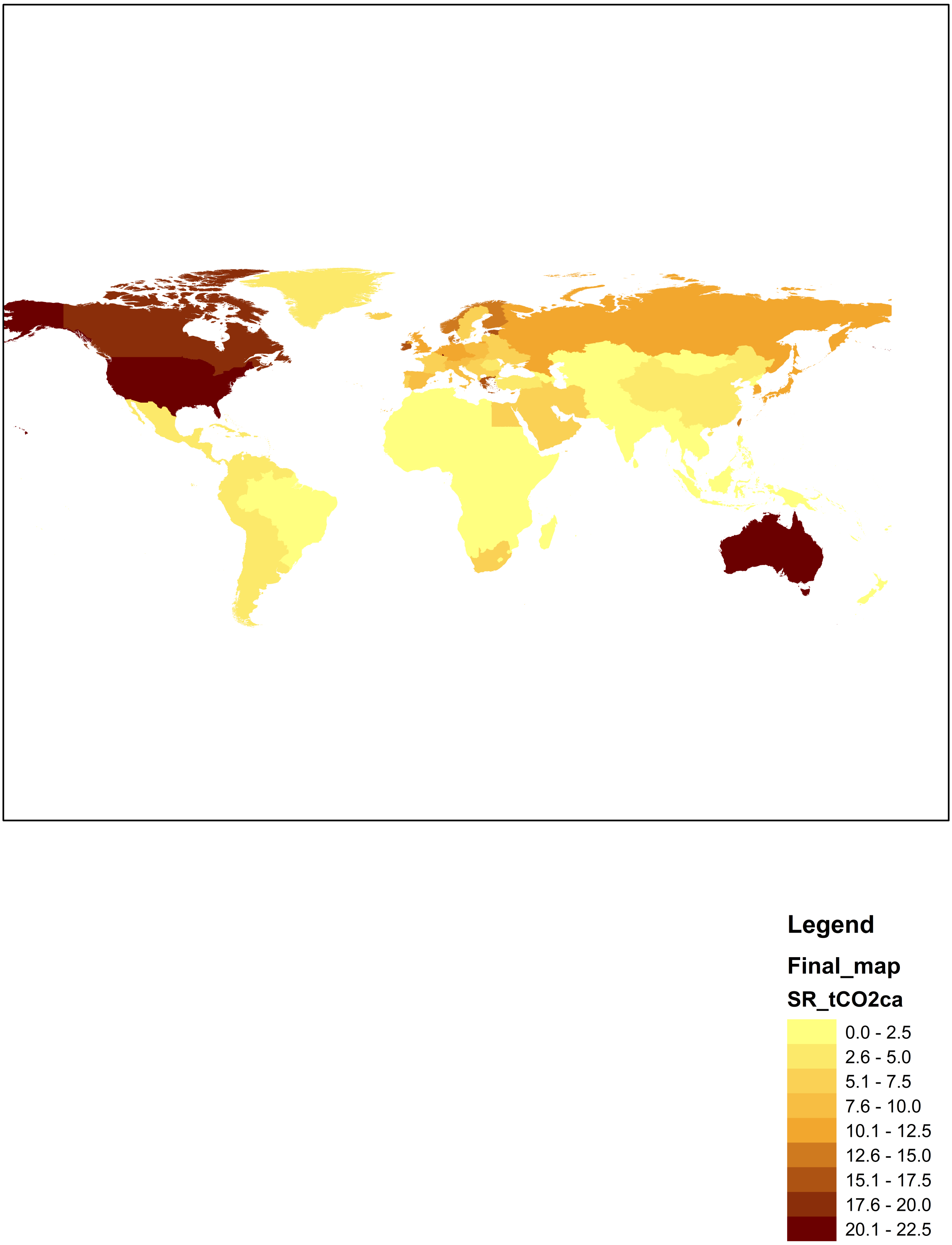

FIGURE B.16: **EWBA per capita emissions for 2007**. Rest of World regions display aggregate emissions.

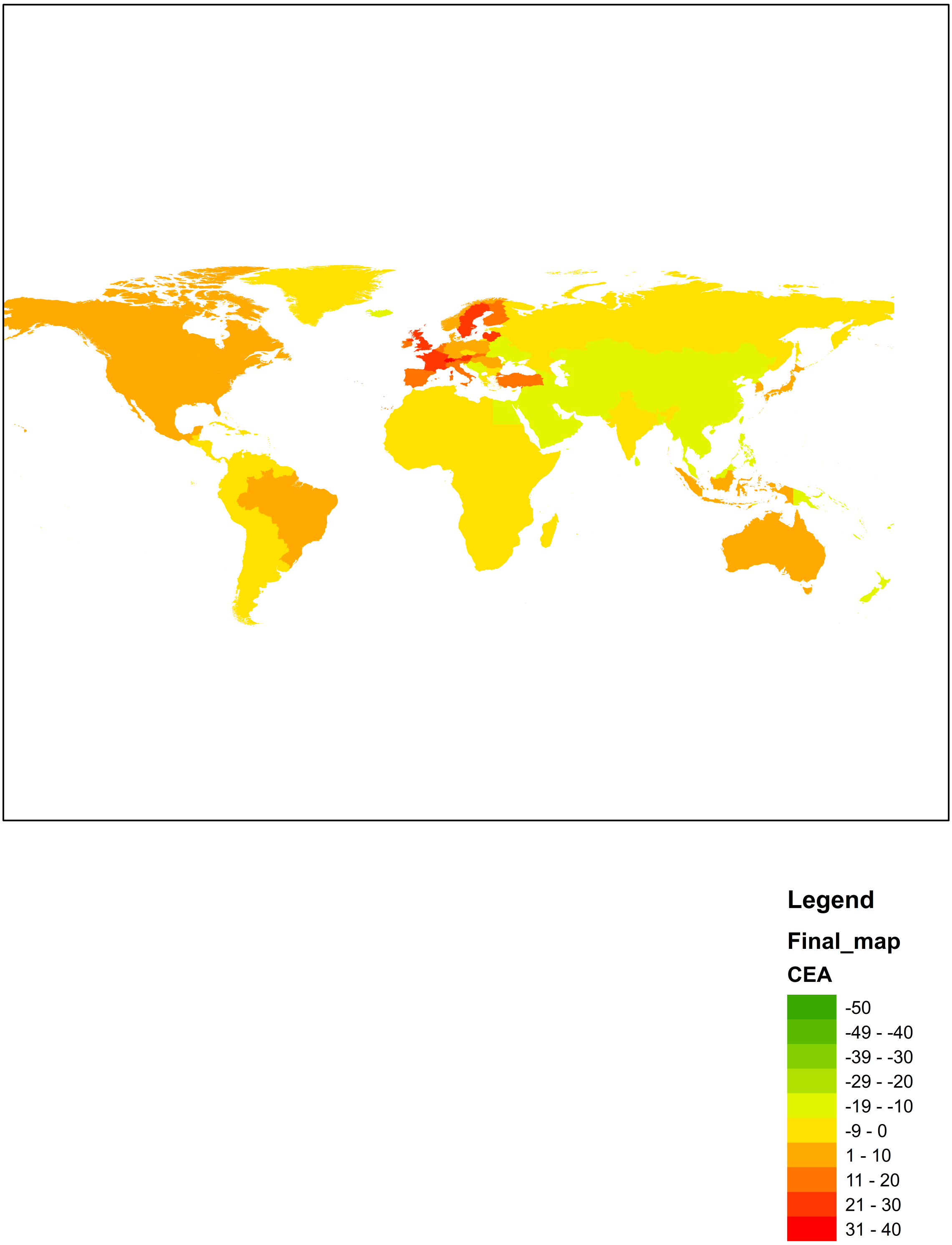

FIGURE B.17: **Percent change of CBA from EABA for 2007.**

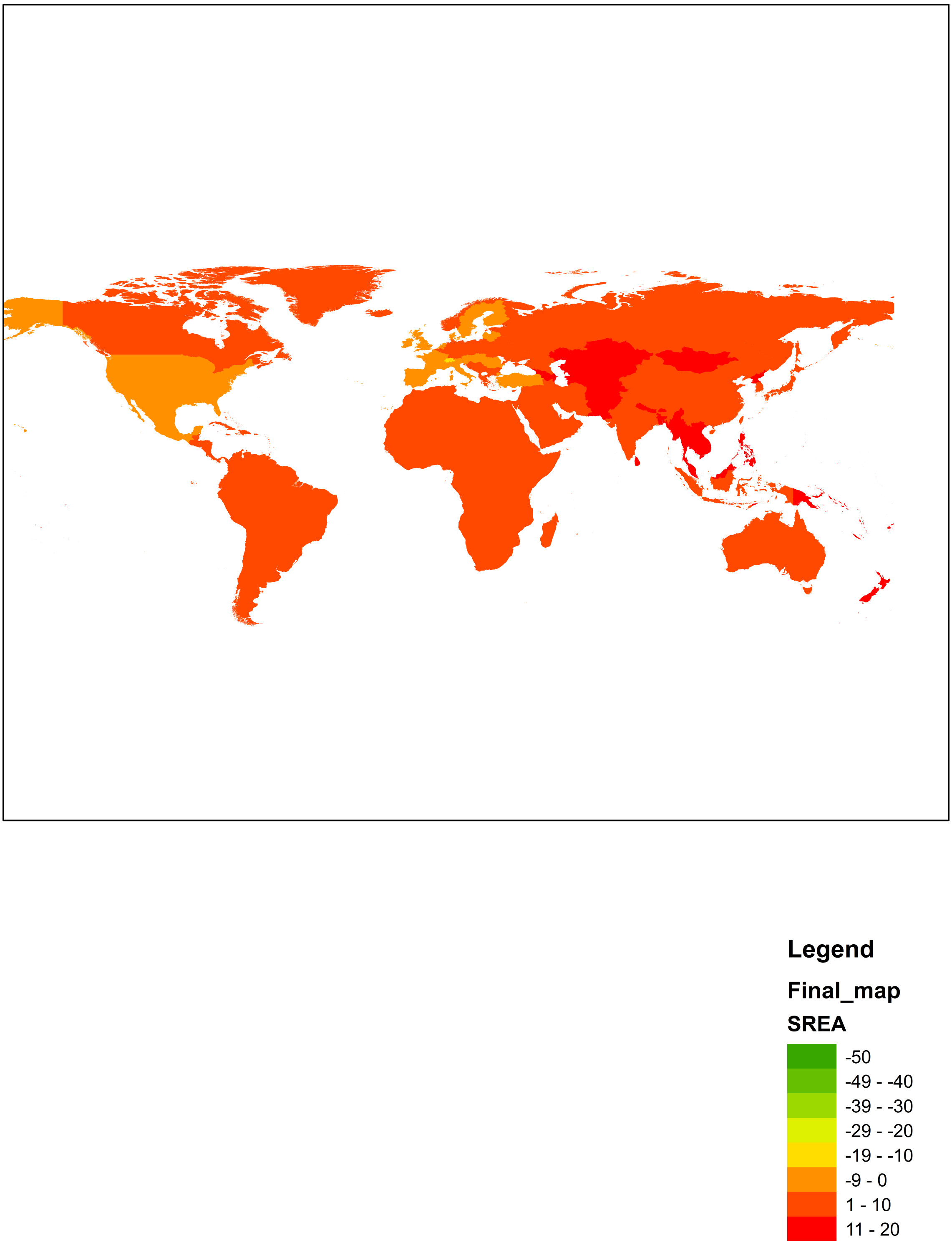

FIGURE B.18: **Percent change of EWBA from EABA for 2007.**

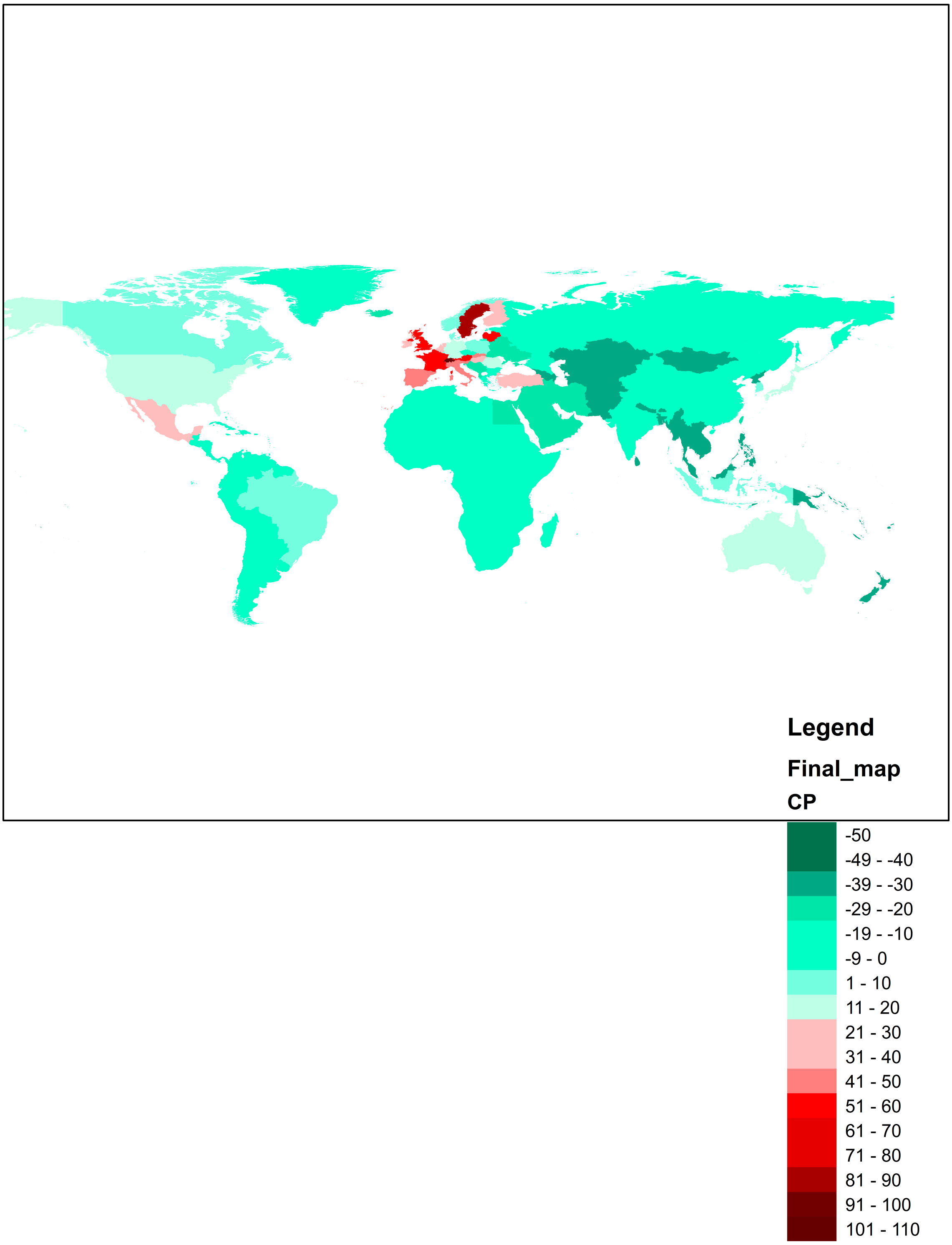

FIGURE B.19: **Percent change of CBA from PBA for 2007.**

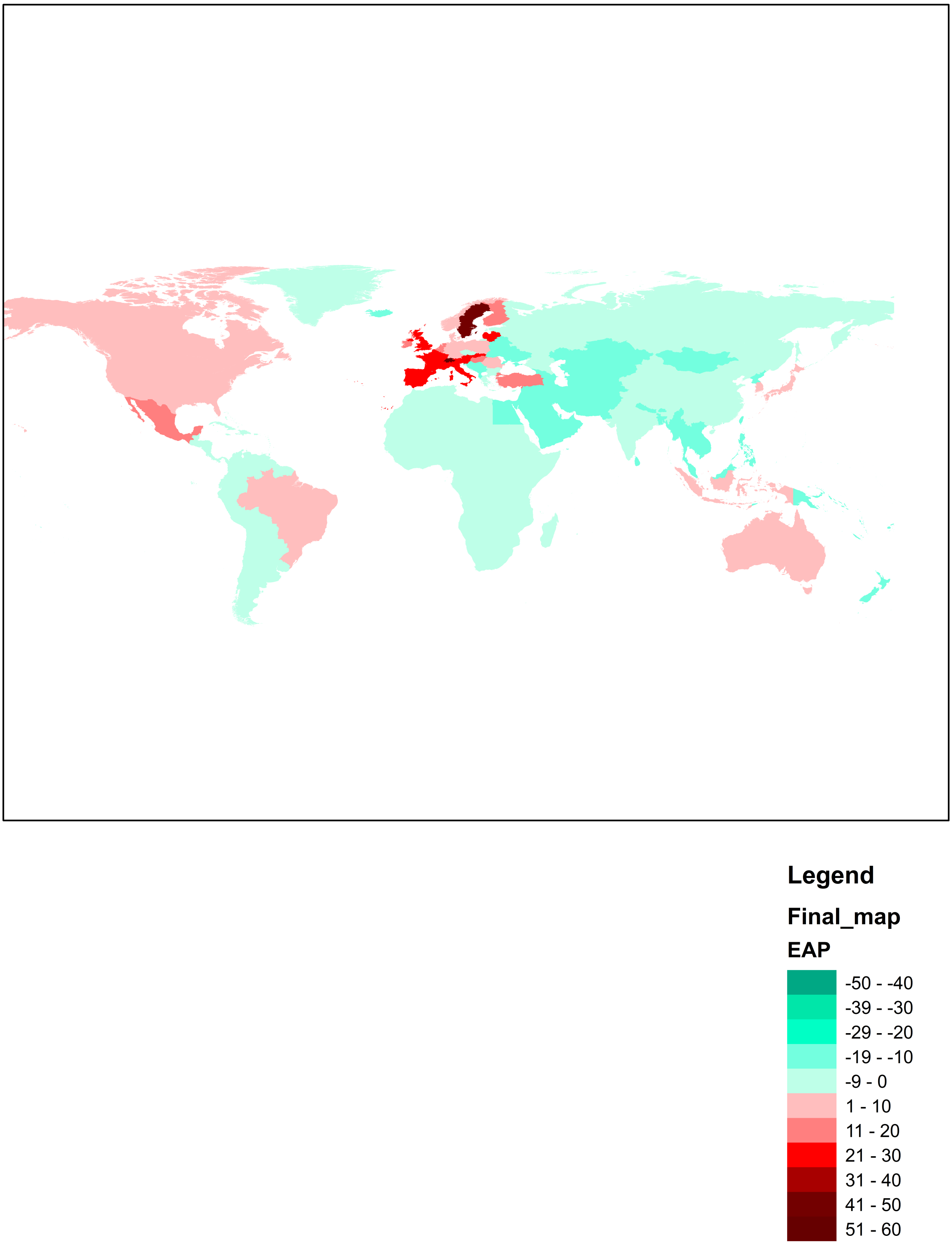

FIGURE B.20: **Percent change of EABA from PBA for 2007.**

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