Nature-based solutions to reduce integrated climate risk

Focusing on both adaptation and mitigation role of nature based solution countries can reduce integrated climate risk

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Abstract

The ultimate goal of all climate solutions is to reduce human suffering for present and future generations. Nature based solutions further both mitigation and adaptation efforts and are therefore a promising path to achieving this goal. Here we develop and illustrate a global approach to measure and optimize potential reductions in integrated climate risk. Using scenarios and models across 150 countries, we show that optimizing on both adaptation and mitigation impacts of NBS can reduce integrated climate risk more than focusing solely on mitigation. Our measure of integrated climate risk also ensures equity - as the income increases the countries' benefit from reduction in integrated climate risk decreases, on an average.

Keywords: Integrated Climate Risk, Nature-based Solution, Climate Change, Land-use optimization, Adaptation, Mitigation

Climate change is the central scientific and policy challenge of our generation. Rising awareness that efforts to reduce greenhouse gas emissions are unlikely to be sufficient has caused businesses, governments, and NGOs alike to think more broadly about climate change strategy to include efforts to remove carbon already emitted to the atmosphere, and to build resilience to climate change we can no longer avoid (*1*). Though these three components are often pursued separately, all three interact and are essential to accomplish the overall goal of reducing the risks from climate change. An integrated strategy can also help address equity issues that loom over climate negotiations in light of the unequal contributions from historical greenhouse gas emission and the unequal vulnerability to climate risks between developed and developing countries (*2*).

Investing in nature-based solutions, such as preventing deforestation, expanding reforestation, and enhancing the capacity of grasslands, soils, sea grasses, and other natural systems to remove and store carbon (*3*, *4*) can contribute to all three components of climate strategy: reducing greenhouse gas emissions, removing carbon already emitted to the atmosphere, and building resilience. For example, restoring native ecosystems can sequester carbon and reduce the risks of floods, droughts, and landslides contributing to community resilience (*5*). Though additional benefits beyond carbon mitigation are often referred to as "co-benefits," they should be considered contributions to the primary goal of reducing overall risk from climate change.

Here we argue that any climate solution, whether it be a nature-based solution, should be evaluated in a holistic way for its ability to reduce overall risks posed by climate change. We develop a measure of Reductions in Integrated Climate Risk (hereinafter, RICR) that combines emissions reduction, carbon storage, and resilience components of an overall climate risk strategy. We show how RICR can inform global investments to reduce climate risks using readily available data applied at a national level for nearly 150 countries worldwide.

To illustrate the application of the RICR approach we compare RICR that combines emissions reduction, carbon storage, and resilience with a more conventional approach to nature-based solutions that aims to maximize carbon removal and storage. We compare the spatial pattern of investments in nature-based solutions, and performance in emissions reduction, increased carbon storage, and increased resilience. We identify trade-offs between increased carbon storage, and increased resilience, as well as highlight equity considerations between the two approaches.

We define RICR as the weighted average of three outcomes - carbon emissions, crop production, and biodiversity. The weights assigned to these factors vary among countries, based on it's relative vulnerability to each factor. Carbon emissions relate to climate mitigation, crop production and biodiversity confer resilience in social and natural systems, respectively. Although climate change will impact on many fronts, crop production and biodiversity represent two important dimensions of adaptation - adaptation to economic impact, and adaptation to ecological impact. We use this simple form of RICR to illustrate our approach, which can be expanded to include additional dimensions of climate risk, more sophisticated models of each, and more specific considerations of equity. We discuss these improvements at the end of the paper.

APPROACH AND METHODS

We used linear programming optimization to identify optimal land use and management practices that maximize the weighted sum of three outputs important for climate resilience: carbon storage, biodiversity, and food production. Land use and management practices include maintaining current use, expanded crop production or crop production with alternative management, and ecosystem restoration. We used a combination of irrigation availability, intensification by closing yield gaps, and protecting riverine buffers and headlands as alternative cropland management. Ecosystem restoration allows the potential vegetation to be restored as if there is no human activity. Land use and management actions do not allow to change urban development and IUCN class I-IV protected areas. We apply the optimization to ~150 countries (see the Supplementary Materials for list of countries).

We modeled output for carbon storage, biodiversity, and food production for each land use and management practice. We calculated monetary return to land for production of ten major crops considering suitability of different crops per parcel. The biodiversity is a composite index including six biodiversity metrics considering land use/land cover using data from the PREDICTS, IUCN, and other global data on forest intactness.

We compare outcomes of two optimization scenarios with a set of constraints. The goal of the first optimization is to maximize carbon storage and sequestration without reducing food production and biodiversity richness. In the second optimization scenario, we maximize RICR without reducing carbon storage and sequestration, food production, or biodiversity. Both optimizations ensure pareto constraints meaning not accepting any ecosystem services loss while maximizing the objective function. A detailed materials and method section is provided in the Supplementary Materials.

RESULTS

Our first result suggests that the potential ecosystem service (PES) returns between both scenarios differ among countries depending on the current status of their realized ecosystem services (RES) namely, food availability, carbon emission, and biome distribution. To illustrate these results, we use two countries – one developing country (Ghana) and one developed country (Germany) to present the PES outcomes of both optimizations – maximizing carbon and maximizing RICR (Figure 1).

On the one hand, results suggest that optimizing carbon sequestration for climate change mitigation yields 60 percent increase in carbon storage in Ghana and nearly 70 percent in

Germany. However, investments focusing on carbon maximization for climate mitigation without considering climate resilience returns in relatively food vulnerable countries like Ghana could stagnate national crop production, risk food availability, threaten food security, and undermine food self-sufficiency. The climate resilience co-benefits (returns on crop production) from maximizing the carbon scenario under pareto constraint are twice higher in Germany than in Ghana.

On the other hand, the optimization results for RICR demonstrate a climate resilience pathway in which crop production benefit increases over 110 percent in a relatively food vulnerable country – Ghana, In contrast, in Germany - a less food vulnerable country, the result yields less than 5 percent increase for crop production. Interestingly, the same RICR optimization scenario produces a 60 percent increase in carbon storage and sequestration for Germany and no positive change on carbon stock for Ghana. The PES difference here is due to Ghana's acute food vulnerability compared to Germany (Figure 1). In Figure 1, the agreement map presents areas of joint agreement or disagreement between the two optimization scenarios. The grey color highlights changed pixels that agreed to using the same plot of land for either crop production or natural regeneration under both optimization scenarios.

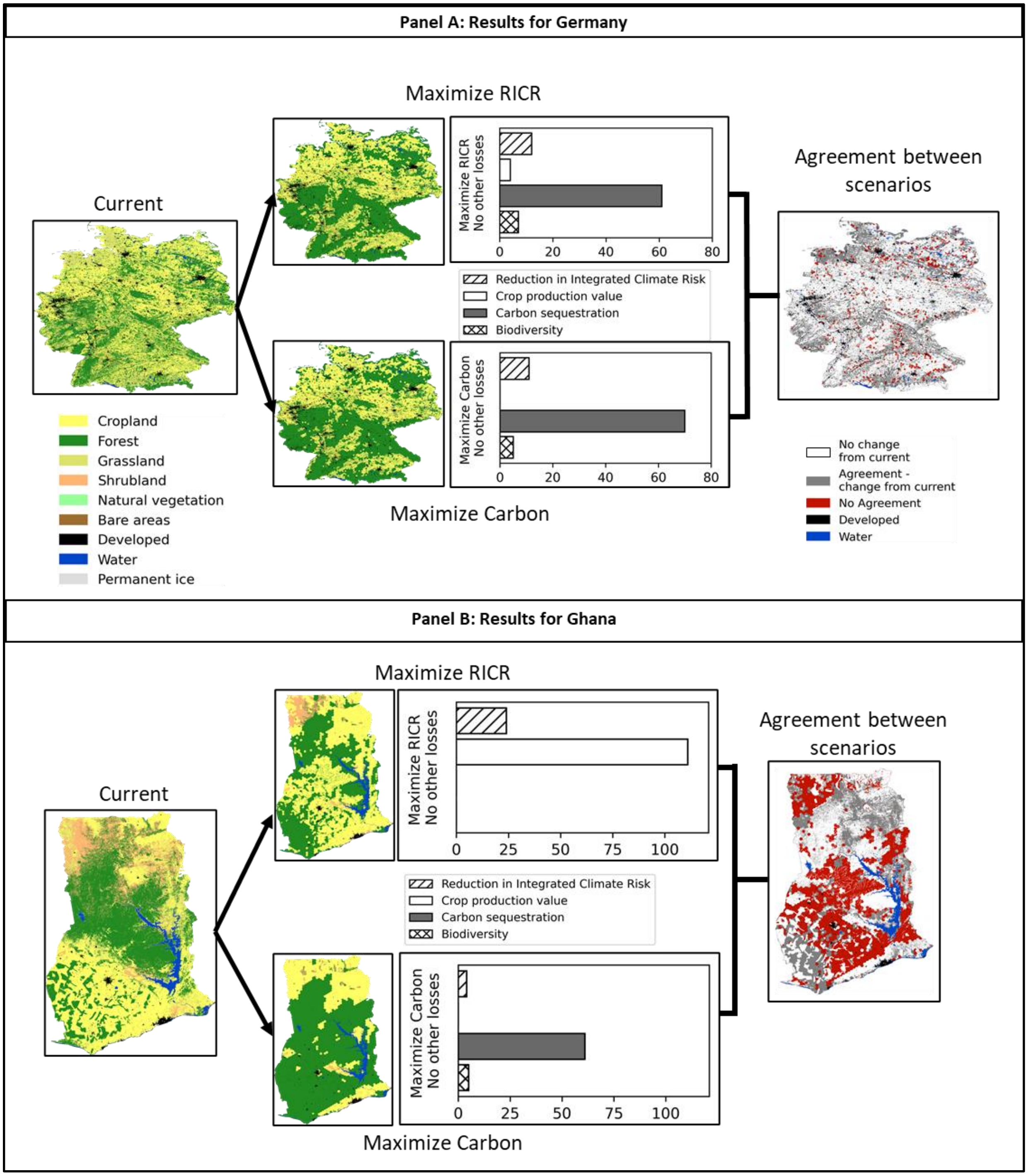

Figure 1: Shows results for two different optimization runs for two countries that have different weights on ecosystem services (ES). Panel A and Panel B shows results for a developed country (Germany) and a developing country (Ghana). From the current landscape, we considered two choices – optimized for RICR (reduction in integrated climate risk) and optimized for carbon. For both optimization options, we used Pareto constraints (No losses in other ESes). The RICR is a synthetic index comprised of three ESes (carbon sequestration, biodiversity, and crop production value) with a combination of weights based on country's circumstances. The agreement map compares land uses and management of two optimization scenarios – no change from current in both optimizations (white), agreement in changes from current (grey), and no agreement in changes from current (red). The bar graph in the right-side compares percentages increases in ESes between two optimizations.

The results from combining the weighted country-based optimization results at the global scale deliver thought provoking policy relevant findings. Should all countries prioritize carbon storage for tackling climate mitigation, the potential carbon sequestration benefit increases by nearly 35 percent with additional 10 percent co-benefit for RICR and 8 percent added benefit on biodiversity richness relative to current realized benefits. Alternatively, should each country optimize the RICR scenario aimed at reducing their current food vulnerabilities and per capita carbon emissions using natural climate solutions (NCS), the potential ecosystem service benefits increase global food production by nearly 30 percent, carbon storage by 22 percent, RICR by 18 percent and biodiversity by 14 percent compared to the realized outcomes for these ecosystems from current land use (Figure 2).

The equity considerations suggest that NCS for carbon mitigation benefits ought to be prioritized by high per capita carbon emitters from developed nations whose vulnerability to food insecurity is lower compared to low per capita carbon emitters – expected to prioritize national food self-sufficiency to reduce food insecurity, hunger, and famine under severe climate change conditions. Under the RICR scenario, equity returns from PES are prominent in developing economies, especially in Africa, Asia, and Latin America. Interestingly, these PES benefits do not undermine the global climate change mitigation efforts from reliance on NCS. Globally, regional variation on pixel agreement for either crop production or land restoration suitability shows no clear spatial pattern. However, the pixel agreement between both scenarios appears noticeable in Central and South American countries, western states in USA and in some parts of Africa, Europe, and Asia. The region with significant disagreement appears to be Australia, North Africa, and the Middle East (Figure 2).

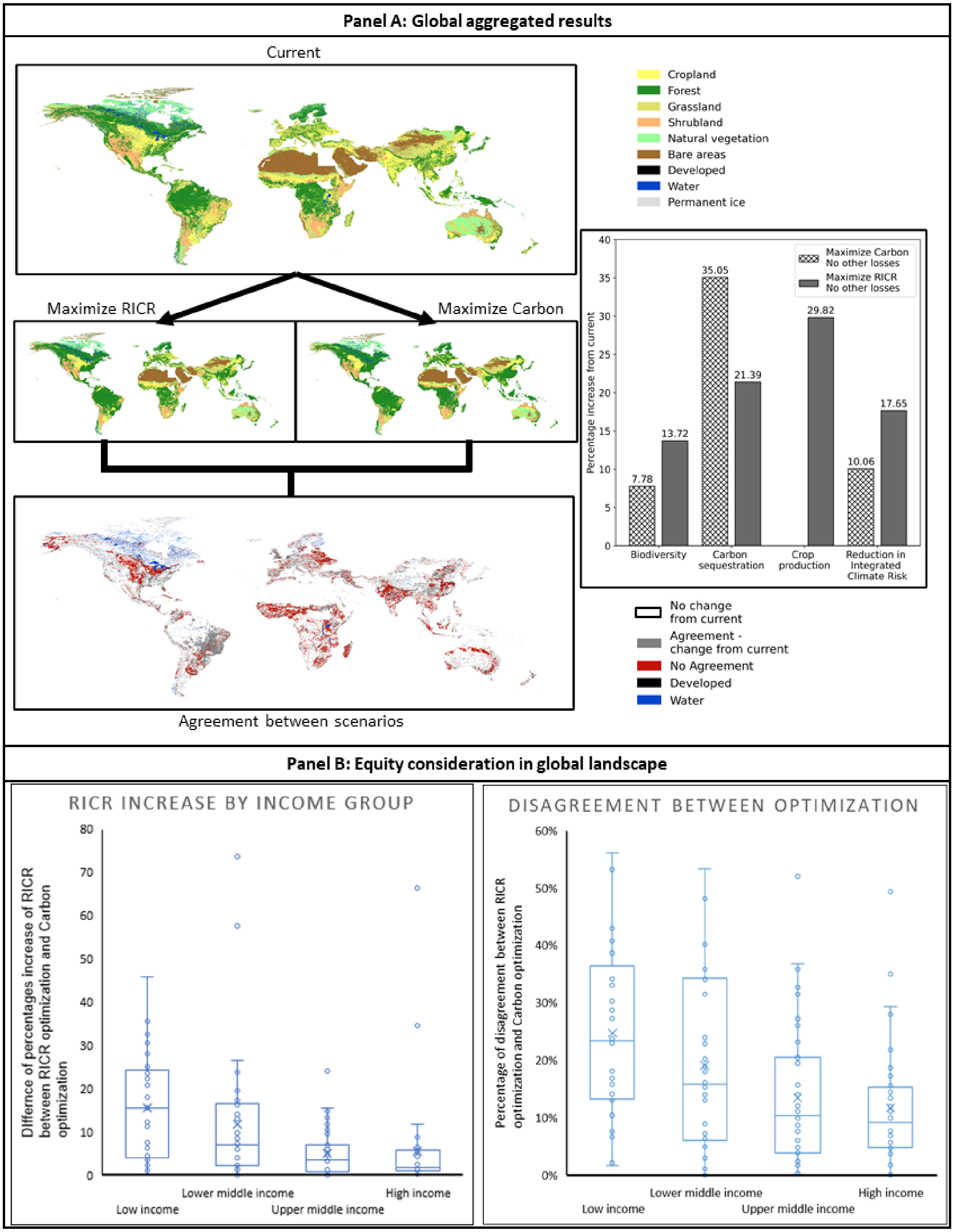

Figure 2: Shows aggregated results for ~150 countries. In aggregating the results, we used weighted average of ecosystem services (Panel A Barplot, on right). We used no weight for carbon, country size for biodiversity and country total population for crop production and RICR. The Panel B shows equity considerations between RICR optimization and carbon optimization. As the income level increases, the difference of percentage increase in RICR (left) and disagreement (right) between RICR optimization and carbon optimization decrease, on an average.

DISCUSSION

Climate change policy should focus on the ultimate objective of reducing risks of harm from climate change. Reduction in harms can be accomplished by various combinations of reducing emissions, removing carbon already emitted to the atmosphere, and building resilience to climate change. Strategies such as net zero emissions, or nature-based solutions, are important but cover only part of the suite of options and further they run the risk of confusing strategy with the end goal. For example, an exclusive focus on emissions reductions may still leave countries ill-equipped to address the consequences of climate change that is already baked in.

Here we focus on the end goal of harm from climate change and show how pursuing this goal would play out in different countries. The vastly different circumstances of countries yield quite different optimal responses. Countries with a high degree of vulnerability to climate change should concentrate on actions that increase climate resilience, as illustrated by Ghana, while countries with high emissions per capita and lower climate vulnerability, as illustrated by the case of Germany, should concentrate on carbon sequestration strategies. In general, low-income countries gain more by focusing on Reductions in Integrated Climate Risk with an emphasis on increasing climate resilience. For high-income countries there is less difference between a strategy that aims to maximize RICR and a strategy that aims to maximize carbon storage. These results are in line with climate equity arguments that vulnerable low-income countries should invest in domestic adaptation to reduce harms while high-income countries should do more to reduce atmospheric CO_2, which has global benefits.

We recognize that the analysis in this paper is only a first step in rigorously analyzing strategies for Reductions in Integrated Climate Risk. There are multiple dimensions of climate resilience and we have included only two.

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Supplementary Materials for

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This Document contains:

Material and Method
Sensitivity Analysis
Figure SI 1-2
Code and Dataset

MATERIAL AND METHOD

We used Restoration Opportunities Optimization Tool (ROOT) linear programming optimization to identify areas with the highest potential to increase ecosystem service (ES) provision under alternative management scenarios (*1*). We divided each country into parcels (hereinafter spatial decision unit, SDU) of hexagon shape and found out what management scenario (hereinafter "activity") provides highest objective value and at the same time meeting constraints for the entire country. The objective value is the weighted average sum of different ESes. For the case of maximizing one ES, we used weights of other ESes as zeros. The optimization provides the value of ecosystem services and corresponding activity. We ran multiple optimizations by varying objectives, weights, and constraints. Formally, our linear programming maximization model set up as follows:

$$\max_{a_s} \sum_{e} \sum_{s} w_e V_{es} a_s$$

$$st\ e \in E = \{carbon, biodiversity, crop\}$$

$$a_s \in (0,1)\ \forall\ a \in A$$
$$= \{sustainable\ current, crop\ production\ with\ alternative\ managements, restoration\}$$

$\sum_s \quad w_e V_{es} a_s \geq V_{sc}\ \forall\ e \in E$ [where applicable]

where, a_s is the fraction of activity (land-use or land management) area in strategic decision unit (SDU) s. The weights assigned to different ecosystem services are denoted by w_s and the value of ecosystem service e in SDU s is V_{es}.

We run different optimizations by varying objectives, weights, and constraints. Our primary interests are in comparing optimization outcomes of maximizing carbon and maximizing reduction in integrated climate risk (RICR). RICR is a synthetic index defined as weighted average of ecosystem services:

$$\begin{aligned} RICR = & \ (crop\ production\ value \times\ crop\ weight) \\ & + (biodiversity \times\ biodiversity\ weight) \\ & + (carbon\ storage\ and\ sequestration \times\ carbon\ weight) \end{aligned}$$

The outcome variables are changes in crop production value, biodiversity, and carbon storage and sequestration potential. All three outcome variables are normalized from 0 to 1. The crop weight, biodiversity weight, and carbon weight are normalized between 0 and 1 and ensured that their sum is equal to 1 for each country. The crop weight, biodiversity weight, and carbon weights are based on food vulnerability index from ND-Gain (*2*), projected change in biome index, also from ND-Gain (*2*) and carbon emissions per capita from the World Development Indicator (*3*).

The crop production value is developed using yield and harvested area data for ten crops (barley, cassava, maize, oil palm, rapeseed, rice, sorghum, soybean, sugarcane, wheat) across ~20,000 political units from 1974-2012 (*4*) and normalized to FAOStat production data (*5*) such that national-scale crop yield and harvested area agree. The suitability of different crops per parcel is a function of slope, weather, soil type, and sustainability of irrigation. We used NDGain's food vulnerability index as weights for maximizing crop production relative to countries' level of vulnerability to food insecurity. The food vulnerability index is constructed by measuring a country' projected change of cereal yields, projected population change, food import dependency, rural population, agriculture capacity, and child malnutrition. Therefore, highly food insecure countries receive greater weights when optimizing for crop production. For example, Ghana's food vulnerability index in 2019 was 0.569, while a more food secure country like Germany has 0.196 food vulnerability index in 2019.

The biodiversity is composite index including 6 biodiversity metrics i) species richness, (ii) habitat for species at risk; (iii) habitat for endemic species; (iv) habitat in rare ecoregions; (v) forest intactness; and (vi) key biodiversity areas (KBAs) (*6*). The index is a function of land use/land cover using data from the PREDICTS, IUCN, and other global data on forest intactness. Given that the index did not account for change in biodiversity with future climate change scenarios, we used the ND-Gain's indicator on projected impact of climate change on changes in the biomes occupying a country as our biodiversity weights. The projected change is the percentage of land area within a country that changes its biome type in the future (2070-2099), relative to the biomes type in baseline years (1961-1990), using IPCC medium emission scenario (*7*). This accounts for variation of changes in future biodiversity and vulnerability of ecosystems to climate change across countries, as climate change threatens vegetation changes, disrupts ecosystems, and damages human well-being with the absence of critical ecosystem services.

The carbon storage and sequestration includes above-ground carbon pools for forest, herbaceous (grass and shrub) and agricultural, forest, grazing, and urban land cover classes for the area's carbon zone (*6*). Likewise changes in food security and biomes distribution due to current and projected climate change, we added national per capita carbon emissions as weights for optimizing carbon storage and sequestration as one of the two alternative pathways. The per capita emissions indicator extracted from the World Bank's Carbon Emission Dataset accounts for differences in per capita carbon emissions by country. On the basis of climate justice and fairness on national commitments to decarbonize and intensify natural climate mitigation strategies, countries with the highest per capita carbon emissions are considered in this analysis to increase their commitments to up-scale natural carbon storage and sequestration within or without national geographical boundaries. For example, a high per capita emitting country (e.g., Germany) can invest in nature-based solutions or ecosystem-based adaptation (e.g., REDD+ programs) for natural carbon removal and sequestration in a low emitting developing country (e.g., Ghana), as the latter is soliciting for more climate financing to restore degraded landscapes for both adaptation and mitigation benefits. The accounted carbon sequestration value will count towards Germany's mitigation commitments while Ghana benefits from strengthening its climate resilience development pathway. Such a cross-boundary commitment has dual benefits for attaining the global climate change mitigation target and for strengthening local climate resilience in the most vulnerable countries.

The optimization is run for each country (total 146 countries in the world). We used country and ecosystem service specific weights to aggregate ecosystem services for the entire world. We used country population as a weight for crop production and RICR, and country land area for biodiversity. We did not use any weight for aggregating carbon values.

SENSITIVITY ANALYSIS

(1) Aggregating country results

In the baseline, we aggregated country results using country and ecosystem services specific weights. Here we used alternative ways of defining these weights. The results are provided in Figure SI 1. Panel A does not use any weights for all the ecosystem services, Panel B is aggregated by the population for all ecosystem services, Panel C is aggregated by the country land area. Panel D is our baseline aggregation strategy where crop production and RICR are weighted by population, biodiversity is weighted by country land area, and carbon has no weight.

If we aggregate country results using population weight, the carbon optimization provides large increase in carbon compared to other aggregation weights, indicating that many densely populated countries can improve their carbon sequestration planning land use and management. All the aggregation weights have similar results between carbon optimization and RICR optimization – RICR optimization increases potential to improve biodiversity and crop production while take a toll on carbon storage and sequestration.

(2) Alternative ecosystem services weights

In the baseline analysis, our ES weights come from ND-Gain (*2*) and Emission per capita (*3*). However, we also want to see how our ES results changes if we change the weights. In this exercise, we change average carbon weights as our main comparison is between carbon optimization and RICR optimization. In addition to set carbon weights for each country based on their relative emission per capita, we set the carbon weights arbitrarily to 10%, 20%, 50% as world average. However, the courtiers are having varied weights on carbon based on their weights on biodiversity and crop production, which we get from ND-Gain.

The sensitivity results shown in figure SI 2. As we emphasize more on carbon the difference between carbon optimization and RICR optimization decreases. In addition, more emphasize on carbon, reduces the increase in crop production.

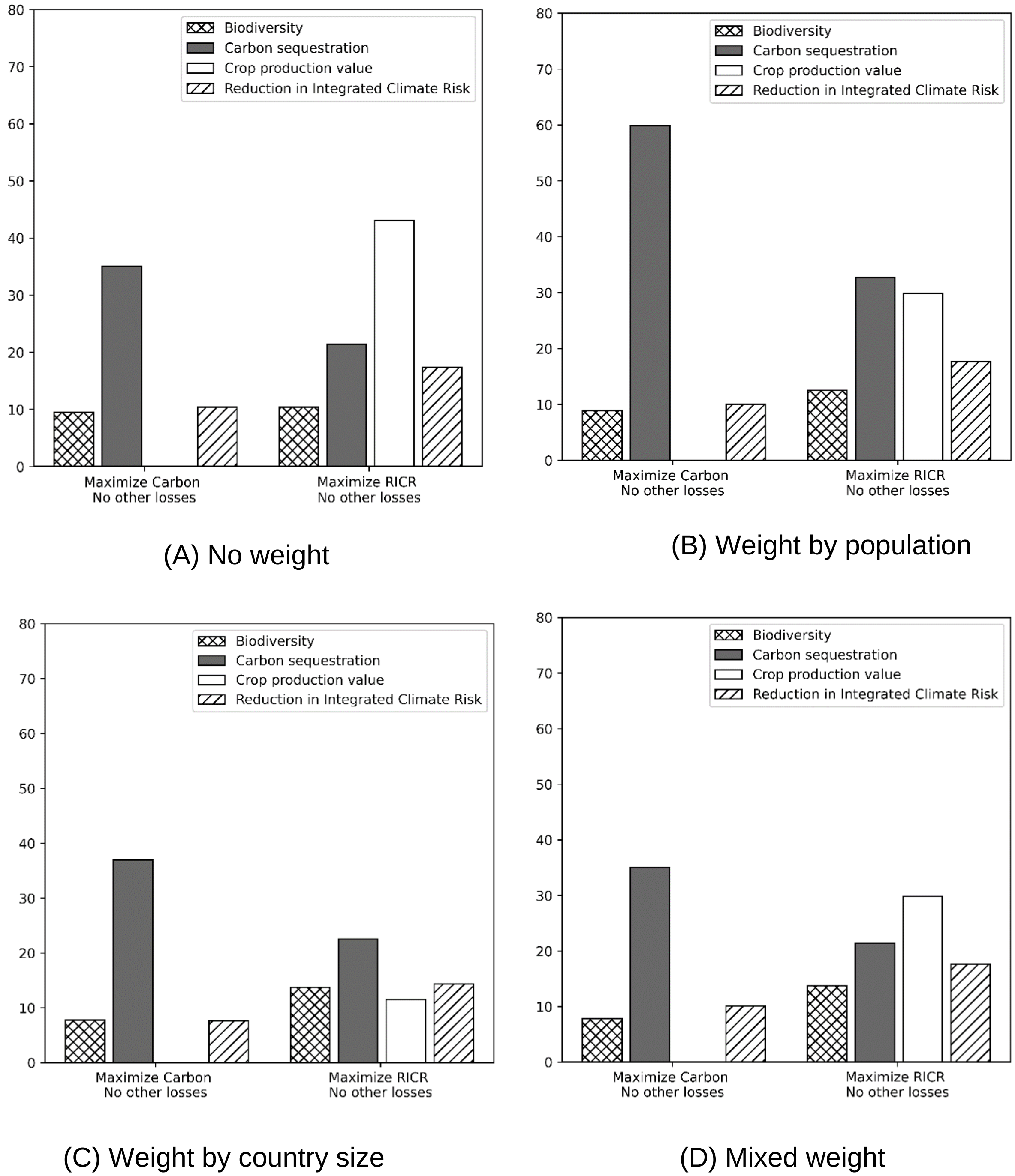
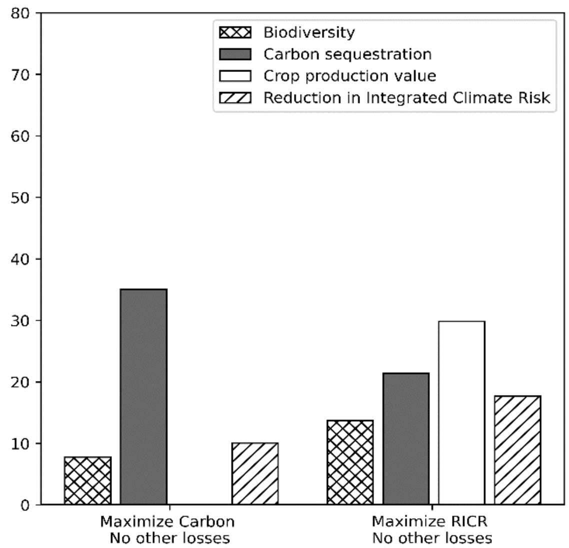
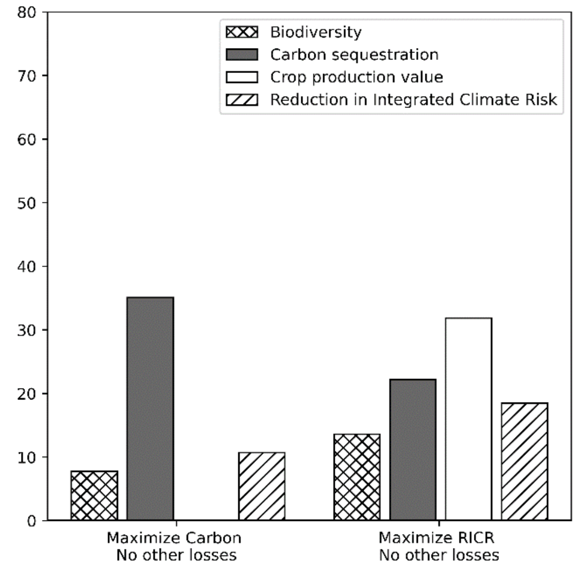


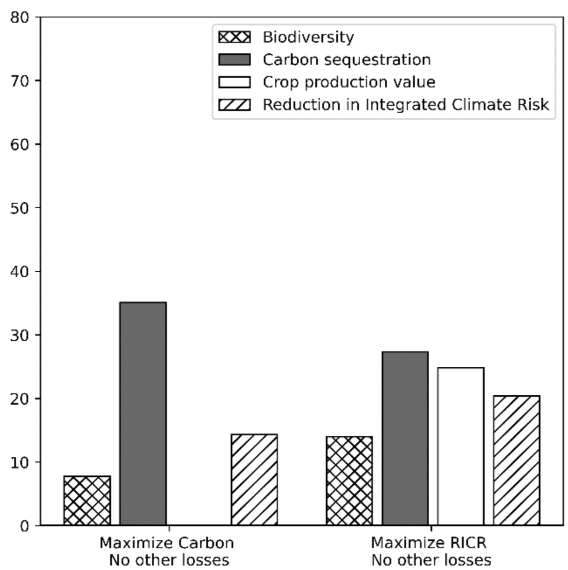
Figure SI 1: Sensitivity of results based on aggregation. Each Panel shows percentage change in ecosystem services for different ways of aggregating the world data. Panel A shows aggregation results when all the countries have the same weight. Panel B aggregated the countries by its population. Panel C aggregated the countries by the size of the country. In Panel D, carbon sequestration has no weight, biodiversity is weighted by country size and crop production value and climate resilience index are weighted by population.



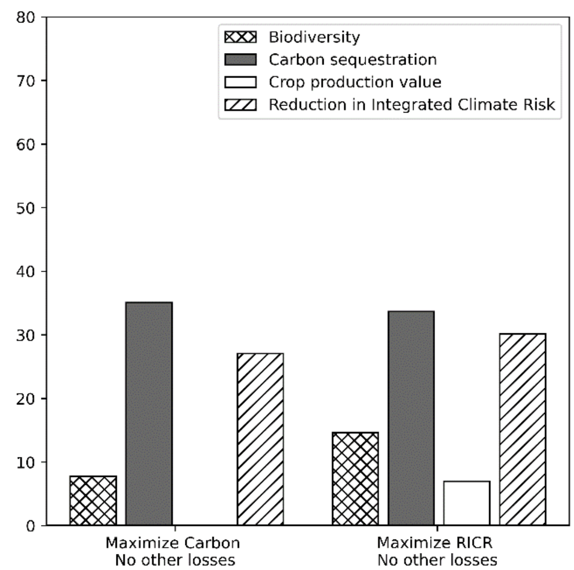
(A) Carbon from per capita emissions



(B) Carbon ~ 10%



(C) Carbon ~ 20%



(D) Carbon ~ 50%

Figure SI 2: Sensitivity of results based on optimization weights. Each Panel shows percentage change in ecosystem services for different weights (optimization priority) for ecosystem services. Biodiversity and crop production country scores are obtained from NDGain database for biome distribution and food vulnerability respectively. The carbon scores come from different sources. Based on the respective scores of ecosystem services (carbon, biodiversity, and crop production), we normalized for each country to make optimization weights for that country. In Panel A, carbon scores are calculated based on per capita emissions. For Panels B, C, and D carbon weights are set arbitrarily on an average of 10%, 20%, and 50% respectively. Note that the average is for the entire world while carbon weights varies by country. Note that individual country's ecosystem services scores are aggregated using mixed aggregation weights (carbon sequestration has no weight, biodiversity is weighted by country size and crop production value and climate resilience index are weighted by population).

CODE AND DATASET

Code and dataset to reproduce the results can be found at:
https://osf.io/ryzg9/?view_only=7252dade742a48049b1158291b1a6886

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