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Multiple carbon accounting to support just and effective climate policies

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Negotiating reductions in greenhouse gas emission involves the allocation of emissions and of emission reductions to specific agents, and notably, within the current UN framework, to associated countries. As production takes place in supply chains, increasingly extending over several countries, there are various options available in which emissions originating from one and the same activity may be attributed to different agents along the supply chain and thus to different countries. In this way, several distinct types of national carbon accounts can be constructed. We argue that these accounts will typically differ in the information they provide to individual countries on the effects their actions have on global emissions; and they may also, to varying degrees, prove useful in supporting the pursuit of an effective and just climate policy. None of the accounting systems, however, prove 'best' in achieving these aims under real-world circumstances; we thus suggest compiling reliable data to aid in the consistent calculation of multiple carbon accounts on a global level.

The current UN emission allocation system for greenhouse gases (GHG) attributes emissions to that country in which emissions physically occur during production (production-based principle)[1]. Three core alternative forms of emission accounting principles have been proposed in the literature. First, irrespective of where they emerge in the supply chain, emissions could be attributed to the country that extracts the fossil fuels that allow for these emissions (extraction-based principle)[2]. Second, one could acknowledge that factors other than fossil fuels, such as labour and capital, also benefit from a polluting production process by earning income (wages, interest, rents). Thus, all emissions discharged along the supply chain could be attributed to specific agents (and countries) according to the value they add in production, and thus according to the income they earn (income-based principle, also known as 'enabled' emissions or downstream responsibility)[3,4]. Finally, emissions occurring in the production process may also be attributed to the very end of the supply chain, that is, to the consumers (or more precisely: the final users) and their country of residence (consumption-based principle, upstream responsibility)[5,6].

As shown in Fig. 1, the global distribution of per capita GHG emissions varies considerably depending on which of these four principles is employed.

'Responsibility' and the question of justice

Propositions for using any one of the above accounting systems are often framed in terms of a need to attach 'responsibility for emissions' to a particular type of agent (consumer, producer, extractor or income beneficiary) and consequently to allocate emissions to that agent[3,4,7–12]. This literature can be interpreted to be based on the principle of compensatory justice (that is, the obligation to compensate for the damage arising[3,4,11] or the benefits gained[7,9] from emissions).

We, however, suggest that the question of how one should respond to climate damage is primarily a question of distributive justice and is thus more a matter of redistribution than of compensation. Distributive justice, as understood here, specifies a baseline distribution in accordance with a specific criterion (such as strict equality or sufficiency) and allows for changes of this distribution owing to people's own responsible (and non-wrongful) choices. Deviations from the baseline may be the result of luck, wrongful harm-doing, or wrongless harm-doing. A duty of compensation only arises in cases of wrongful harm-doing. Any responsibilities to pay for climate damages or measures of adaptation that cannot be linked to wrongful harm-doing must be justified by the redistributive rationale[13–15].

There are three main relevant principles of compensatory justice[16–19]: the 'polluter pays' principle (PPP) attributes the compensation responsibility to the wrongful emitter, the 'beneficiary pays' principle (BPP) to the beneficiary of wrongful emissions, and the 'community pays' principle (CPP) to people based on their membership of a community in which they or some other (previous) members caused the wrongful emissions[20–24]. In contexts other than climate change, PPP is more widely accepted than either BPP or CPP.

At least four problems arise when determining compensation on the basis of PPP. First, there is the problem of identifying those agents who are causally responsible for the harmful emissions. Applying the 'but-for' test is no help. No matter for which agent we perform the test, we find that but for their actions there would have been no emissions[25–30]. Second, there is no agreement on how to determine relative causal shares in any instance of joint causation of harm, where each single agent's contributions were neither necessary nor sufficient[31,32]. Third, it is difficult to identify those people harmed in the future as a result of actions carried out in the present, when the latter are necessary conditions for the very existence of the allegedly harmed persons, provided that these persons will have 'a life worth living' (the so-called non-identity problem)[33,34]. Fourth, potential bearers of compensatory duties might be blamelessly ignorant of the harmful impact of their emission-generating activities. Even if they can be said to have known about the consequences, their actions may be permissible if restricting their emissions to protect future generations would place excessive demands on them[35–38].

These problems have the potential to seriously limit the applicability of compensatory justice. Thus, compensation payments for

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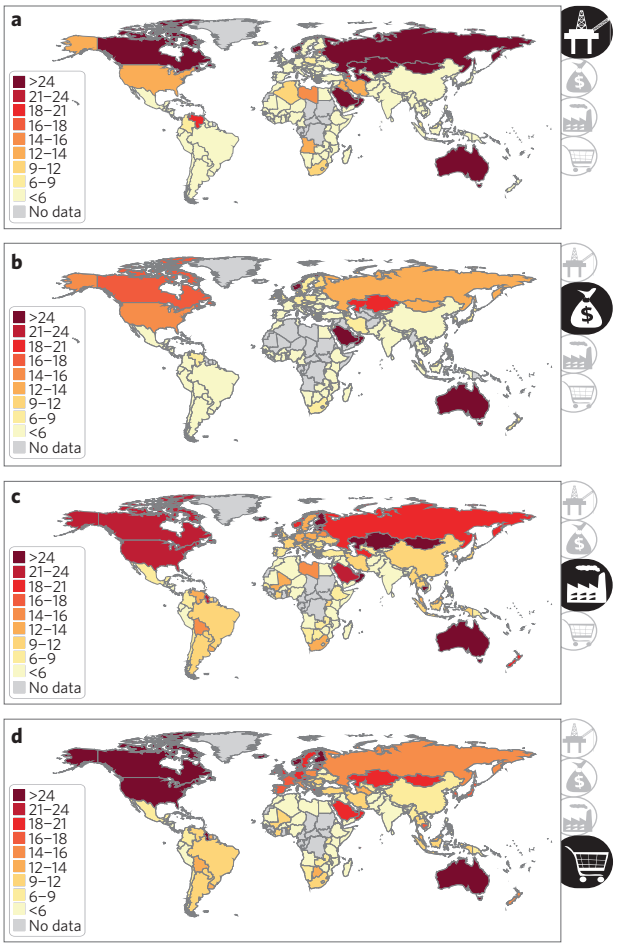

Figure 1 | Countries' emissions per capita according to different accounting principles (in the year 2011). a–d, Panels show emissions, in tonnes CO_2 or CO_2 equivalent, according to: extraction-based accounting, reflecting the carbon content of fossil fuels extracted (**a**); income-based accounting, 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[98]). See Supplementary Information for methodological and data information, and additional panels. Figure courtesy of Sabine Tschürtz

climate damage are very difficult to justify. Insofar as justifications succeed, they do so only for a fraction of those who cause and those who suffer from climate change. This has been shown for all three principles of compensatory justice distinguished above[18]. For our context, this means that even if the harm caused by emission-generating activities could be determined (the third problem) and the blameworthiness of the agents causing the harm established (the fourth problem), we will not be able to identify single (groups of) agents in the supply chain (the extractor, the income generator, the producer or the consumer) as the agents solely responsible for emissions (the first problem), and the question of meaningfully apportioning responsibility among the agents remains highly contentious (the second problem).

However, as many effects of climate change can be seen as undeserved harms, often associated with undeserved benefits for others, attempting to equalize climate effect impacts on the basis of a concern for distributive justice seems more promising. Given the limited applicability of compensatory justice, the focus should be directed towards achieving a more equitable distribution of undeserved benefits and harms rather than focusing on compensating wronged persons[36,39–41].

Assessing policies in terms of distributive justice, however, is outcome-oriented. We ask whose well-being is affected by a specific policy, and we usually find that not only those who have to carry out the policy are affected. For example, using a production-based accounting system, climate policy might take the form of a carbon tax applied to the emissions recorded in production-based emissions accounts. This, however, does not imply that the producer will bear the full tax burden. As analysed in the tax incidence literature[42], part of or even the entire tax burden will be passed on to consumers and suppliers of factors of production. A similar argument can be made for other types of policy instruments and for the other accounting principles. In general, irrespective of which accounting system is chosen, typically all agents along the supply chain are affected. Thus, to evaluate policy outcomes in terms of distributive justice we have to analyse the effects of abatement policies based on the respective accounting principle, and not simply rely on having selected a particular accounting system. For example, it is sometimes argued that consumption-based accounting is 'fairer' than production-based accounting[9,10] because it attributes a larger share of global emissions to industrialized countries. But if consumption-based policies are adopted to meet these targets, the conclusions drawn with respect to 'fairness' may actually be reversed[43], as some types of such policies have been found to pass on a larger part of the abatement burden to developing and emerging economies[44,45].

Different uses of GHG accounts and evaluation criteria

As the concept of 'responsibility' is therefore not sufficient as a criterion for selecting a specific accounting principle, we need to employ other criteria. There is a broad consensus that international climate policy should be both just and effective[46]. The system of GHG accounts adopted should support just and effective policymaking. We use two effectiveness criteria suggested by the Intergovernmental Panel on Climate Change — environmental effectiveness and cost-effectiveness[46] — as well as the carbon leakage criterion (affecting both environmental and cost-effectiveness) for comparing policies based on the different GHG accounting principles. The question of justice is evaluated in an outcome-orientated way: by identifying the international distributional effects of the respective policies.

National GHG accounts are employed nationally and internationally (for example in the UN Framework Convention on Climate Change, UNFCCC) for a number of different purposes. First, such accounts serve as a reference scale for internationally agreed abatement targets (they serve as a target base[47]). The Kyoto Protocol is a prime example. Second, individual countries use national GHG accounts to evaluate how their actions and policies influence GHG emissions (monitoring base). Third, policy instruments could target exactly those emissions that are recorded in GHG accounts (instrument base[43,47]).

Often, these three uses of carbon accounts go hand-in-hand. For example, under the current system of production-based targets, it is natural for individual countries (interested in a good performance with respect to these targets) to use their production-based GHG accounts also as their prime monitoring base. Furthermore, the most effective policy in meeting production-based targets is one geared exactly to those emissions registered in production-based GHG accounts, that is, a policy relying on the same accounts as an instrument base. A similar argument can be made for all the GHG accounting principles[43].

By deciding on a target base, international climate negotiators thus have some control over the type of climate policy that individual countries choose. This is important for assessing the 'effectiveness' and 'justice' of the four types of GHG accounting systems.

As argued above, it is not the accounting system as such that can be considered 'just'; and, equally, 'effectiveness' does not depend on the accounting system as such. Rather, one has to analyse the impacts of the policy implied by the respective accounting principle[47].

The type of climate policy currently almost universally followed qualifies as a production-based policy. Consumption-based policies, although discussed in the literature[43,47–50], have so far not been implemented in practice, at least not across their full range. One implementation option of such a policy is the use of full border carbon adjustments (BCA)[48]. There is a rich literature both on the possible effects of BCA[44,51–55] and on options for their practical implementation[56–59]. The exemption of exports from GHG pricing (as implemented within the EU Emissions Trading System[60] for carbon intensive and trade-exposed industries) can be seen as an example of a partial BCA application. As regards extraction-based policies — currently being discussed under the rubric of 'supply-side' policies — several proposals exist concerning the introduction of (tradable) depletion quotas or rights to exploit fossil fuel deposits[61], or carbon-pricing at the point of extraction[2].

Insights from the analysis of an idealized setting

The advantages and disadvantages of the adoption of each of the four accounting principles crucially depend on the economic and institutional implementation environment. To provide a point of reference, we first analyse an idealized setting, considered 'first-best' by neoclassical economists. If markets are complete and fully competitive, and if climate policy (i) covers all GHG emissions globally and (ii) imposes (at least implicitly) a globally uniform (shadow) price on each type of GHG (which, if it equals marginal damages, additionally ensures overall efficiency), then environmental and cost-effectiveness are guaranteed irrespective of which accounting system is chosen, that is, irrespective of where in the supply chain (extractor, producer, income beneficiary or consumer) the targets are set and the instruments are applied. In such a setting, markets pass on the incentives fully to all other agents in the supply chain, both upstream and downstream.

In a similar fashion, all the burdens and benefits of the policy are also passed on. To which agent they accrue depends only on the elasticities of supply and demand for goods and primary inputs, but not on the accounting system. Thus, theoretically, the same international distribution of income can be achieved irrespective of which of the four accounting systems (and corresponding policies) is chosen. This, however, requires that — for example, if climate policy is negotiated by means of the allocation of GHG emission rights — country endowments are set accordingly; for instance, countries can be endowed with production-based emission permits or a corresponding amount of extraction-based emission permits. Political feasibility may, however, require a different allocation: extraction-based permits might be distributed only to extracting countries if an extraction-based accounting principle is introduced, for example, whereas under a production-based system permits might only go to countries hosting emitting industries. Thus, the choice of a particular accounting system may also have distributional implications.

Evaluation for 'real-world' circumstances

Reality is characterized neither by complete and fully competitive markets nor by the near-term possibility of implementing a climate policy that encompasses all GHG emissions globally and that results at least implicitly in a uniform CO_2 equivalent (CO_2e) price across all GHGs and countries. In such a 'second-best' world, climate policies pursued by individual countries or 'coalitions of the willing' are (globally) less environmental and cost-effective than in a 'first-best' world. How much effectiveness is lost typically depends on the particular accounting system choice (and the associated policies)[62].

Countries can influence three core areas by their climate policy — their production, their consumption and their extraction of fossil fuels. Each of these policy areas is reflected, and best covered in terms of direct impacts on emissions, by one of the accounting approaches. Note that it is debatable whether downstream emissions, as recorded in income-based emissions accounts, can be directly addressed by policy. But although production-based, consumption-based and extraction-based accounts are ideally suited to reflecting the impacts of specific policies, none of the four accounting methods covers all emissions that a country can influence and that it therefore could address through its policies; that is, they all have their policy 'blind spots'. Thus, some emission reduction potentials are likely to remain unexploited. In particular, (i) the production-based accounting principle reflects neither a country's discretion with respect to choice of import supplier (and the corresponding GHG intensity of imports) nor its discretion with respect to the emissions enabled by fossil fuels extracted and exported; (ii) the consumption-based principle fails to reflect a country's discretion regarding its own exports (and their carbon intensity) and the fuels extracted and exported; (iii) the extraction-based principle fails to reflect a country's discretion concerning production and consumption; and (iv) the income-based principle captures emissions associated with how a country earns its income, but not those related to how the income is spent.

But these most obvious ones are not the only 'blind spots'. In countries where national climate policy is not synchronized with global policy, national activities and policies may impact global emission levels indirectly through 'carbon leakage'[49,63,64]. Carbon leakage refers to a change in emissions in non-abating countries that is triggered by the introduction of a (stricter) climate policy in abating countries. To date, this has primarily been analysed for production-based policies[65]. In the respective literature, the most important of these indirect and typically unintended impacts are referred to as 'leakage channels' and include the following effects: (i) national production-based climate policy may trigger redirection of trade flows or relocation of industry to other countries and thus increase emissions there (relocation or competitiveness channel); (ii) climate policy may reduce global demand for fossil fuels and consequently bring down world fuel prices leading to a rise in fossil fuel demand (and thus in emissions) in 'uncapped' world regions (energy market channel); (iii) climate policy induces a redistribution of income, typically causing changes in global emissions (income channel); (iv) climate policy induces development of (clean) technologies with possible spillover to other countries (technology spillover channel). The leakage concept can also be generalized to apply to the other accounting principles[43,47]. For example, for extraction-based accounting and related policies, the relocation channel may be considered to refer to the relocation of production capacities in extraction to uncapped regions. Leakage typically lowers the environmental and cost-effectiveness of a policy.

In comparing the four accounting principles, we often find that leakage reduction through one channel is associated with a rise in leakage through some other channel. For example, relative to production-based accounting, the extraction-based approach and an associated policy followed by some, but not all, extracting countries does not redirect trade flows in intermediate and final goods or lead to relocation of industry producing these goods, but may cause a redirection of trade in fossil fuels and a relocation of extraction sites to extracting countries that are not part of the abating coalition. These countries may also experience an increase in resource rents, possibly triggering emission effects through the income channel.

The blind spots of production-based accounting (and production-based policy variants) have been extensively studied in the literature on quantitative carbon leakage by means of multiregional computable general equilibrium models. For larger abating coalitions, the energy market channel is typically found to be the quantitatively most important leakage channel, whereas for smaller coalitions the competitiveness channel usually dominates[66]. The literature on BCA provides insights into the effects of

consumption-based policy variants. These may involve less leakage through the competitiveness channel than production-based policies, but if introduced by simple, easy-to-administer forms of BCA, there seems to be little difference between the two policy variants in terms of cost-effectiveness[67]. Furthermore, the consumption-based policies' distributional effects typically work to the disadvantage of developing and emerging economies[44]. Little is known about the quantitative importance of blind spots under extraction-based and income-based accounting. As energy market leakage seems to be large under the current accounting system, the further study of accounting systems that directly address fossil fuel supply, such as those based on extraction-based accounting, may be warranted[2,68].

It has been suggested that some of the four accounting systems described here be combined into a single indicator[7,9,11,12]. Some such proposals intend thereby to affect abatement burden-sharing, for example, between producers and consumers[9,10]. But as burdens are passed on to others, the specific shares used in combining accounting indicators are unlikely to directly inform us about how burden-sharing is really affected[47]. As the distribution of burdens depends on demand and supply elasticities, only a model-based analysis of the proposed combined indicators will reveal their impacts on burden-sharing. Another motivation for constructing combined indicators is to provide countries with an improved instrument — with fewer blind spots — to monitor their own policy. The recent proposal of technology-adjusted consumption-based accounting[69] is an improvement on consumption-based accounting in that it addresses the blind spot of a country's exports. Unfortunately, it introduces other shortcomings. For example, as emissions are not uniformly weighted, even when applied in a 'first-best' setting, policies based on this indicator clearly lead to inefficiencies; in a 'second-best' setting its properties depend on the specifics of the situation studied.

We conclude that all accounting systems (including single-indicator combinations of them) and related policies are characterized by blind spots and leakage effects. Notwithstanding this, there are still some general arguments that support the use of specific accounting systems. These are discussed below.

Scope of emissions covered. In contrast to the other accounting principles, extraction-based accounting — at least in the form proposed in the literature[2] — does not cover all GHGs. Only CO_2 emissions are included, and not even all of those; process-related CO_2 emissions not linked to fossil fuels (such as CO_2 emissions from the chemical process in cement production) are not covered. On the other hand, even those fuels that are not combusted immediately, but used as material input (for example to produce plastics), may be wrongly counted as emissions contributors. Therefore, extraction-based accounts are not suitable for use as the sole GHG emission monitoring or target base.

Achievable environmental stringency. In a second-best world, both the level of environmental stringency achievable and the scope of emissions targeted in abatement are likely to differ across GHG accounting systems. Environmental stringency on a global level may be enhanced by adopting an accounting system that allocates a larger share of emissions — and thus emission reductions — to those countries that express a stronger willingness to abate. Judging by the pledges made under the current UNFCCC process, extracting countries seem, on average, to be less ambitious than many industrialized countries[70,71]. This suggests that using a consumption-based or income-based accounting system as a target base rather than an extraction-based one is likely to enable stronger actual reductions.

Transaction cost. As there are far fewer parties extracting fossil fuels than there are burning these fuels or consuming goods that have been produced using fossil energy, transaction costs associated with monitoring and policy implementation are likely to be lowest in extraction-based accounting.[2] Production-based accounting has benefited from the institutional and practical experience that has been gained through its use by the UNFCCC. This may have lowered respective transaction costs. No such experience has been gained with respect to consumption-based accounting. In addition, proposals for its practical implementation[59] (even simple ones relying on benchmarks[56–58]) seem to involve implementation and monitoring costs exceeding those of production-based accounting.

Data uncertainty. The degree of uncertainty for production-based accounting has repeatedly been analysed[72–75]. For country-level fossil CO_2 emissions, estimates of the 95% confidence interval uncertainties range from 3–5% up to 50% or more for countries with poor statistical infrastructures[76]. Global emissions shift towards the latter type of countries; revisions thus are often of global significance[77]. Income- and consumption-based accounts, on the other hand, are typically based on the production-based accounting system and make use of additional modelling assumptions, for example by relying on sectoral carbon intensities in foreign trade[78]. They thus suffer from both the uncertainties of production-based accounting and those stemming from their own assumptions, with indications that the former fraction of uncertainty is larger than the latter[79,80].

In addition, for reasons of practicability, consumption-based and income-based approaches may use sectoral averages rather than product-specific carbon data. Thus the actual content of carbon embodied in a specific product might diverge hugely from that registered in the accounting scheme, raising concerns in terms of procedural justice and transparency. Agreed-upon international norms may help to overcome these concerns and to ease trade-related product-oriented climate policies[50], much as the adoption of the GATT rules of origin did.

Beyond production-based GHG accounting in practice

We have compared consumption-, income- and extraction-based accounting to the currently applied principle of production-based accounting. Apart from these four accounting methods, which involve only current emissions, methods including historic[81] or future (committed) emissions[82–84] as well as methods relating to different levels of actors (governments, corporations, individuals)[85–87] or addressing national dependence[88] are discussed in the literature. In principle, accounts for historic or committed emissions can be generated according to each of the four accounting methods introduced here, for example for consumption-based emissions[89]. Often, the inclusion of historic emissions intends to rebalance the international distribution of abatement burdens. Our discussion, however, shows that thereby in a second-best world the effectiveness of the associated policies may also be altered. An in-depth discussion of these further accounting dimensions and their links to our analysis is beyond the scope of this Perspective.

Regarding the four accounting principles (and related policies) considered here, our discussion has shown that in a second-best world we cannot expect one policy option to fare best in terms of effectiveness or justice under all circumstances; what is best depends on the situation at hand. The possibility of using not just one but all four accounts will open up new options for the monitoring of emissions and for policy design in individual countries, 'coalitions of the willing' and the UNFCCC. In the following, we present four such options.

Multiple monitoring bases. If the international climate policy framework continues to rely on a single type of abatement target such as production-based emissions, the three other carbon accounts could still be used as additional monitoring bases. This would provide countries with a more complete picture of the effects of their actions and policies[90]. Such *ex-post* policy performance analysis would be advantageous in that it would help inform the debate

on mitigation in international climate negotiations[91], and could thus aid the development of future policy options. 'Better' monitoring may thus be seen as a first step on the way to 'better' policies.

Switching the internationally agreed target base. Some early authors suggested a switch in UN GHG accounting and target-setting to a consumption-based system[5]. Also, the possible advantages of the adoption of extraction-based accounting[2] and policies[68] have been explored. In the short term, however, international agreement on a switch in the target base seems unlikely. Our discussion shows that although such a switch may improve policy performance in terms of some criteria, it also introduces further problems. In particular, using extraction-based accounts as a target and instrument base may reduce transaction costs, but as only CO_2 and not even all CO_2 emissions are covered, additional accounting schemes for other GHGs would need to be introduced; also, the level of policy stringency achievable might be low. On the other hand, to be cost-effective, a fully consumption-oriented target and instrument system requires information on embodied carbon established globally by bottom-up methods[43] — which does not seem practicable at the moment — or alternatively, that mitigation projects in countries that are not part of the 'coalition of the willing' are directly supported[92].

Multiple instrument bases. If the international target base remains production-based, in a second-best world, countries willing to pursue an ambitious climate policy may nevertheless find that the optimal policy mix uses a combination of instruments based on different accounting systems to minimize leakage. For example, proposals for BCAs that include only imports but not exports[57–59] combine a production-based with a consumption-based approach. Other combinations of accounting systems are conceivable: for example, some countries might be willing to complement the current production-based instruments by using depletion quotas, an extraction-based policy instrument.

Parallel agreements based on different accounting systems. The scope of emissions targeted in reduction may be enhanced on a global level not only by increasing the number of countries that commit themselves to targets under the current production-based system, but also by complementing these commitments by ones based on an alternative accounting principle. This suggests that research on parallel climate agreements among disjunctive or partly overlapping groups of participating countries may be warranted. For example, if a group of countries coordinates to introduce BCA, this constitutes an agreement on consumption-based accounting in parallel to the UNFCCC's production-based system. As another example, imagine a group of extracting countries that follow the example of Ecuador's Yasuni ITT initiative and agree on a permanent confiscation of a fraction of *in situ* carbon resources[93] accompanied by financial compensation. As shown for the current system, overlapping regulations may, however, also have adverse effects on policy effectiveness[94]. In addition, negotiations on multiple agreements may slow down progress on a globally coordinated and harmonized abatement strategy. Multi-agreement paths therefore need to be explored carefully before any conclusions are drawn regarding their practicability.

The way ahead

We argue that none of the above accounting systems — nor any type of combination — is *per se* 'best' when attempting to generate a just and effective climate policy in a second-best world. The relative justice and effectiveness of each proposal depend on specifics such as: the size and the composition of the abating coalition; the stringency of the targets envisaged; the responsiveness of demand and supply of goods and factors of production to price changes; market structures; trade flows; and the technologies available. Furthermore, the creation of undesirable distributional effects is no reason to automatically reject a particular variant, as the distribution of burdens can always be changed through side-payments or by rechannelling the revenues associated with the application of the climate policy instruments (for example carbon tax revenues)[47]. At any rate, only a detailed analysis of the situation at hand — possibly with the help of simulation models — will allow a ranking of the accounting systems. Today, lack of adequate data means that there are still limits not only to performing such comprehensive analyses, but also to introducing new policies linked to a transparent and thus internationally accepted data basis. We therefore suggest compiling consistent and reliable data, as required for the calculation of consumption-based, income-based and extraction-based GHG accounts, in an internationally agreed procedure, acknowledging data uncertainties, and possibly at shorter intervals than at present. This would aid in the introduction of multiple monitoring bases as discussed above.

The availability of multiple GHG accounts is expected to result in several advantages:

- An improvement in transparency and knowledge concerning GHG transfers across economic sectors and countries;
- A more complete and accurate picture for specific countries of the impact of their policies on global emissions;
- Support of a more informed debate on mitigation in international negotiations;
- An improvement in *ex-ante* mapping of possible GHG mitigation pathways;
- Benefits for the development of climate policy instruments due to an internationally agreed data basis and standard to which these can refer;
- A better basis for countries willing to tackle climate change by using additional, more effective abatement policies;
- Possibly the facilitation of parallel agreements based on different accounting systems.

Satellite accounts

Recent developments in the system of national accounts can help to point the way in establishing a system of multiple GHG accounting. In the 1990s, the traditional System of National Accounts depicting economic activities was expanded by satellite accounts (to reflect changes in natural and environmental resource stocks and flows)[95–97]. Similarly, in carbon accounting, the considerable experience gained in the provision of energy and process emission statistics, on which production-based carbon accounting and its international monitoring rely, suggests that such accounts be retained as core indicator. But we also propose inclusion of the three other GHG accounting schemes in the internationally established GHG accounting system, in the form of satellite accounts based on common guidelines. This would keep current emission balances intact, while at the same time improving our knowledge on GHG transfers throughout the supply chain and possibly opening up options for the implementation of more just and effective policies.

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Author contributions

All authors contributed to the study design. K.W.S. and C.L. took the lead in writing the paper and L.H.M. did so for the section on responsibility. P.M. and T.S. assisted the writing of the whole paper. T.S. and P.M. collected and processed data and P.M. analysed data, with assistance from K.W.S. and T.S. K.W.S. edited the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to K.W.S.

Competing financial interests

The authors declare no competing financial interests.