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Doing burden-sharing right to deliver natural climate solutions for carbon dioxide removal

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ABSTRACT

Carbon dioxide removal (CDR) figures prominently in modelled pathways to achieve the Paris Agreement's goal of limiting global warming to 1.5-2°C compared to pre-industrial levels. However, national roles and responsibilities to deliver CDR have been informed with CDR quota analyses that focus on developed economies and global major emitters. This study extends the discussion to implications for developing countries. For that purpose, we employ a diverse set of allocation methods on a wide range of global emissions scenarios to address equitability and uncertainty in sharing the burden of climate change mitigation. We further focus on tropical developing countries due to their large potential for natural climate solutions (NCS) that deliver CDR. Our analysis indicates the potential for stringent CDR quotas for the top seven countries that contribute ~60% of pantropical cost-effective NCS potential, with median national quotas across emissions scenarios ranging from 0.1-29 GtCO2. However, the results reveal strong heterogeneity of quotas and inherent bias across allocation methods making agreement on an 'equitable' quota unlikely. Competition among NCS and non-NCS CDR options may arise when ambitious CDR quotas are implemented in countries with vast forest areas or large potential for expansion of tree cover. Therefore, it is important to not use CDR quotas to evaluate national climate actions or to inform climate targets that could exacerbate trade-offs between emissions reduction, biodiversity and ecosystem services in these NCS-rich countries. Instead, results from burden-sharing exercises could foster higher ambition if used to inform voluntary cooperation mechanisms. Discrepancy between perceived fairness and CDR quotas should be critically and transparently embraced to encourage acknowledgment of socio-ecological co-benefits as compensation. Such an approach will allow tropical developing economies to prioritise protection and restoration of nature in their climate change mitigation pathways.

1. CDR quota and tropical developing countries

Large-scale implementation of CDR is required in pathways limiting global warming within 1.5-2°C [1–4]. CDR is needed for further reducing near-term GHG emissions levels [5], addressing temperature overshoot [6,7] and offsetting residual greenhouse gas (GHG) emissions [8]. Discussions about roles and responsibilities of individual nations to deliver CDR have been limited, despite acknowledgements of their importance [9,10]. Recent studies attempted to address this knowledge gap by quantifying potential CDR contributions of countries [11,12]. This is done through using various burden-sharing approaches to calculate national CDR 'quotas' which are sum of annual negative emission requirements of countries to collectively meet global emissions trajectories from Integrated Assessment Models (IAMs) projections. These CDR quotas are clearly a long distance away from becoming actual national targets. However, such an exercise could be used to

Abbreviations: CDR, NCS.

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evaluate the level of ambition of national climate change mitigation commitments [13,14] or to derive policy-relevant recommendations for CDR deployment [11].

Studies on sharing the burden of CDR derived their conclusions and policy recommendations with a focus on developed economies and major emitters [11,12]. However, the resulting national quotas for these countries are a subset of national quotas that are generated for all individual countries simultaneously as result of the calculation process. As such, it is important to note that assumptions (e.g. equity principle, selection of datasets, national entities and their administrative boundaries) of allocation methods that were applied to developed economies or major emitters also apply to other countries. If recommendations from CDR quota analyses are only applied to certain parts of the world, the underlying premise to deliver a global CDR requirement will be compromised. On the other hand, it is clearly problematic to extend conclusions and recommendations for developed economies to the rest of the world. Therefore, discussing the implication of CDR quota analyses for developing economies is crucial. The aim is by no means to suggest for CDR quotas to be applied in these countries, but to simply shed light on 'the other side of the coin' of the discussion of CDR quotas for developed economies.

As CDR can be achieved through NCS, the importance of NCS in recent climate negotiations justifies a further zoom-in to tropical developing countries. Terrestrial productivity is highest in the tropics. Focusing on the seven tropical countries with the largest NCS potential (Indonesia, Brazil, Democratic Republic of Congo (DRC), India, Malaysia, Mexico and Colombia) alone covers ~60% of pantropical or ~35% of global cost-effective NCS potential [15,16].

Likewise, the seven countries also generate significant land-based GHG emissions (the basis for avoided emissions NCS pathways). Indonesia, Brazil and India are the top global emitters of the agriculture, forestry and land use sector [17] currently. However, all but two of the seven countries demonstrate a decreasing trend for land sector emissions (Fig. 1). Land sector emissions of Indonesia and the DRC show stabilizing trends, with the former also projecting the energy sector to replace the land sector as its main source of GHG emissions [18]. As shown in Fig. 1, a gradual shift from the land sector towards the energy sector as the main contributor of national GHG emissions is also seen in Brazil and Colombia, while the shift already took place in India, Malaysia and Mexico. The phenomena suggest that the future relevance of CDR in these NCS-rich countries may be more related to the need of decarbonizing the energy sector, which will appeal more to CDR measures such as BECCS, while land resources will remain constrained.Fig. 2.

2. NCS and non-NCS CDR options

Widely discussed terrestrial CDR options include BECCS, afforestation/reforestation (AR), direct air carbon capture and storage (DACCS), soil carbon sequestration (SCS), biochar and enhanced weathering (EW) [19,20]. AR, SCS, EW and biochar have partial overlap with NCS measures in their definitions (Fig. 2a).

NCS is defined as the conservation, restoration and improved land management measures that increase terrestrial carbon storage or avoid GHG emissions across forests, wetlands, grasslands, and agricultural lands [16,21]. NCS refer to nature-based climate change mitigation. It is a subset of more broadly defined nature-based solutions (NbS) which are inclusive of climate change mitigation and adaptation. While NCS emerge as significant contributor to achieve Paris targets, they also receive growing interests that expand beyond climate change mitigation due to contributions towards conservation and the delivery of other ecosystem services [22–26].

AR can be regarded as a form of NCS only if it expands the spatial extent of natural land cover types (e.g. restoring tree cover to a degraded cattle pasture in a forest ecoregion) [16]. For example, as NCS, AR is only inclusive of reforestation and the portion of afforestation without negative biodiversity impacts. Discrepancies between AR as NCS CDR option vis-à-vis AR as non-NCS CDR option occur in a specific situation where AR expand non-native land cover types, such as planting eucalyptus in a savanna ecoregion. Similarly, SCS, biochar and terrestrial EW can be regarded as NCS CDR options as they improve management practices in existing food, fuel and fibre production areas, but only as long as they do not result in adverse outcomes for biodiversity.

Other CDR options, together with implementation of AR, SCS, terrestrial EW and biochar with adverse outcomes for e.g. biodiversity, are collectively addressed as non-NCS CDR options in this study. Further parallels and distinctions between CDR options and NCS measures are illustrated in Fig. 2. DACCS is distinct from other CDR options and NCS measures (Fig. 2b), although DACCS competes with BECCS for CO_2 storage space. Fig. 2c illustrates the competition for land resources, indicated by the overlapping of shapes, among CDR options and NCS measures.

3. Knowledge gaps and research objectives

Studies looking at the role of CDR in national contexts are dominated by discussions about principles for target setting and policy design [27–29]. Recent studies attempting to examine fair-sharing mechanisms for allocating a global CDR quota focus on countries within the European Union [11] and major global emitters [12]. Examining quota allocations in these studies from the perspective of developing countries reveals problematic issues.

Pozo et al. generated national CDR quotas by distributing a global CDR quota, instead of deriving national CDR quotas by breaking down a global emissions trajectory [11]. This is problematic as the authors' approach excludes allocation methods that would allow higher CDR requirements for certain countries to compensate additional emissions allowances for poorer lower-emitting countries. Although Pozo et al. then distributed the global CDR quota using calculation methods that

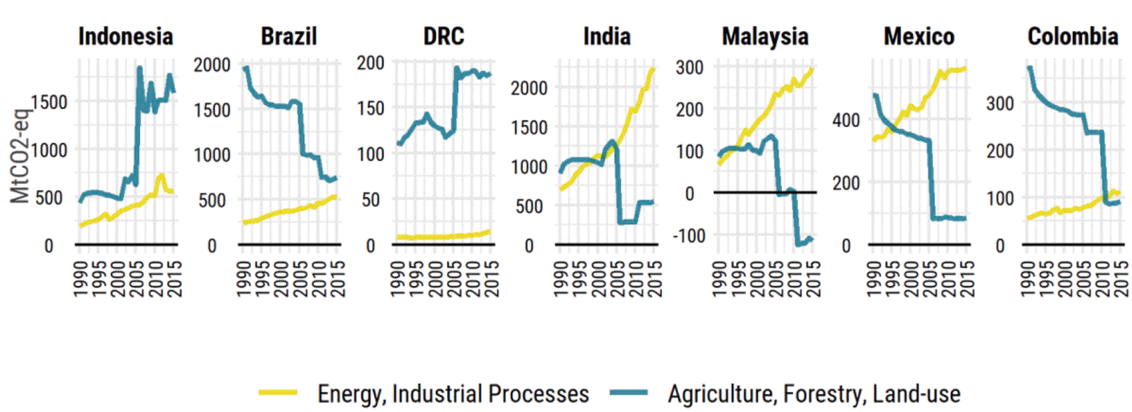

Fig. 1. Historical energy and industrial processes emissions from PRIMAP historical dataset and agriculture, forestry and land-use emissions from FAOSTAT.

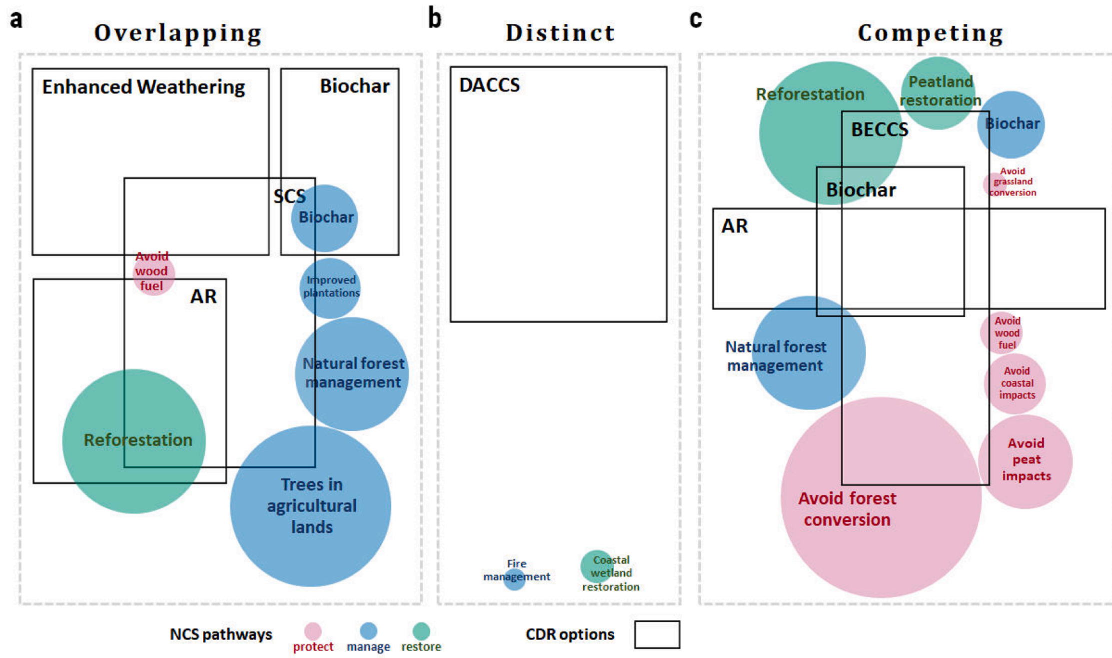

Fig. 2. Stylized illustration of potentials for terrestrial CDR options 21 (in squares) and tropical NCS pathways with <US$ 100 cost constraint 15,16 (in color-coded circles). The potentials are grouped based on their (a) overlap in definition (overlap of areas represent the extent of overlapping potential), (b) distinction with other CDR options and NCS pathways and (c) competition over land resources (overlap of areas represent the extent of competing potential). Area of the shapes represent order of magnitude for potential annual CO2 sequestration. The potentials are not reconcilable as potentials for CDR options are not broken down for different cost ranges. Hence, Interpreting the graph in regard to the potential should consider different scopes and definitions the studies use for comparable measures (e.g. AR and reforestation), as well as varying temporal calibration in generating yearly potential.

reflect equity principles of Responsibility, Equality and Capacity, the step they took prior to the distribution effectively diluted the responsibility of major GHG emitters, and undermined developing countries Rights to Development—an equity principle in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [30] that was not mentioned in their study.

Fyson et al. derived national CDR quotas from distributing a global emissions trajectory from various pathways, but they only used two allocation methods to represent 'fair distribution' [12]. On top of the authors' acknowledgement that "the approaches are not necessarily 'equitable' by all definitions", they also exclude allocation methods exclusively based on the Responsibility principle. Such an exclusion is similar to the work of du Pont et al. [14] which has been criticized as biased in favor of wealthier and higher-emitting countries [31]. Moreover, similar to Pozo et al., the allocation methods that are used by Fyson et al. also do not reflect the Rights to Development principle.

As allocation methods are simultaneously applied to all countries to generate CDR quota, discussions on the implication of CDR quotas need to be extended to developing countries as well. For that purpose, it is important to cover a wide range of allocation methods to be inclusive towards burden-sharing principles on which the methods are based. Moreover, it is also important to evaluate the implication of the CDR quotas on specific topics that concern developing countries. This study presents state-of-the-art CDR quota analysis using a diverse set of allocation methods. Informed by insights from the calculation process, we evaluate the relevance of CDR quota for NCS-rich tropical developing countries and extend these insights for policy recommendations and areas of further research on CDR.

4. Methodology

4.1. Identification of global targets

To cover a wide range of uncertainties, we set global carbon budget targets based on Energy and Agriculture, Forestry and Land-Use emissions of 32 shared socio-economic pathways (SSP) scenarios that keep global warming to below 1.5°C (RCP 1.9) and 2°C (RCP 2.6). Each SSP features distinguished characteristics in terms of demographic, human development, economic, lifestyle, policies, institutions, technology, environment, and natural resource, and use as input to model regions projections of economy, energy, land/natural resource, and emissions [32–34]. We exclude SSP3 scenarios as they are not feasible to generate lower than 2°C warming by the end of 2100. The scenarios are derived from global cost-optimal scenarios [35] assessed by six different IAMs, namely AIM/CGE 2.0, GCAM 4.2, IMAGE 3.0.1, MESSAGE-GLOBIOM 1.0, REMIND-MAgPIE 1.5, and WITCH-GLOBIOM 3.1. There are four main Kyoto-GHGs (i.e. carbon dioxide, methane, and nitrous oxide, including industrial F-gasses) that are included within this study. The emissions values follow the Global Warming Potential for a 100-year time horizon introduced in the Second Assessment Report of the IPCC and used under the United Nations Framework Convention on Climate Change (UNFCCC). Countries' gross domestic products (GDP) and population projections for these scenarios (income, in billion US$ adjusted to 2010 values) are obtained from the IIASA-SSP Database [36, 37].

4.2. Historical data

We take into account all countries' historical emissions starting from 1990, when the second World Climate Conference occurred and the publication of the first IPCC report informing policy makers of anthropogenic contributions to climate change came out. This selection is due to data availability limitation with crucial implications that will be discussed in more detail in the next section. Countries' historical emissions are sourced from the PRIMAP-hist dataset [38] that combines datasets from UNFCCC CRF Inventories for Annex I countries [39], EDGARv4.2 for non-Annex I countries [40], and downscaled CDIAC dataset [41]; Agriculture, forest, and land-use related emissions using FAOSTAT dataset [42]. This study allocates countries' emissions allowances starting from year 2016, which is in the past, relative to the year of this article's publication due to the availability and completeness of countries' historical emissions data. Note that bunker emissions (from international naval and air transport activities) are considered in the input database of countries' emissions and are not separated from the 'target' global emissions. Countries' historical GDP and population are sourced from World Development Indicators dataset [43] from The World Bank.

4.3. Data harmonization

Carbon budget targets from the selected global scenarios are harmonized with the PRIMAP-hist dataset for total 2015 emissions of 43.01 GtCO2-eq [44] (Energy, Industrial Processes, Agriculture, Forestry, and Land-use related Kyoto GHG emissions). The factors are then applied for the following years with gradual linear progression until they reach the value of 1 in 2040. The harmonisation procedure is also applied to national GDP and population projections respective to SSP scenarios.

4.4. Allocation methods

We generate national breakdowns of the global targets by employing multiple allocation methods informed by previous studies [14,45–56]. The calculation was done using Microsoft Excel. Description of equations for the allocation methods can be found in the **Supplementary Information 1** while input data and calculation worksheets are also openly available (see **Data availability**). We cover a wide spectrum of allocation methods to distribute 32 global targets into national emissions allowances to assess the implication of CDR quota analysis for developing countries (Table 1). We include methods that are based on each equity principle and combinations of multiple equity principles of Responsibility, Equality and Capacity. Similarly, we also include methods that reflect the Grandfathering principle [57] despite strong criticism towards its fairness [58].

We introduce effort-based allocation methods to include the equity principle of Right to Development, which is both crucial for developing countries but missing from previous studies on national CDR quota. In effort-based allocation methods, national baseline emissions are calculated based on regional baseline emissions from the RCP8.5 scenario [54]. In doing so, the methods consider varying development trajectories of different countries [55,56,59].

5. Results and discussions

Adherence to a global emissions trajectory combined with the rollout of future socio-economic development and the accompanying GHG emissions result in a specific timeline where removals have to accumulate to meet global climate targets throughout the 21st century. This is reflected in this study's allocation methods which generated net national emissions that can be broken down into a GHG emissions allowance and a CDR quota.

Our use of 13 allocation methods on 32 SSP scenario-based global carbon budgets result in 416 national emissions scenarios. We focus on Indonesia, Brazil, DRC, India, Malaysia, Mexico and Colombia in presenting our results as they represent developing countries of various stages while being the top ~60% of countries in terms of pan-tropical cost-effective NCS potential.

The analysis shows that ambitious CDR quotas are present in the majority of national emissions scenarios for all seven countries (Fig. 3a) despite the countries' varying stages of development and characteristics of GHG emissions sources. For the 2°C targets, the lowest median value of national CDR quotas is obtained for Mexico (0.1 $GtCO_2$) while the highest value is obtained for India (~5.2 $GtCO_2$). Keeping global warming within 1.5°C dramatically changes the CDR quotas. Within this constraint, Mexico's median CDR quota reaches 3.10 $GtCO_2$, while the median quota for India increases to ~29 $GtCO_2$. Still under the 1.5°C global warming targets, collective median CDR quotas of the seven countries amount to ~20% of the corresponding GHG emissions allowance (Fig. 3b). These ambitious CDR quotas have specific implications towards the selection of CDR options and perception of equitability for aforementioned countries.

5.1. CDR quota and trade-offs among CDR options

CDR quotas can be implemented as implicit requirements resulting from emissions reduction targets, as well as explicit targets in future climate policies [28]. Competition for land and climate finance will intensify when countries with vast forest areas at risk of deforestation, and/or large potential for expansion of tree cover, are challenged with ambitious CDR quotas. Hence, stringent CDR quotas can exacerbate trade-offs between NCS and non-NCS CDR options in the seven countries, leading either to failure in meeting the quota or achieving it at the expense of ecosystems and the services they provide. For example,

Table 1
Description of allocation methods.

	Code	Name	Short Description	Featured Principles
Resource-based allocation	RES	Responsibility based allowance	National GHG emissions level is inversely proportional to cumulative historical GHG emissions [45,46]	Responsibility
	CAP	Capacity based allowance	National GHG emissions level is inversely proportional to GDP per capita [14,45,47,48]	Capacity
	RCX	Responsibility and Capacity based allowance	Responsibility consideration are combined with capacity consideration with equal weights [48]	Responsibility, Capacity
	EPC	Equal per-capita allowance	National GHG emissions level is determined based on population [4,46,50]	Equality
	ECPC	Equal cumulative per-capita allowance	National GHG emissions level is determined based on population and historical GHG emissions [14,45,50,51]	Responsibility, Equality
	CER	Constant emissions rates	Countries' shares of global emissions is maintained at 2015 level [14,45,47]	Grandfathering
	RES30	Responsibility based allowance with transition	Countries are given linear transition from current levels of emission to the introduction of RES in 2030 [45,46,52]	Responsibility, Grandfathering
	CAP30	Capacity based allowance with transition	Countries are given linear transition from current levels of emission to the introduction of CAP in 2030 [14,45,47,48,52]	Capacity, Grandfathering
	EPC30	Equal per capita allowance with transition	Countries are given linear transition from current levels of emission to the introduction of EPC in 2030 [14,49,52,53]	Equality, Grandfathering
Effort-based allocation	RESmit	Responsibility based mitigation	Instead of emissions level, the RESmit, CAPmit, RCXmit and EPCmit approach is applied towards global emission reductions requirement resulting from comparing targets with regional baseline emissions from RCP8.5 scenario [54]. Such an approach acknowledges countries varying development trajectories represented in the baseline scenario [55,56,59].	Responsibility, Right to development
	CAPmit	Capacity based mitigation		Capacity, Right to development
	RCXmit	Responsibility and Capacity based mitigation		Responsibility, Capacity, Right to development
	EPCmit	Equal per-capita mitigation		Equality, Right to development

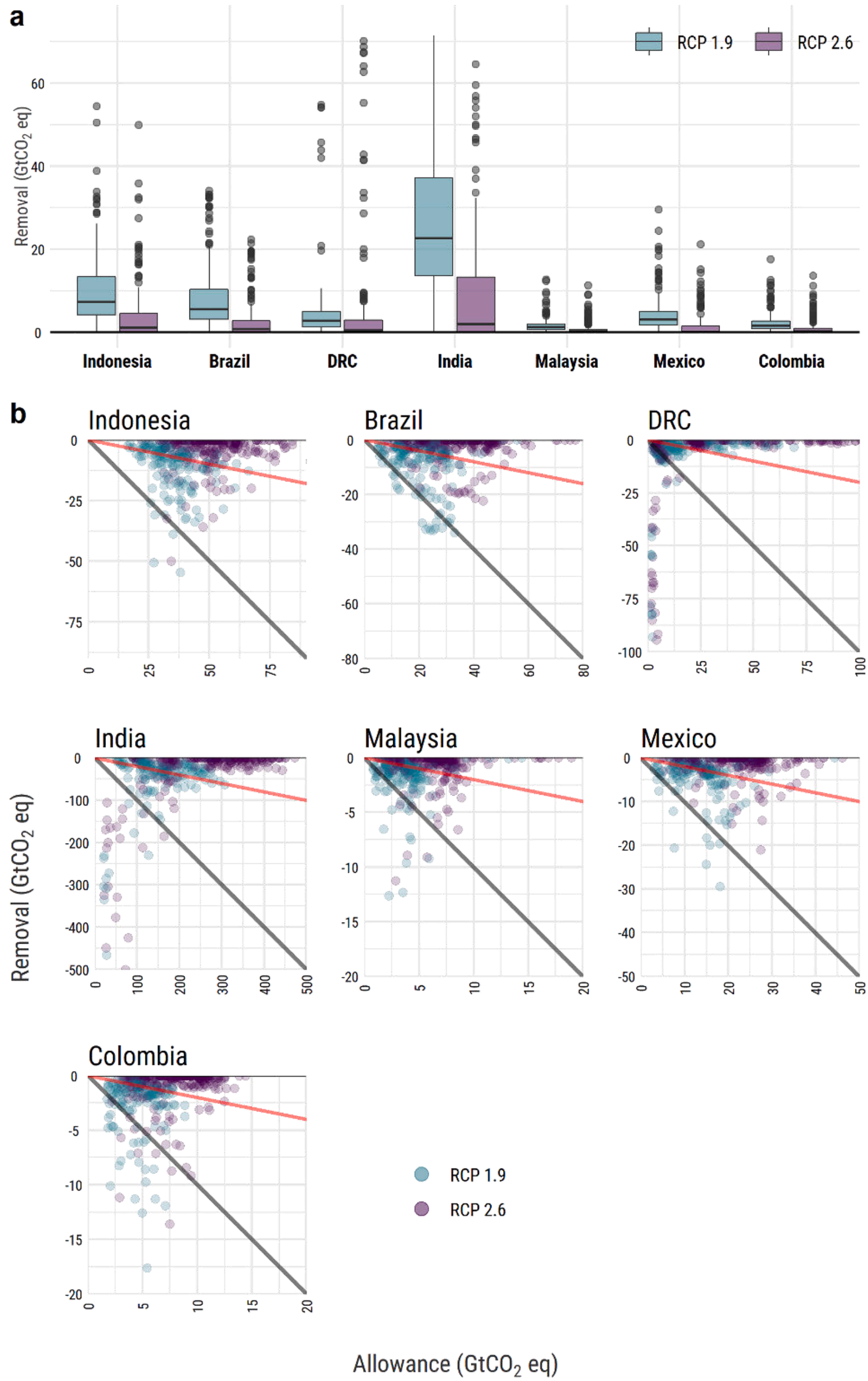

Fig. 3. a) Distribution of CDR quotas from 416 national emissions scenarios. The graph excludes several extreme emissions allowance scenarios for India and the DRC (> 70 GtCO2-eq). b) National emissions scenarios plotted with the GHG emissions allowance on the x-axis and the CDR quota on the y-axis. The red line indicates collective median CDR quotas i.e. ~20% removal requirement of GHG emissions.

preference towards BECCS due to its advantages of permanence [60] and simultaneous provision of reliable energy [61,62] might reduce the opportunity for implementing low-cost NCS potential such as avoided deforestation or natural reforestation, as they compete with BECCS for land resources [60,63].

Carbon sequestration from AR and SCS saturates over time, limiting the duration of their ability to remove CO_2 from the atmosphere after mid-century [64]. This concern could be minimized when actions are prioritized in the majority of ecosystems which are experiencing increasing removals capacity due to CO_2 fertilization and lengthening growing seasons [65,66]. Forest carbon can also be released to the atmosphere due to natural disturbance and future land use changes. As demonstrated by the linkage between climate change and net carbon sinks in the coming decade [67,68], implementing AR and SCS at large scales needed with risk mitigation mechanisms (e. g. buffer pools) could minimize such a permanence concern. Similarly, management practices for SCS need to be maintained to avoid reversal, including after saturation of sequestration [69].

On the other hand, BECCS also poses potential threats in terms of land availability for food production, biodiversity and forest conservation due to the land requirement for bioenergy production [60,63,70]. While the true extent of land competition requires a detailed spatial analysis, a theoretical trade-off exists between the implementation of BECCS vis-à-vis all NCS measures (including the ones that overlap with CDR options), as they concern existing natural ecosystems and production areas for food, fuel and fibre. The same is also applicable—though to a lesser degree—for certain types of AR, especially large-scale monoculture afforestation [25].

Along with storage potential, bioenergy potentially acts as the main constraint in assessing global BECCS availability. Low estimates of global bioenergy potential already demonstrate the direct impact of applying land constraints to the BECCS potential. Limiting bioenergy deployment to degraded [71,72] or marginal land [73] to avoid encroachment to areas for food production, or in conservation areas with low-yield sustainable management strategies [74] generates similar results in bioenergy potential estimates of around 60 EJ yr^{-1}. The value corresponds to the lower range of global BECCS potential estimated at 0.5-5 $GtCO_2\ yr^{-1}$ by 2050 [60]. Conversely, relaxing land constraints increases the bioenergy potential available to BECCS to 130-267 EJ yr^{-1}, [75–78], which would be beneficial to meet deep decarbonization requirements, but may result in allowing more encroachment to croplands or natural ecosystems. While land competition is among the main concerns of large-scale BECCS implementation, the negative side-effect of BECCS can be alleviated, especially if applied at small-scale and as part of sustainably managed landscapes [79].

Other than land availability, cost is also an important issue that can cause competition between CDR options and NCS measures for accessing climate finance. Cost estimates of CDR options remain high, with the costs of BECCS and DACCS — two of the most prominent CDR options with combined potential ranging between 1-10 $GtCO_2\ yr^{-1}$ by 2050 — estimated between 100-200 US\$ tCO_2^{-1} and 100-300 US\$ tCO_2^{-1}, respectively [60]. In contrast, the maximum potential of NCS measures with costs under ~100 US\$ tCO_2^{-1} is estimated to reach 11.3 $GtCO_2e$ yr^{-1} by 2030, subject to roughly 40% potential overlap with AR, SCS and biochar [16].

5.2. *Perception of equitability as challenge and opportunity*

Avoiding threats to NCS and broader sustainable development needs while ensuring achievement of climate targets requires thoughtful CDR deliberation. As such, accurate calculation of CDR quotas is key in informing climate policies. The equitability of allocation approaches is thus central in informing the validity of potential CDR quotas derived from them. Ambitious CDR quotas for the seven countries may raise questions on the equitability of the allocation, mainly due to the discrepancy between the level of ambition and the countries' historical contribution to climate change. Nevertheless, regardless of the validity of the principles and correctness of calculation, achieving equitable results may be challenging for the following reasons.

Firstly, equity principles can have different implications, even among parties complying with the same principles (Fig. 4). Within the 1.5°C constraint, our calculations demonstrate that the ECPC approach (featuring Responsibility and Equality principles) is most advantageous for India and DRC, as it results in no CDR requirement. However, the approach generates the most ambitious Brazilian CDR quota compared to other allocation approaches. Conversely, the EPCmit approach (featuring principles of Equality and Right to development) generates the lowest CDR quota for Brazil, Malaysia and Mexico, but delivers the highest CDR quota for India, DRC and Colombia.

Secondly, allocation approaches may also have implicit issues that undermine their featured principles. Informed by studies that highlight the principle of Right to development or Needs [55,56,59], the effort-sharing approaches in our calculation (RESmit, CAPmit, RCXmit and EPCmit) use regional baselines in RCP 8.5 scenario to represent varying development rights of different world regions [54]. However, an implicit issue arises in that the approach relies on assumptions of future development pathways compared to other approaches that mainly rely on empirical data (e.g. historical emissions, population and GDP) in the formalization of their featured principles. The issue can be problematic as the addition of the Right to development principle — in its specific method of formalization — results in harsher CDR ambition vis-à-vis their resource-sharing counterparts (RES, CAP, RCX and EPC, see Extended Data for more details).

Finally, the ability of allocation approaches to fully reflect the equity principles they adopt can be limited by data. The significance of land sector emissions in the seven countries suggests that consistent analyses of both land and energy sectors are required to provide a holistic picture of historical responsibility and future contribution. In this regard, calculating emissions allowances for these countries are constrained by the lack of historical land use, land use change and forestry (LULUCF) emissions data [38]. To allow both historical and future time frames to consistently account for both energy and land sectors, our calculation starts from 1990 onwards in accordance with LULUCF data availability [17]. Such an approach implies that the resulting emissions allowances are not fully reflecting historical responsibilities of (mainly) developed economies, effectively generating more or less emissions allowances for the seven countries. An alternative approach commonly adopted in previous studies is to exclude LULUCF emissions [14,52], which allows calculations to go back further in accounting for historical responsibilities. However, such an approach amplifies bias in favour of countries with land sector emissions that predates data availability. Moreover, the exclusion could also obscure justifications for allocating funding resources for NCS CDR options vis-à-vis for energy sector decarbonization.

These challenges do not diminish the importance of equitable approaches. Instead, the challenges can also be an opportunity for a more purposeful role under the context of voluntary cooperation [80]. Suggestions of an international cooperation mechanism for CDR have emerged due to its high cost [81] and mismatch between biophysical productivity and storage availability [11]. Within such a mechanism, results from multiple allocation approaches with varying equity principles could foster higher ambition among cooperating parties when discrepancy between perceived fairness and calculated allowances are acknowledged. Under such a premise, agreement upon ambitious emissions reduction targets could be substituted with formulation of robust CDR policy design that utilizes co-benefits to compensate for the discrepancy. This would allow CDR project implementation to (i) be evaluated using indicators for ecosystem services that directly contribute to local sustainable development needs, while (ii) still be able to inform its contribution to global climate change mitigation. Such a design will minimize trade-offs between emissions reduction against broader ecosystem services and sustainable development needs [29],

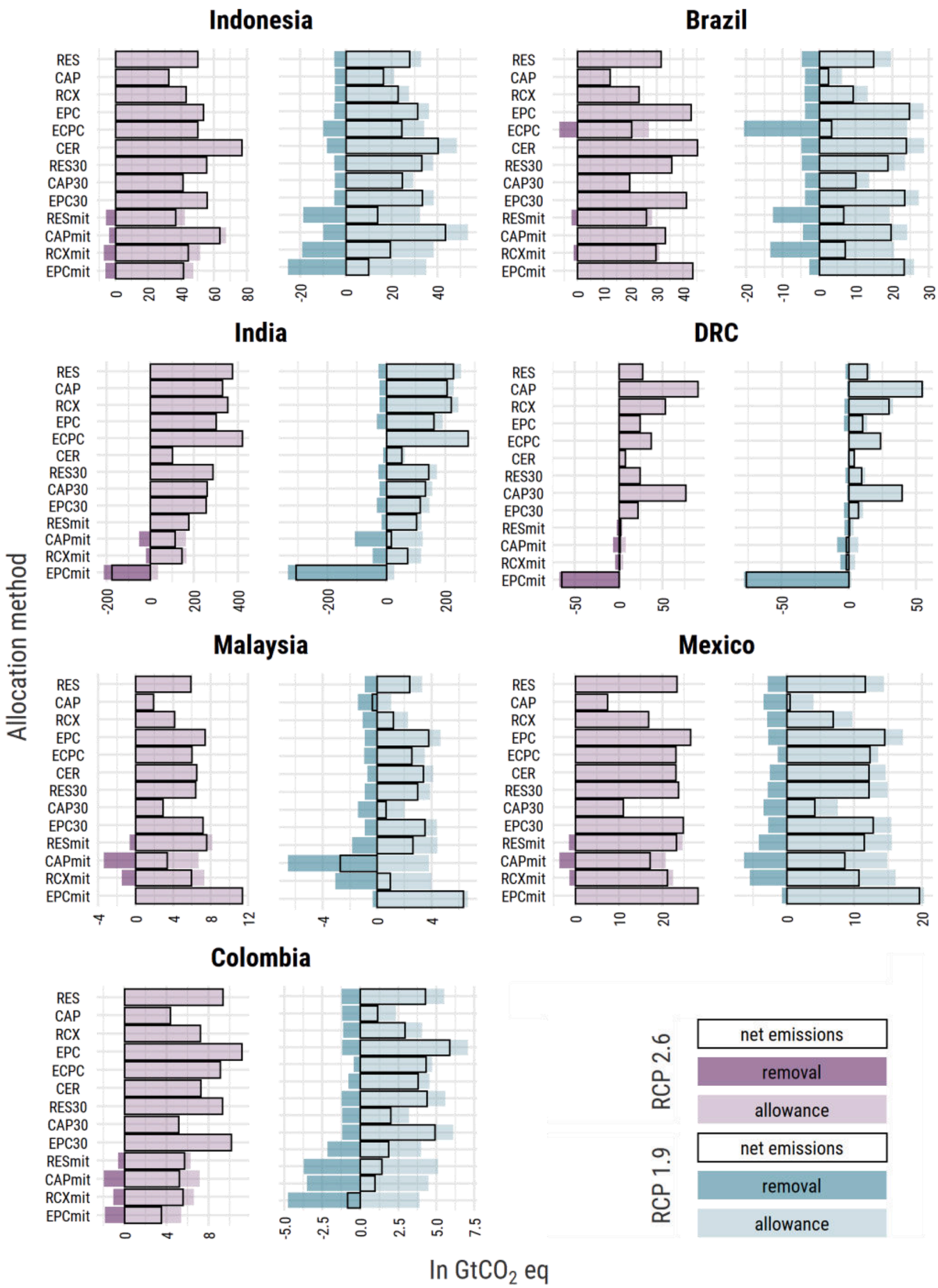

Fig. 4. Break down of median national emissions scenarios resulting from various allocation methods (see Table 1) for 32 SSP scenario-based global carbon budgets

ultimately alleviating potential competition between NCS and non-NCS CDR options.

6. Conclusions

Keeping global warming within 1.5°C above pre-industrial levels requires tropical countries with the largest cost-effective NCS potential [15] to implement ambitious levels of CDR. For the aforementioned countries, achieving this ambition through applying quota-based CDR targets could potentially obscure negative side-effects of non-NCS CDR options. Moreover, a carbon-focused approach could also lead countries to put less emphasis on the co-benefits of NCS. This is further exacerbated by the fact that non-NCS CDR options such as DACCS and BECCS are more straightforward to certify as capture from point sources can be monitored more easily than sequestration by many NCS CDR options [82]. Criteria of project success encompassing permanence of carbon benefits could also make NCS look less attractive from an investment perspective.

It is important to emphasize that the above messages should not be confused with strict preference towards implementing NCS options for CDR. Since we need significant amounts of CDR to achieve global climate goals, it is necessary to have the flexibility of deploying both NCS and non-NCS CDR options along with other climate change mitigation measures. Nevertheless, to achieve maximum overall climate mitigation before mid-century in a sustainable way, the selection of CDR options need to balance trade-offs that (i) avoid perverse local impacts for people and nature, and (ii) maximize emissions reduction outcome given constraints on institutional and financial resources.

Inclusion of CDR targets in climate policies will require some degree of consensus on the equitability of sharing global climate change mitigation efforts. As discussed in 5.2, allocation methods have limited capability in generating such a consensus. This suggests that evaluating CDR options beyond their contribution to emissions reduction is also necessary from a climate justice perspective. Moreover, it is important to not use CDR quotas to evaluate the contribution of national climate actions. CDR quotas that are generated from multiple allocation methods—being informed by different equity principles—could foster higher ambition if used to inform voluntary cooperation mechanisms. For such a purpose, it is beneficial to embrace discrepancy between perceived fairness and CDR quotas, and compensate the discrepancy by acknowledging co-benefits towards broader ecosystem services and sustainable development indicators.

Acknowledging co-benefits is also crucial for minimizing trade-offs between NCS and other non-NCS CDR options. Further investigation should move beyond the conventional top-down approach, and not quantify potential trade-offs based on pre-determined climate targets informed by CDR quotas. Instead, stakeholders will benefit more from a non-constrained, hence value-free, bottom-up potential assessment looking at indicators covering both climate and non-climate benefits of all CDR options. This approach also justifies separate accounting of emissions reduction and negative emissions, which is important in informing sector specific interventions [28,29], and revealing temporal trade-offs [83] among varying emissions reduction measures.

- **Social**

  In the face of increasingly urgent need for carbon dioxide removal, our study extends scientific recommendations on 'fair' and 'equitable' CDR burden-sharing based on analyses that represent the perspectives of developing countries. This is a novel representation compared to previous studies that largely focused on developed economies and major emitters.

- **Environmental**

  Moreover, our study focuses on demonstrating how more equitable CDR burden-sharing could deliver natural climate solutions for CDR. This will minimize trade-offs and promote synergy between GHG emission reduction and ecological conservation/restoration.

- **Economic**

  The study includes burden-sharing methods that are based on 'rights to development' principle. Such a principle provides space for economic growth in developing countries to balance with requirements of ambitious climate targets. Our study also provides insights on enabling conditions for natural climate solutions to access climate financing.

Data availability

All datasets that are used for the calculation are available from the references cited. The calculation results for key tropical countries are summarized in the Supplementary Materials. The complete dataset of results can be accessed through doi:10.5281/zenodo.504540.

Code availability

Calculation for national allocation of global emissions scenarios is conducted in Microsoft Excel. Calculation worksheets can be accessed through doi:10.5281/zenodo.504540. Calculation results are visualized in R. R codes are available upon request to the corresponding author.

Author contributions

B.Y. and P.Y. contributed equally to the work. P.Y., F.K. and B.Y. conceived the idea and developed the concept for the study. P.Y. led the writing and analysis. B.Y. co-led the writing and performed calculations and data harmonization. S.F., B.W.G., and P.S. provided data related to CDR options and NCS pathways. All authors discussed the idea and contributed to the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the link to my data/code in Data availability section

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2022.100048.

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