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A Replicable Methodology for Incorporating Key Mangrove Ecosystem Services into World Bank Macroeconomic Models

Tijen Arin, Ally M. Finkbeiner, Ragchaasuren Galindev, R. Barış Tercioğlu, Ernest Frimpong Asamoah, Mike Beck

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Introduction

Mangroves are found in dozens of countries, along coastlines in tropical areas. They are extremely important trees which generate entire ecosystems that depend on their health and vitality. These ecosystems provide numerous and wide-reaching services that impact both humans and wildlife alike, including habitat provision for a wide range of species, including notably fish (zu Ermgassen et al. 2020), coastal protection from erosion and storm surges, up to four times local carbon sequestration compared to mature tropical forests at plot level (Murray et al. 2011, Taillardat et al. 2018), and a myriad of provisioning services for the communities that live near these habitats, including timber, fuelwood, and other non-wood forest products. These ecosystem services are becoming increasingly important in the context of climate mitigation and adaptation.

However, due to factors including climate change and habitat degradation caused by economic development and urban expansion, the quantity and health of mangrove forests worldwide is in decline. According to the 2020 Global Forest Resources Assessment published by the Food and Agriculture Organization of the United Nations, the area of mangroves globally decreased by 1.04 million hectares between 1990 and 2020. Per the Global Mangrove Alliance's 2024 report on the State of the World's Mangroves, half of the world's 36 mangrove provinces, or geographically distinct regions characterized by the prevalence and importance of mangrove ecosystems are considered threatened. The threats are numerous, but the conversion of mangroves for aquaculture, oil palm plantations, and rice cultivation accounted for 43.3% of global mangrove loss between 2000 and 2020 (Leal and Spalding 2024). To preserve these critical ecosystems, countries are increasingly putting in place plans to restore mangroves as part of their Nationally Determined Contributions (NDCs) to realize adaptation and mitigation benefits.

This methodology note is produced as part of a World Bank global advisory services and analytics (ASA) work *Mainstreaming Nature into World Bank Macroeconomic Models*. Jointly implemented by the bank's Environment and Economic Policy Departments, the ASA aims to integrate natural capital and ecosystem services (NCES) into the World Bank's key macroeconomic models and core country diagnostics. This integration aims to better assess the role of NCES in countries' growth and climate agendas and to help estimate the impact of changes in ecosystem services on various economic indicators including GDP, employment, and poverty. Of the ASA's two pillars, the first focuses on developing methodologies for integrating key terrestrial and marine / coastal ecosystem services in pilot countries, while the second will develop a roadmap for mainstreaming the resulting nature-aware macroeconomic models in the Bank's country-specific core diagnostic ASAs. Mangroves are a key part many tropical coastal World Bank client countries' natural capital and therefore the ecosystem services they provide are prioritized for methodology development under this global ASA.

The focus of the ASA is on integrating NCES into both the World Bank's computable general equilibrium (CGE) MANAGE-WB model and the macrostructural MFMod model, which are widely used in the Bank's core analytical work, including Country Climate and Development Reports, Country Growth and Jobs Reports, and Public Finance Reviews. Macrostructural (MS) models, commonly employed by central banks, ministries of finance, international institutions, and the private sector for projecting economic variables and conducting policy experiments, differ significantly from CGE models. MS models typically rely on time series data to estimate country-specific economic parameters, notably the intertemporal and out-of-equilibrium behavior of variables, while CGE models often depend on a detailed snapshot at a single point in time (a social accounting matrix) and parameters drawn from the literature. At the World Bank, MANAGE-WB and MFMod have been utilized to evaluate the economy-wide impacts of policy, economic, climate, and other shocks on economic output, employment and other key macroeconomic indicators.

Literature on Mangrove Ecosystem Services

Hundreds of valuation studies have been conducted on mangrove forests in an attempt to put a dollar value on the benefits provided by these ecosystems (Himes-Cornell et al. 2018). A wide range of methods including benefit transfer, contingent valuation, and the travel cost method have been employed to analyze provisioning services such as fish and timber, regulating services including wastewater treatment, erosion prevention, and storm surge moderation, and even supporting and cultural services ranging from nutrient cycling and soil fertility to recreation and tourism. The majority of these valuation studies have been conducted in Southeast Asia due to the crucial role that mangrove forests play in local economies in this region. Provisioning and regulating services are typically the focus of these studies due to the relative ease of quantifying these benefits in comparison to non-market services such as aesthetic and cultural importance. Additionally, most studies focus on a single ecosystem service rather than a holistic valuation of all the benefits that mangroves provide.

In contrast to the literature on mangroves, many other ecosystem services have been successfully integrated into macroeconomic models in order to understand the value of these services within the broader economy, beyond a simple partial equilibrium valuation study. Regulating services such as carbon sequestration, pollination, and sediment retention have been incorporated into the World Bank's macroeconomic models in several existing projects, along with provisioning services such as timber, crops, and non-timber forest products. However, it is significant that the majority of nature-aware macroeconomic modeling work has focused on terrestrial ecosystem services, so there is a noticeable gap for the inclusion of ecosystem services provided by mangroves, including blue carbon sequestration. Papers such as Murray et al. (2011), Jakovac et al. (2020), and Song et al. (2023) provide key estimates of the carbon storage and sequestration capabilities of mangroves that are necessary for addressing this gap in the literature.

There have been few attempts to integrate mangrove ecosystem services into macroeconomic models to identify the economy-wide impacts of restoration. One method has been utilized in the 2020 Global Futures report prepared for WWF (Johnson et al. 2020) which links the Global Trade Analysis Project (GTAP) CGE model with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) suite of models from the Natural Capital Project. The Global Futures report analyzes six different ecosystem service models in total, and mangroves are included in the coastal protection model. This method evaluates how the loss of land due to flooding and inundation affects GDP and other economic indicators. The InVEST Coastal Vulnerability model is used to produce a vulnerability index, which provides a qualitative estimate of exposure to erosion and inundation during storms based on the biological and physical characteristics of the coastline. The vulnerability index ranges from values of 1 (very low exposure) to 5 (very high exposure), and, in this method, a threshold of 3.3 on the vulnerability index is used to designate a coastline as "at risk". The index score is combined with population and gridded GDP data (300m grid cells) to identify coastal areas where humans and built capital are most vulnerable to storm surge.[1] The economic impact of the model is reflected in the avoidance of damages to assets and people from flooding, which is based on the percentage of GDP production in grid-cells newly at risk from flooding due to sea-level rise. In the 2020 Global Futures paper, it was assumed that 5% of the GDP within each grid-cell that is designated as "at risk" is lost.

The advantage of the InVEST Coastal Vulnerability Model is that it covers both coastal erosion and flooding, is a simple model with relatively basic data requirements, and it is applicable across the globe on a flexible scale. However, the major issue with this approach is the arbitrary choice of a 5% GDP impact, as also acknowledged by Johnson et al. (2020). Perhaps more importantly, the *a priori* assumption of a GDP impact, albeit at the grid level, is inconsistent the objective of macroeconomic modeling to assess the impact of a change in ecosystem services on GDP and other key macroeconomic indicators.

This note presents an alternative method for estimating and integrating coastal protection benefits provided by mangroves, as well as carbon sequestration and storage ("blue carbon"). While mangroves generate a variety of other ecosystem services too, our focus is on these two services motivated mainly by the ready availability of Changing Wealth of Nations (CWON) and other global datasets which we expect will allow the incorporation of mangroves into macroeconomic models as part of World Bank core analytical studies at scale and in a consistent manner. But, where robust data are available on other ecosystem services provided my mangroves, we encourage teams to use them.

Next we discuss the proposed methods for incorporating the said ecosystem services into macroeconomic models followed by a presentation of their application in India and Sri Lanka. The discussion section proposes future directions on priority areas for improvement.

Methods

In this section we first discuss that scenario-based modelling that underlies macroeconomic analyses is applied to mangrove ecosystem services. We then describe the method for estimating and valuing the coastal protection ecosystem service and carbon emissions/sequestration. We also present the estimation of costs associated with each scenario. The section ends with a discussion of the impact channels through which the coastal protection values and costs are incorporated in MANAGE-WB and MFMod.

Scenario-based Modeling

Consistent with the scenario-based approach to policy analysis through macroeconomic modelling, we adopt two types of scenarios, namely a business-as-usual (BAU) scenario and a policy or alternative scenario. The BAU scenario assumes that there are no new policies or interventions. The BAU scenario involves projections on mangrove extent during the modeling period based on historical trends. Global Mangrove Watch (GMW) data indicate many countries experienced losses in mangrove extent between 1996 and 2020, although for most of those countries, the rate of loss was significantly lower from 2010 to 2020 than it was from 1996 to 2010, some countries registered gains in the latter period (World Bank 2024b). This suggests that the choice of the historical period will affect the trend projected for the

[1] Information comes from the User Guide for the Coastal Vulnerability Model. Natural Capital Project. http://releases.naturalcapitalproject.org/invest-userguide/latest/en/coastal_vulnerability.html

period under analysis. Where continued loss of mangroves is projected, further decline in ecosystem services will occur. With regard to carbon, this will mean a release over time of carbon stored in the biomass and sediments associated with the mangrove trees, as well as additional sequestration of carbon that these mangroves may have done if they were not uprooted.

An alternative or policy scenario reflects the government's policy plans regarding mangrove cover during the modeling period. This scenario may involve conservation efforts to slow down or halt mangrove loss (where loss was the historical trend) or restoration to add to the existing mangrove extent. Countries' motivations for conservation and restoration include the wish to realize the benefits provided by mangroves including notably coastal protection, habitat provision to commercially important fish and marine species and carbon sequestration. Halting of mangrove loss stops loss of stored carbon, while restoration allows new sequestration of carbon. For countries that have committed to achieving net zero carbon emissions, stopped to lose stored carbon and increasing sequestration count as negative emissions.

Land use changes, including conversion from and to mangrove forests are bounded by biophysical, climatic, and economic conditions. And the location of mangrove losses or gains has a bearing on the ecosystem services they provide. Therefore, ideally, any projections regarding mangrove land conversions need to take into account these conditions as well as historic patterns of conversion in terms of economic activities taking over the lost mangrove areas. Similarly, in policy scenarios where governments have broadly set a numeric target for restoration but have not identified the specific locations taking into account the above-named suitability criteria, projections should be made through land-use land-cover (LULC) models that incorporate such criteria. However, LULC models using in the context of ecosystem service modeling do not explicitly differentiate mangrove land.

Ecosystem Service Values

Coastal Protection against Flooding

For the integration of coastal protection services into the MANAGE-WB and MFMod models, we rely on the spatially explicit "annual expected averted damages" to capital stock in 2020 reported by the World Bank's Changing Wealth of Nations (CWON) publication (World Bank 2024a). *Annual averted expected damages* is defined as the difference of annual expected damages to capital stock exposed to coastal storms without and with mangroves (Box 1). As such, it is a monetary measure of the coastal protection service provided by mangroves, as the presence of mangroves averts part of the expected damage. Under certain assumptions discussed below, we use these data to estimate the increase and decrease in coastal protection benefits associated with mangrove restoration and loss, respectively.

Box 1. Summary of estimation of annual averted expected damages to capital stock in CWON

The estimation of annual averted expected damages to capital stock at the pixel level involved several steps which are discussed in detail in World Bank (2024b). In summary, calculation of annual expected damages from flooding requires first the determination of exposed capital stock and then the calculation of damages under a range of storms of varying strength with and without mangroves. To calculate the exposed capital stock in each 250mx250m pixel, the authors first determine the number of exposed people in each pixel. To this end, they use global data on population distribution and density as well as offshore storm models with coastal processes and flood models. Then they multiply the number of exposed people by the per-capita capital stock value of the corresponding country. National capital stock information is sourced from the Pew World Tables version 10.0.

and comprises built assets[2]. Damage under each storm return period to capital stock is calculated as a function of flood water depth. The annual expected damage is the integral of damages of under a range of storms return periods. The mangrove extent data are sourced from the Global Mangrove Watch dataset.

To estimate the increase in coastal protection benefits due to mangrove restoration, following Beck et al. (2022), we assume that the additional protection benefit per hectare of the restored mangrove area is equal to the average per hectare expected averted damage provided by the existing mangroves. Thus, in a given restoration area, the total additional protection is the product of the said average and the number of hectares of restored mangroves. Like Beck et al. (2022), we feel that this approximation is not unreasonable and possibly serves as an underestimation of the benefit to be gained from restoration activities, considering that restoration will be prioritized in areas with high asset values. Similarly, to estimate the loss in protection benefits due to conversion to other economic uses, we assume that the marginal loss per hectare of mangroves converted is equal to the average benefits provided by the existing mangroves. To the extent mangrove conversion is likely to occur in areas with larger population density and keeping in mind that the initial CWON estimate of the pixel level asset value is proportional to population density, it may be argued that this assumption too may not be an overestimation of lost protection value.

Two sources exist for the average protection value provided by existing mangroves, depending on the scale of mangrove restoration or loss. The first source is the interactive online dashboard maintained by the Center for Coastal Resilience at the University of California at Santa Cruz (UCSC) that presents the same data as in CWON 2.0 (World Bank 2024a).[3] Specifically, for each 20km spatial unit, the expected economic damages without mangroves and expected economic damages with mangroves are presented, as well as the per hectare economic benefit of the existing mangroves in that unit, all expressed in in constant 2020 US$. Thus, the UCSC database can be used in scenarios where the 20km spatial units are an appropriate scale, and no GIS software or additional calculations are necessary.

The second source is the CWON 2.0 spatial dataset[4] which analysts can refer to when restoration plans are defined for administrative units, such as a state or province in a country. This dataset provides, for 20km spatial units (i) mangrove extent in hectares ("Mang-Ha"), (ii) the annual expected damage to capital stock *with mangroves* ("Risk_Stock"), and (iii) annual protection benefits provided by mangroves to capital stock ("Ben_Stock). The sum of Risk_Stock and Ben_Stock equals the annual expected damage to capital stock without mangroves, namely if no mangroves were present in that 20km spatial unit. These data are contained in a shapefile; to aggregate Mang_Ha and Ben_Stock to an administrative unit, such as state or province, it is necessary to summarize the Mang_Ha and Ben_Stock values across all the units that fall within each such administrative unit using a GIS software. This method could be repeated to acquire the relevant values for any administrative unit for which restoration plans are defined in the country in question, including metropolitan areas, counties, states, regions, etc. To acquire the per-

[2]The data include residential and non-residential structures, machinery including computers, communication equipment and other equipment, transport equipment and other assets including software, other intellectual property products and cultivated assets, including livestock for dairy or breeding, vineyards, orchards (Rijksuniversiteit Groningen ND) https://www.rug.nl/ggdc/docs/pwt100-user-guide-to-data-files.pdf. and personal communication with PWT staff in October 2024.

[3] https://coastalresilienceexplorer.org/

[4] https://www.dropbox.com.mcas.ms/scl/fo/d5vpb4fnl94m795ml1tda/h?rlkey=i8hk42po8qehnewp9ftlqlup6&e=2&dl=0

hectare capital stock protection benefits for the relevant administrative unit, we divide the summarized benefits by the total number of hectares in that administrative unit. Then, we multiply the per-hectare benefits by each unit's restoration target in hectares to find the predicted annual benefits of capital stock protection if the restoration target is achieved. The same process applies when mangrove losses are available in administrative units.

There are some caveats to this approach. First, it focuses only on coastal protection from flooding, and does not capture coastal erosion reduction which mangroves also provide. Second, the spatial specificity of capital stock is limited to population density in grid cells and relies on per capital stock value across the nation, as such it ignores any specific concentrations of capital or lack thereof. This method also means that unpopulated areas are assigned no capital value. Furthermore, the capital stock measure used consists entirely of human-made capital assets including some cultivated assets but excluding natural assets which can hold significant economic value. As such, the benefit estimates are not suitable for ranking potential restoration sites (World Bank 2024b) and the coastal protection value thus estimated can be incomplete. Additionally, this method can only generate estimates of damages or benefits associated with a decrease or increase in mangrove extent, but not changes and variation in the condition, age structure, species or density of mangroves all of which impact their capacity to reduce flooding since the Global Mangrove Watch database does not include such detailed information.

Provisioning Services

Unlike unproductive, grey coastal protection infrastructure, mangroves provide a multitude of benefits to the economy, including habitat to commercially important fish and opportunities for recreation/tourism. These benefits are lost when mangrove areas are converted to other uses; they are maintained when mangroves are conserved; and enhanced when mangroves are restored. It is important that these benefits be reflected in nature-aware macroeconomic models given their economy-wide impacts on incomes and employment.

To our knowledge, global datasets that estimate such ecosystem services using a consistent methodology across countries, do not exist currently. Under these circumstances, where analysts have robust country-specific estimates, they are encouraged to use them. For example, the Nature-based Solutions Opportunity Scans (NBSOS) series which is produced on individual World Bank client countries in support of CCDRs and other analytical country diagnostic work, includes estimates for fish and other resource extraction, and tourism benefits for priority areas it identifies for restoration using a consistent benefits transfer method (World Bank 2024c). These estimates are per hectare of mangroves. The analyst must determine carefully to what extent these estimates can be applied to the entire area projected to be lost or planned to be restored.

Carbon Storage and Sequestration

In this section we present how we estimate the release of stored carbon when mangroves are lost and the sequestration of carbon when mangrove areas are established or restored. The MANAGE-WB and MFMod models do not assign monetary value to carbon emissions, therefore we limit our effort to estimation of volumes of emissions/sequestration.

Emission of stored carbon when mangroves are lost

Carbon is stored in aboveground biomass (AGB), belowground biomass (BGB), and sediments, collectively known as the carbon pool. Carbon contained in sediments, known as soil organic carbon, make up most of the carbon stored by mangroves. The CWON 2.0 dataset on mangrove carbon storage provides data on AGB and SOC at the country level for the years 1996, 2007, 2010, 2015, 2018, and 2020. The data are divided into climate zones: tropical wet, tropical dry, subtropical, and arid. As a global dataset, the CWON data are based on the mangrove extent reported by the Global Mangrove Watch (GMW) and are reported at a 30m resolution.

The AGB data are reported in tons of biomass per hectare. To determine the total AGB associated with the mangrove area projected to be converted/conserved under a business as usual /restoration scenario, we first identify the areas to be lost/conserved. We then find the average pixel value within those target areas, weighted by the frequency of each pixel value. We multiply this average by the number of hectares to be lost/conserved within the area to find the total AGB. Finally, to convert from tons of AGB to tons of carbon stock, we use the IPCC Tier 1 carbon conversion factor of 0.45, as described in the World Bank technical report associated with the dataset (World Bank 2024d).

This AGB dataset can also be used to calculate the belowground biomass (BGB) using the appropriate root to shoot ratio, which varies based on the climate zone. After finding the total AGB associated with the projected conversion/conservation area as described above, we apply the root to shoot ratio to estimate the associated BGB. Finally, to convert to carbon stock associated with AGB and BGB, use the default carbon fraction conversion factor of 0.39 as described in World Bank (2024d).

The soil organic carbon (SOC) data are reported in tons of carbon per hectare. The same approach used for the AGB calculations can be applied here. First, identify the area of conversion or conservation. Then, find the average pixel value for tons of carbon per hectare within this area. Multiply the average by the total area of conversion /conversation to find the total SOC stock associated with a given restoration target or projected loss at each site.

When mangrove areas are converted to other uses, the carbon stored in the biomass and sediments is released. Murray et al. (2011) state that where conversion involves excavation of the top one-meter soil layer, such as conversion to shrimp aquaculture, soil carbon and biomass begin to decompose immediately. In their modelling of stored carbon emissions from mangrove conversions in tropical Asia they conservatively "that 75% of it is burned away on habitat conversion. Decay of the remaining biomass carbon is much slower, and 8% of it remains at the end of the 25-year period." We follow the same approach to estimate annual loss of stored carbon following conversion. These estimates will pertain to the business-as-usual (BAU) scenario where mangrove conversion is projected based on historical trends.

The magnitude of carbon losses from mangrove conversion highlights the importance of conserving existing mangroves relative to mangrove restoration which we discuss next.

Carbon sequestration by newly established or restored mangroves

Here the objective is to estimate annual sequestration by newly planted mangroves. Song et al (2023) report estimated carbon storage in reforested and afforested mangrove areas based on 379 restoration sites around the world. Their estimates include average carbon stored in AGB, BGB, and sediments, over a forty-year period, together with the upper and lower bounds of respective 95 percent confidence intervals confidence intervals (Table 1). The total average carbon sequestration over the first forty years was estimated at about 306 tons carbon per hectare in case of reforestation versus 191 tons c/ha for afforestation, a 60 percent difference. Dividing by 40 and applying the standard conversion factor of 3.67 yields annual CO_2 equivalent sequestration of 28.04 tons and 17.50 tons, respectively.

Table 1. Estimated annual carbon sequestration in reforested and afforested mangrove areas

	Reforestation			Afforestation		
	average	lower	upper	average	lower	upper
Aboveground biomass (t C /ha)	127.7	110.7	144.7	88.7	70.2	107.2
Belowground biomass (t C /ha)	38.7	30.1	47.3	37	22.9	51.2
Sediment (t C /ha)	139.2	136.4	142.1	65	-3.7	133.7
Total (t C /ha)	305.6	277.2	334.1	190.7	89.4	292.1
Annual over 40 years (t C /ha/year)	7.64	6.93	8.35	4.77	2.24	7.30
CO_2 equivalent* (t CO_2e /ha/year)	28.04	25.43	30.65	17.50	8.20	26.80

Source: Based on data reported in Song et al. (2023)
Note: * Derived using the standard conversion factor of 3.67

Costs

Direct Costs

Direct Costs of Restoration

Direct costs of restoration consist of (i) initial costs incurred at reforestation and afforestation, and (ii) after-care costs.

Initial costs

A handful of literature reviews have focused on building databases of cost estimates for mangrove restoration projects. The most detailed data come from studies in Florida and the Caribbean, with limited information available for other regions. A frequently cited systematic review conducted in 2016 surveyed dozens of mangrove restoration projects worldwide and generated average and median restoration cost estimates per hectare for the world at large, as well as estimates for "developed" and "developing" countries, but nothing more specific (Bayraktarov et al. 2016). Narayan et al. (2016) synthesize the median costs of 12 mangrove projects conducted around the world, with values from the UK, the USA, Vietnam, and parts of South America. Beck et al. (2022) use estimates from these papers and include a literature review of projects conducted between 2016 and 2019 as well as direct surveys of restoration practitioners in the Caribbean, to generate cost estimates per hectare for Florida, the Caribbean, and "All Other Regions".

The Nature-Based Solutions Opportunity Scan (NBSOS) (World Bank 2024c) at the World Bank uses value functions to estimate the cost of mangrove restoration. It is essentially a regression fitted to observed mangrove restoration cost data globally with explanatory variables that describe the project context, such as adjusted GDP per capita and the size of the project.[5]

[5] Personal communication with Boris Ton van Zanten, August 2024

Where the information is available, it is preferable to use country or region-specific restoration cost estimates. However, data is especially scarce in many developing countries, in which case general global estimates from the aforementioned literature could be a suitable replacement.

Cost of Conservation

Ensuring that mangroves remain intact and are not converted to other uses, is mainly a regulatory enforcement function but could also be achieved through payment for ecosystem services where private actors have tenure rights over mangrove areas. Costs are highly specific to country and governance circumstances. A global database of such costs is not available. Teams are advised to consult with government counterparts for estimates. Where available, NBSOS estimates can constitute a starting point for discussions with government counterparts.

Opportunity Costs

Key reasons for losses of mangrove areas are land use for economic sectors, including notably aquaculture, agriculture, or tourism (Jakovac et al. 2020, Murray et al., 2011). In other words, while the loss of mangroves leads to economic losses, which are often of public good nature and often not traded in the market, the alternative uses generate economic gain, which are often of private nature and have backward and forward linkages in the economy. Conversely, mangrove restoration precludes such alternative economic streams and thus they present an opportunity cost of restoration. Any economic analysis, whether partial and equilibrium, that does not take into account the economic gains or losses of alternative uses overestimates mangrove benefits and is thus incomplete (Van Zanten et al 2023?).

Jakovac et al. (2020) have estimated average per hectare land opportunity costs for 103 mangrove-holding countries. They report the cost in the terms of net present value (NPV) for 40 years considering a 5 percent discount rate, in constant 2019 US$. The dataset mainly relies on agriculture and livestock, which may underestimate the opportunity cost in some countries where mangroves are converted to aquaculture. Nevertheless, the consistency of the derived cost estimates makes it a preferred source of data for incorporating mangroves in country-specific macroeconomic models across World Bank client countries. In our analysis we derive a stream of annual values from the NPV.

Incorporating Mangroves in MANAGE-WB and MFMod

Table 2 summarizes the impact channels through which the benefit and cost elements associated with mangrove restoration are incorporated in MANAGE-WB and MFMod.

Table 2.

Impact channel	Description
Asset damage	For each scenario, the country's capital base is depreciated annually by the estimated expected annual damages due to coastal flooding, given the exiting mangrove extent that year. This depreciation leads to reduced production which reverberates through the economy through the economy (multiplier effect). When the expected damage is reduced through restoration of mangroves, the economy wide impacts are also reduced, as determined by various assumptions on elasticities impacting mobility of factors of production.

Fish and other resource extraction	Where this estimate exists, it is incorporated into MANAGE-WB / MFMod as a output/productivity shock to the respective economic sector, respectively. The shock is negative in case of mangrove loss, and positive in case of restoration.
Direct costs of mangrove management (conservation or restoration)	Any costs associated with mangrove conservation, or planting and after care financed by the government enter the model as government expenditure. They crowd out other expenditures by government.
Opportunity cost of mangroves	If in BAU mangroves are lost, it is likely that revenue-generating economic activities such as agriculture, aquaculture, or tourism is take place on the cleared areas. Conversely restoration of mangroves, likely leads to foregone revenues from such activities. These streams of revenues are reflected as output shocks in MANAGE-WB and TFP shocks in MFMod. These shocks are positive in case of mangrove loss and negative in case of restoration. Since the opportunity cost estimates we use are from agriculture (Jakovac et al 2020), agricultural output/TFP is shocked.

Pilot Country Applications

Pilot Application to MANAGE-WB in India

Context

Mangrove forests cover more than 30 percent of India's 33,694-kilometer coastline.[6] The top five states with significant mangrove extent and associated ecosystem services are West Bengal, Gujarat, Andra Pradesh, Maharashtra and Odisha (FSI 2022), home to over 400 million people, and containing three major coastal metropoles: Kolkata (West Bengal), Chennai (Tamil Nadu), and Mumbai (Maharashtra). Mangroves provide important ecosystem services, protecting coastal assets against coastal flooding and erosion, sequestering carbon at a rate up to four times that of tropical terrestrial forests at the pot level (Murray et al. 2011; Taillardat et al. 2018), and supporting fisheries with habitats at different life stages. The government of India plans to carry out reforestation and afforestation in nearly 50,000 hectares of mangrove areas during the next 10 years, under the Mangrove Initiative for Shoreline Habitats & Tangible Incomes (MISHTI) program.[7] This program is intended to counteract climate change-induced coastal vulnerability highlighted in India's first NDC[8] and contribute to the plan presented in its updated first NDC[9] to create an additional carbon sink of 2.5–3 billion tons of CO_2 equivalent through additional forest and tree cover by 2030, as well as its 2070 net zero target.

[6] Based on Global Mangrove Watch estimate of mangrove area of 4,038km^2 in 2020. The estimate in the *2021 India State of Forest Report* (FSI 2022) is higher, at 4,992 km^2 (499,232 hectares).

[7] https://www.indiascienceandtechnology.gov.in/programme-schemes/societal-development/mangrove-initiative-shoreline-habitats-tangible-incomes-mishti.

[8] https://unfccc.int/sites/default/files/NDC/2022-06/INDIA%20INDC%20TO%20UNFCCC.pdf.

[9] https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20First%20Nationally%20Determined%20Contrib.pdf.

Scenarios

Business-as-Usual Scenario

In the BAU scenario simulated by MANAGE-WB, the mangrove extent of a country stays as in the baseline during the modeling period.

Restoration Scenario

The MISHTI program is implemented in 12 states over a 10-year period (table 3). As explained below, we focus our benefit and cost estimates on 47,857 hectares in 9 states for which CWON coastal protection estimates are available. Based on the government's rough reforestation / afforestation ratio, in this exercise we assume that 35,000ha will be reforested and 12,857ha will be afforested. We assume that reforestation and afforestation activities will be carried out from 2025 to 2034, at equal annual increments (first row in table 5).

Table 3. MISHTI mangrove restoration targets by state

State	Restoration Target (ha)
Gujarat	25,339
Daman & Diu	10
Maharashtra	3,942
Goa	5
Karnataka	510
Kerala	611
Tamil Nadu	1,365
Puducherry	10
Andhra Pradesh	6,730
Odisha	4,695
West Bengal	3,666
Andaman & Nicobar	2,100
Total	48,983

Source: MISHTI Program

Ecosystem Service Values

Coastal Protection against Flooding

The value of coastal flood protection services resulting from the restoration scenario is calculated based on the CWON spatial data. Since the restoration targets are provided at the state level, we are interested in knowing the per-hectare capital stock protection benefits of mangroves within each state. The UCSC Coastal Resilience Mapper provides per hectare capital stock protection benefits at the 20km unit level, but in order to aggregate to the state level for the India application we must take the original CWON dataset and analyze it via GIS software.

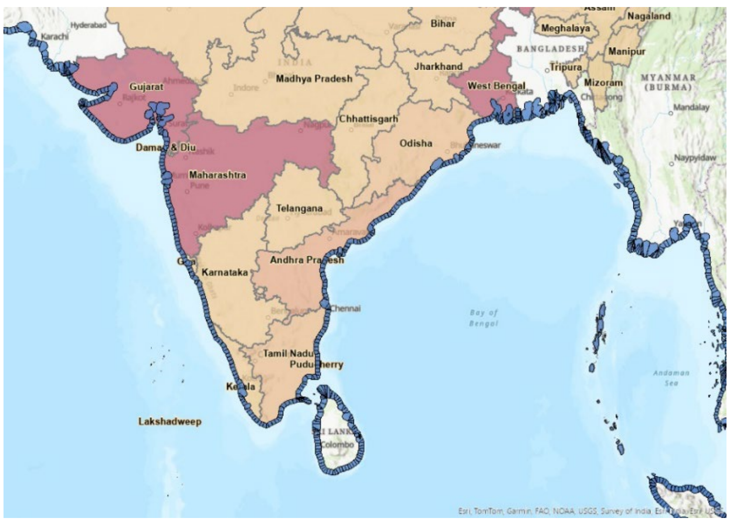
Using the ARCGIS Online software, we summarize the values of mangrove extent ("Mang_Ha"), estimated annual expected damage with mangroves (Risk_Stock) and capital stock protection

("Ben_Stock") across each of the 12 Indian states listed in table 3.[10] For each state, we then divide the summarized capital stock protection by the mangrove extent to generate the estimated annual capital stock protection value per hectare of mangroves within that state (column e in table 4). To find the incremental annual coastal benefits of the planned restoration (column g), we multiply the per-hectare benefit value for each state by that state's restoration target, as seen in table 4.

As Table 4 indicates, several of the states with listed restoration targets (table 3) do not have any anticipated value, because, as noted in the methods section, the CWON dataset only accounts for mangroves when they provide direct socioeconomic benefits, and the global model does not detect flood protection benefits to people and capital stock in these regions.

Map 1 below contains three layers: the CWON spatial dataset in 20km units (in blue), India's administrative boundaries, and a layer we generated which summarizes the mangrove extent and capital stock protection benefits within each state, shaded by the level of benefits.

Map 1.



Source: Survey of India, Esri India, Menéndez, Losada, Torres-Ortega, Narayan & Beck. The Global Flood Protection Benefits of Mangroves. 2020. https://doi.org/10.1038/s41598-020-61136-6 –›

For integration in MANAGE-WB, assume that under the BAU scenario the stream of annual expected damages remain unchanged from the 2020 value, US$ (2020) 846.5 million (see bottom of column (c) in table 4, and table 5), while in the restoration scenario, the expected damages decrease annually as restoration activities advance. Assuming that the restoration occurs in equal annual increments, the annual incremental protection is US$ (2020) 44.4 million. Thus, the annual expected damage reaches US$(2020) 443.8 million in 2034. In the absence of additional restoration, this figure persists through the end of the modeling period (table 5).

[10] The sum of the value in Risk_Stock and Ben_Stock is the estimated annual expected damages *without* mangroves.

Table 4: Summarized values of existing mangrove extent and estimated existing and incremental annual coastal protection benefits across the states of India.

(a)	(b)	(c)	(d)	(e)	(f)	(g)
State	**Mangroves (Mang_Ha)**	**Annual Expected Damages *with* Mangroves (Risk_Stock) (US$ 2020/year)**	**Annual Coastal Protection Benefits (Ben_Stock)* (US$ 2020 /year)**	**Benefits per Hectare (US$ 2020 /year)** = d / b	**Restoration Target (ha)**	**Incremental Annual Coastal Protection Benefit (US$ 2020/year)** = e* f
Gujarat	30,683.00	195,192,035	326,882,171	10,653	25,339	269,949,728
Daman & Diu	56.55	1,541,478	2,893,406	51,166	10	511,664
Maharashtra	15,936.35	313,942,024	569,124,307	35,712	3,942	140,778,042
Goa	0		0	0		
Karnataka	0		0	0		
Kerala	0		0	0		
Tamil Nadu	2,563.99	121,525,693	19,126,234	7,459	1,365	10,182,317
Puducherry	345.48	8,143,912	238,731	691	10	6,910
Andhra Pradesh	28,800.70	70,362,039	45,988,924	1,597	6,730	10,746,455
Odisha	10,369.26	45,221,366	18,728,512	1,806	4,695	8,479,910
West Bengal	206,457.81	85,576,858	153,565,627	744	3,666	2,726,812
Andaman & Nicobar	47,731.09	4,985,201	9,067,894	190	2,100	398,955
Sum		846,490,606	1,145,615,806		47,857	443,780,793

Source: CWON Dataset[11]

Notes: * The annual coastal protection benefit is the difference between annual expected damages in 2020 if there were no mangroves and annual expected damages with mangroves in 2020.
The column headings in parentheses mirror the column headings in the CWON database.

This annual increment benefit is constant throughout the modeling period and any increases in the value of the protected infrastructure assets overtime are not reflected. As such, the economic returns of mangrove restoration may be underestimated in the later years of the modelling period.

Carbon Sequestration

To estimate the associated annual carbon sequestration, we apply annual averages derived from Song et al. (2023) data (Table 1). Specifically, for reforested mangroves we use 28.04 Mg $C0_2e$ /ha/year and for afforested mangroves we use 17.50 Mg CO_2e /ha/year. These values are applied to respective annual cumulative reforested/afforested mangrove areas. As Table 5 indicates, by 2035, the new mangrove areas will sequester annually 1.2 million tons of CO_2 equivalent.

Costs

Direct costs

In 2024, the M S Swaminathan Research Foundation (MSSRF) estimated the average cost of restoring mangroves at Rs.150,000 which is equivalent to around US$ (2020) 1,551 per hectare.[12] Furthermore, after care costs are estimated at Rs. 15,000 (around US$ (2020) 155) per hectare for maintenance of

[11] Menéndez, Losada, Torres-Ortega, Narayan & Beck. *The Global Flood Protection Benefits of Mangroves. 2020.* *https://doi.org/10.1038/s41598-020-61136-6 –›*
[12] Personal communication with MSSRF by Anuja Shukla in August 2024.

water feeding channels and at Rs.15,000 (around US$ (2020) 155) per hectare for replantation.[13] We apply the after-care costs for six years from the year of reforestation / afforestation.

Opportunity Costs

We use an average annual opportunity cost of US$ (2020) 280 per hectare which derived from an estimated mean NPV of US$ (2019) 4,748 (d=0.05, 40 years) from Jakovac et al. (2020). We multiply this amount with cumulative restored mangrove area each year during the modeling period. We thus project that the total opportunity cost of reforesting/afforesting nearly 48,000ha with mangroves is US$ (2020) 13.4 million in 2034 (Table 5).

Stream of Annual Benefits and Costs

Table 5 presents the stream of estimated annual coastal protection benefits, incremental carbon sequestration, and costs.

[13] Personal discussion with sector experts in India by Anuja Shukla, August 2024.

*Table 5: Stream of annual benefits, costs, and carbon sequestration under mangrove restoration**

Year	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040 - 2070**
Cumulative mangroves restored (ha)	4,786	9,571	14,357	19,143	23,929	28,714	33,500	38,286	43,071	47,857	47,857	47,857	47,857	47,857	47,857	47,857
Protection of coastal human-made assets																
Expected damages in BAU (million USD 2020)	846.5	846.5	846.5	846.5	846.5	846.5	846.5	846.5	846.5	846.5	846.5	846.5	846.5	846.5	846.5	846.5
Expected damages in Restoration scenario (million USD 2020)	802.1	757.7	713.4	669.0	624.6	580.2	535.8	491.5	447.1	402.7	402.7	402.7	402.7	402.7	402.7	402.7
Cumulative incremental protection benefits (million USD 2020)	44.4	88.8	133.1	177.5	221.9	266.3	310.6	355.0	399.4	443.8	443.8	443.8	443.8	443.8	443.8	443.8
Costs																
Direct costs - government spending (million USD 2020)	8.9	10.4	11.9	13.4	14.8	16.3	16.3	16.3	16.3	16.3	7.4	5.9	4.5	3.0	1.5	0.0
Opportunity costs - forgone economic revenues (million USD 2020)	1.3	2.7	4.0	5.4	6.7	8.1	9.4	10.7	12.1	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Incremental C sequestered (million t CO_2e)	0.12	0.24	0.36	0.48	0.60	0.72	0.84	0.97	1.09	1.21	1.21	1.21	1.21	1.21	1.21	1.21

Note: * About two thirds of mangrove areas are reforested, the rest afforested. See text.

Incorporation of Benefits and Costs in MANAGE-WB India

As mentioned earlier, the BAU scenario in MANAGE-WB does not consider any additional efforts to restore mangroves. The loss of capital stock in the economy for any reasons including natural disasters is already reflected in the capital depreciation rate. In the alternative, “restoration” scenario, we consider the additional efforts. Specifically, we assume that the government increases its capital expenditure by borrowing from the domestic loanable fund market. The increased spending is used to restore the mangroves which reduces the expected damages to capital stock from coastal flooding. Here we discuss briefly how these channels work. Equation (1) shows that the expected capital stock $kStock_{t+1}$ is current year stock minus depreciation plus productive investments $prodInv_t$:

$$kStock_{t+1} = (1 - depr_t)kStock_t + prodInv_t \tag{1}$$

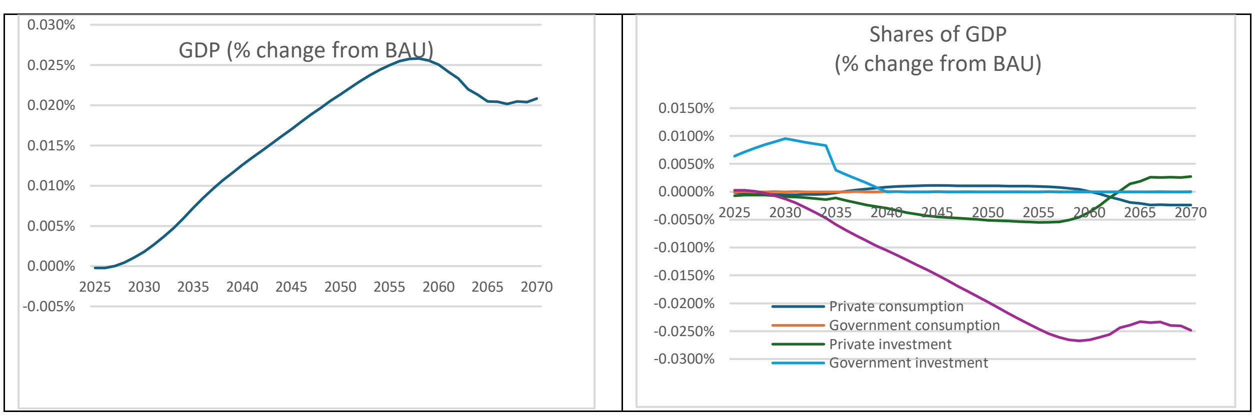
The productive investments $prodInv_t$ defined in equation (2) are the sum of private investments $xfd_{inv,f}$, a share $phiPcInv_t$ of government $xfd_{ginv,t}$, minus investments into R&D services under the endogenous technology module and exogenous non-productive investments $nonProdInv_{inv,t}$:

$$prodInv_t = xfd_{inv,f} + phiPcInv_t xfd_{ginv,t} - xfRd_{inv,t} - nonProdInv_{inv,t} \tag{2}$$

The restoration has costs and a benefit. The cost is the restoration investment does not create capital stock so that $prodInv_t$ falls – i.e., the restoration investment is $nonProdInv_{inv,t}$. Another cost is the usual crowing out effect of government borrowing – i.e., $xfd_{inv,f}$ falls as $xfd_{ginv,t}$ increases in the loanable fund market. The benefit, on the other hand, is that the restoration increases capital stock by reducing the capital depreciation, $depr_t kStock_t$ (the annually recurring expected averted damage).

Direct costs of the restoration project in Table 5 represents the non-productive investment while cumulative incremental protection benefits in the same table are the reduced capital depreciation. Clearly the benefits are greater than the direct costs. We also consider the opportunity costs (forgone economic revenue) of the restoration project as it pushes the existing businesses out of the restoration areas. We assume that those businesses belong to the crops sector and translate this disruption into a TFP shock. In doing so, we calibrate the TFP shock such that the revenue loss is captured in the absence of the direct costs and the benefit of the restoration project as they impose additional shocks.

Figure 1. Simulation results: Impact of the Restoration Project (MANAGE-WB)



We simulate the MANAGE-WB model from 2022 to 2070 in two scenarios – the BAU and restoration scenarios. The simulation results for selected macroeconomic variables are displayed in Figure 1 – i.e., percentage changes from the BAU. Although the macroeconomic impact of the restoration project is small due to the size of costs and benefits of the project compared to the size of the Indian economy (e.g., the annual benefit of USD 443 million in 2035 while GDP is expected to be over USD 8 trillion given the high growth scenario), the impact on GDP is positive.

Pilot Application to MFMod in Sri Lanka

Background

In 2020, Sri Lanka's mangrove extent was about 19,000 hectares.[14] Sri Lanka 30 30x30 Plan (Sri Lanka X 30 2024)[15] reports that approximately 6,000 hectares had been lost since 1999. The same document presents a plan to restore about 3,500 hectares by 2030. In this pilot study, we estimate changes in key ecosystem services provided by mangroves under a business-as-usual (BAU) scenario and a restoration scenario. We then evaluate the economywide impacts of these changes in the MFMod model.

Scenarios

Business-as Usual Scenario

A land-use land-cover (LULC) modeling exercise for landscape management in Sri Lanka in general tentatively projected further mangrove conversion of some 12,000 hectares of mangrove areas to non-paddy crops, paddy, grassland, and urban lands. The projection built on the trend of conversion between 1999-2020, took into account key driver of change including slope and elevation, soil types, resource accessibility (through road networks or rivers), urban and cropland expansion, population growth, presence of protected areas and climate change. The modeling exercise also made adjustments to address challenges associated with discrepancies between national and international data on mangrove (Rutebuka and Asamoah 2025). However, discrepancies between national and international datasets on extent and pixel-level locations of mangroves in Sri Lanka likely led to an overprojection of mangrove losses in the said exercise. To be conservative, in this pilot application, we trim loss projections so they cannot exceed the 2020 GMW extent in each 20km unit. This process leads to a total projected loss of 7,073 hectares.

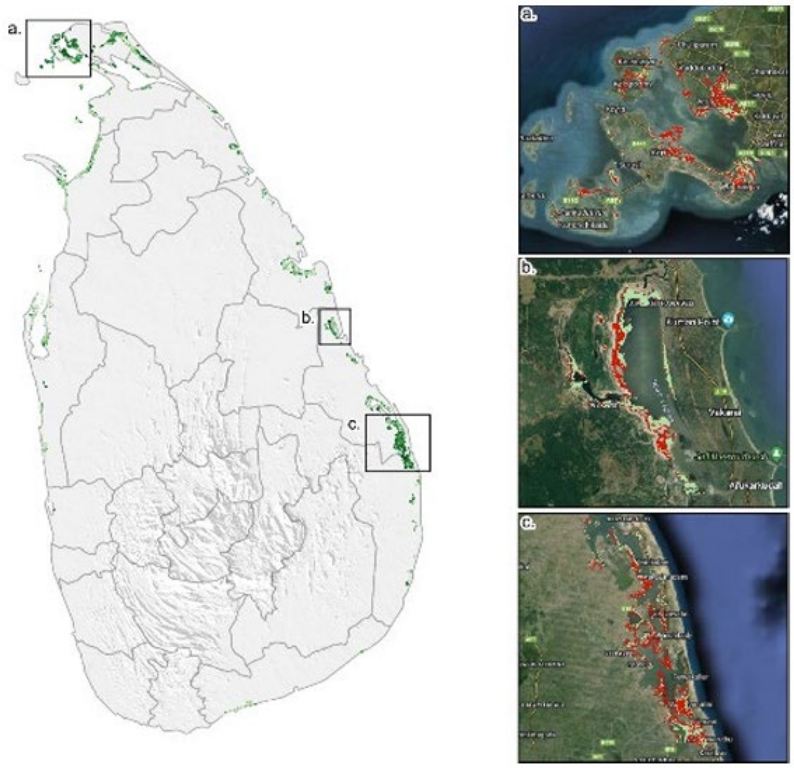
We assume a linear progression of mangrove extent losses by 236ha/year over the 30-year modeling period towards the total projected total loss of 7,073ha in 2050. In other words, each year the cumulative mangrove area lost increases by 236 ha (table 11).

Restoration Scenario

Under its Sri Lanka 30 X 30 initiative, the Government of Sri Lanka targets to restore up to 3,600 hectares of mangroves at three priority sites (Sri Lanka 30 X 30, 2024). One site ("Site A") is in the northern district of Jaffna, Site B is located within the district of Batticaloa, and Site C straddles the districts of Batticaloa and Ampara (figure 2 and table 6).

[14] According to the Sri Lanka Forest Department 2020 Forest Map it was 19,508 ha. According to the Global Mangrove Watch, it was 19,874 hectares, representing a linear coverage of 24.98% of the 3,328.20 km of the coastline.
[15] A government of Sri Lanka planning document for conserving 30% of the country's land and ocean by 2030 ("30x30") in alignment with the Global Biodiversity Framework under the Convention on Biological Diversity. https://srilanka30x30.com/

Figure 2: Potential mangrove restoration sites identified in the Sri Lanka 30x30 initiative.



Source: Sri Lanka 30 X 30 (2024)

Table 6: Proposed mangrove restoration sites and targets under the 30x30 program.

Restoration Site	District	Restoration Target (ha)
Site A	Jaffna	1,300
Site B	Batticaloa	300
Site C	Batticaloa and Amhara	1,900

Source: Sri Lanka 30 X 30

Table 7 presents Sri Lanka's approximate schedule for achieving its target of 3,500ha of restored mangrove forests by 2030 and the annual restoration schedule assumed in this analysis.

Table 7. Sri Lanka 30X30 targets for mangrove restoration

Year	2024	2025	2026	2027	2028	2029	2030
Cumulative target in 30X30 (ha)	800	1,000		2,000		2,500	3,500
Annual schedule of restoration assumed (ha)	800	200	500	500	250	250	1,000

Importantly, in this scenario, we also assume that mangrove loss would be prevented. In other words, the mangrove loss projected in the BAU scenario would not materialize due to enhanced enforcement.

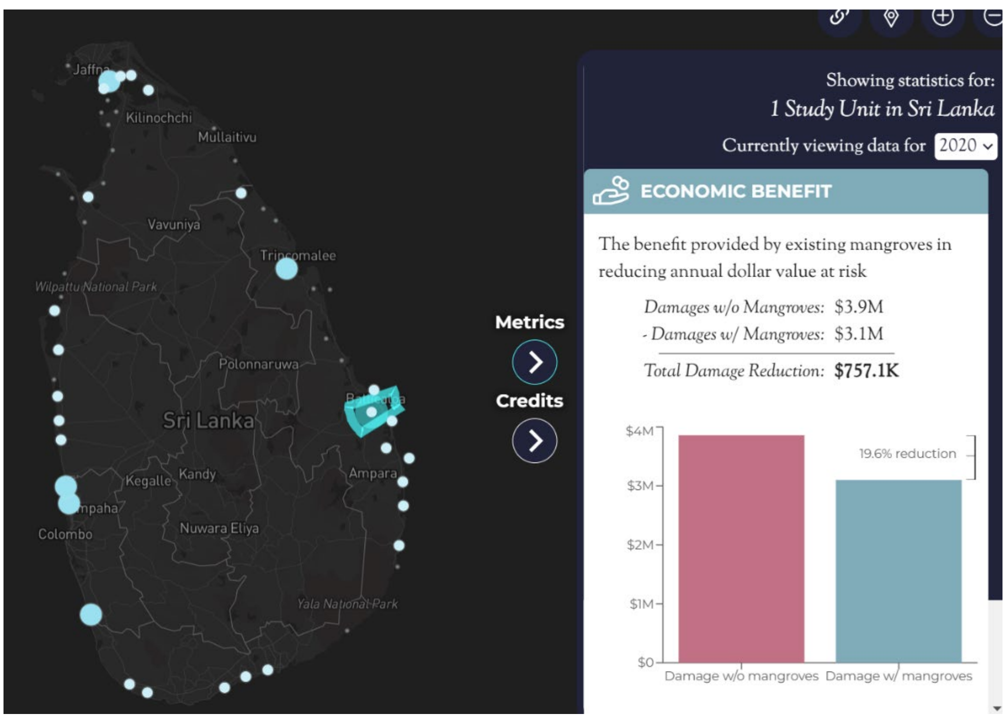
Ecosystem Service Values

Coastal Protection against Flooding

Loss of mangroves under the BAU scenario leads to reduction in coastal protection and therefore an increase in the annual expected damages to coastal assets, relative to the baseline year of 2020. Conversely, under the Restoration scenario, expected damages not only not increase since mangrove loss is halted, but they also decline due to the addition of restored mangrove extent.

We project the stream of expected annual damages under each scenario relative to the total expected damages given the total mangrove extent in Sri Lanka in 2020. The CWON database estimates this value as US$(2020) 164,5 million ("baseline"). For the BAU scenario, we obtain the average per hectare coastal protection benefit of the mangroves that are projected to be lost. As discussed in the methodology section, this is the difference between expected annual damages without and with mangroves divided by mangrove extent. We assume that this average protection benefit equals the marginal reduction in protection benefits for each hectare of mangrove lost. So, we use the UCSC Coastal Resilience Explorer to obtain the per-hectare protection benefits of mangroves in each of the 20km units where mangroves are projected to be lost and multiply this average with the number of hectares projected to be lost in the same unit. Figure 3 below demonstrates the UCSC Coastal Resilience Explorer in action. We then derive a weighted average of the per-hectare (to-be-lost) protection benefits across the 20-km units. For each year during the modeling period, we multiply this weighted average with the cumulative hectares of mangrove loss, and add the product to the baseline expected damage.[16] The additional annual expected damage due coastal flooding in 2050 is thus estimated at US$ (2020) 10 million (table 11).

Figure 3: UCSC Coastal Resilience Explorer used to determine per ha benefits of mangroves in Sri Lanka.



Source: Menéndez, Losada, Torres-Ortega, Narayan & Beck. The Global Flood Protection Benefits of Mangroves. 2020. https://doi.org/10.1038/s41598-020-61136-6 –›; https://coastalresilienceexplorer.org/

[16] We use the weighted average given uncertainty about specific areas where mangrove loss may occur in specific years during the modeling period.

For the restoration scenario, we follow a similar process, deducting the additional protection benefits provided by restored mangroves from the baseline annual expected damages. We derive the per-hectare coastal protection benefits for each of the restoration sites and calculate the total additional benefits that would accrue when restoration is complete (Table 8).

Table 8: Estimated benefits of mangrove restoration across the proposed sites.

Restoration Site	Benefits per Hectare (US$/ha/year)	Restoration Target (ha)	Annual Restoration Benefit (US$/year)
Site A	452.60	1,300	588,386
Site B	137.02	300	41,106
Site C	331.82	1,900	630,456

Using the ARCGIS Pro software, we summarize the values of mangrove extent ("Mang_Ha" in the CWON dataset) and capital stock protection ("Ben_Stock") in 20km spatial units within the boundaries of the proposed restoration sites as opposed to across the entire district.[17] Figure 4 shows the site areas used for this method, which follow those outlined in figure 2. We divide summarized capital stock protection by the summarized mangrove extent to generate an estimate of benefits per hectare that is more specific to the proposed restoration site. These values are listed in table 9.[18]

Table 9: Summarized values of existing mangrove extent and estimated protection benefits across the restoration sites.

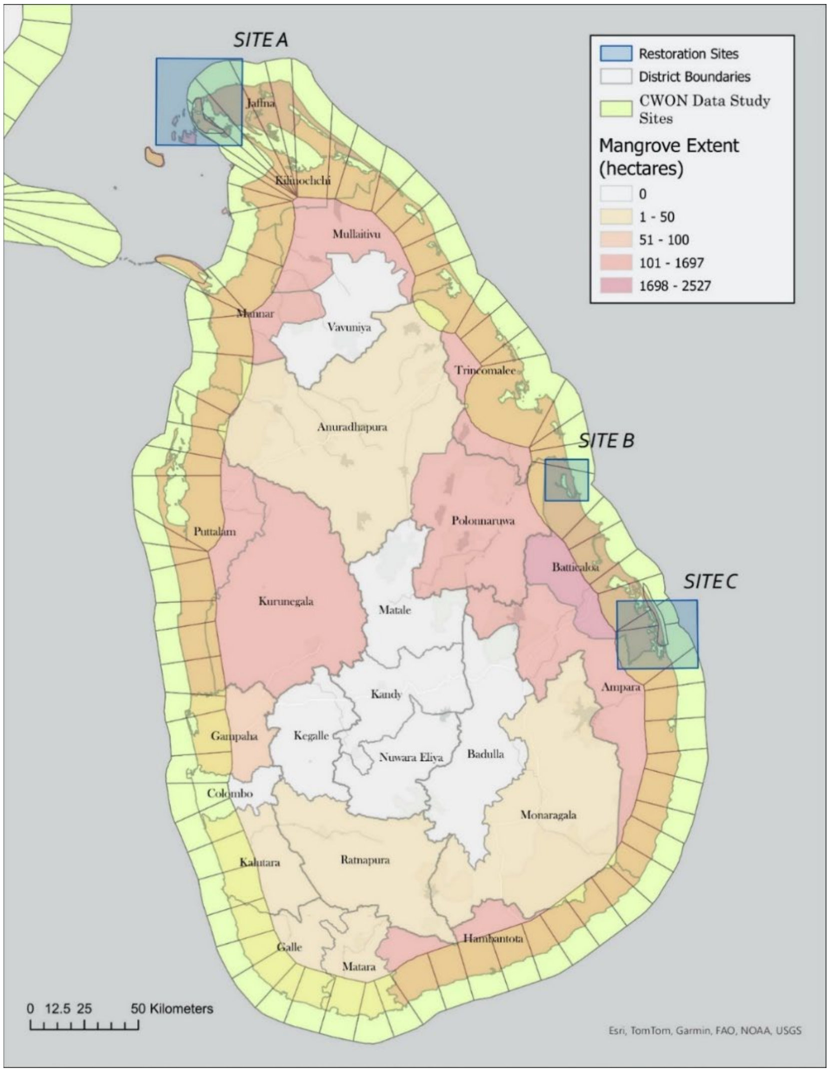
Restoration Site	Existing Mangrove Extent (ha)	Benefits (US$/year)	Benefits per Hectare (US$/ha/year)
Site A	2,318	1,049,138	452.60
Site B	197	26,993	137.02
Site C	4,087	1,356,144	331.82

Source: CWON dataset and own calculations

Figure 4. Restoration sites and mangrove extent by district across Sri Lanka.

[17] In this scenario we use the GIS software, rather than the UCSC dashboard, since we are looking at the restoration sites rather than the 20km units.

[18]



Source: CWON dataset and Esri

Provisioning Services

To estimate the losses in revenues from fish and other resource extractions, we multiply the per hectare estimate of USD 85 /ha (constant 2020 USD) presented in NBSOS for Sri Lanka (GFDDR 2024) with annual cumulative mangrove losses throughout the modeling period by 2050, the estimated lost benefits in this category amount to USD 599.500 (in constant 2020 USD).

Carbon Storage and Sequestration

Loss of Stored Carbon under the Business-as-Usual Scenario

To estimate the loss of stored carbon under BAU, we use ArcGIS Pro software to analyze the CWON carbon datasets for aboveground biomass (AGB) and soil organic carbon (SOC). For AGB, we first classify each 20km spatial unit by climate zone, as either tropical dry or tropical wet. Then, we find the average AGB per hectare in each 20km spatial unit and multiplied this by the number of hectares of projected loss in that unit. We then applied the IPCC tier 1 carbon conversion factor of 0.45 to convert the total AGB lost in each unit to total carbon stock lost in each unit.

For belowground biomass (BGB), we take the total AGB from each spatial unit, as calculated above, and applied the appropriate root to shoot ratio depending on the climate zone. For tropical dry, the ratio is 0.29 and for tropical wet the ratio is 0.49. This gives us the total BGB projected to be lost, which we then multiply by the default carbon fraction conversion factor of 0.39 to find the total carbon stock lost in BGB.

For soil organic carbon (SOC), we utilize the same approach as above and find the average tons of SOC per hectare within each 20km spatial unit using ArcGIS Pro. We then multiply this value by the number of hectares projected to be lost in each unit to find the total SOC projected to be lost under BAU. The total values for estimated carbon lost from AGB, BGB, and SOC are reported in Table 10 below.[19]

Table 10: Estimated carbon stock lost from each pool under BAU scenario.

Total AGB lost (tons of biomass)	Total carbon stock lost in AGB (tons of C)	Total BGB lost (tons of biomass)	Total carbon stock lost in BGB (tons of C)	Total SOC lost (tons of C)	Total carbon stock lost in BAU (tons of C)
350,126	157,557	144,702	56,434	2,520,494	2,734,485

Source: CWON dataset and own calculations

Carbon Sequestration in the Restoration Scenario

Estimates exist of the average carbon stored in three carbon pools (aboveground biomass, below ground biomass and sediments) associated with Sri Lankan mangroves, notably 534.9tC/ha by Jakovac et al (2020) or 524.25 tC/ha by Perara et al (2024). However, these findings do not indicate the number of years over which this amount of C was accumulated therefore it is not possible to derive the annual carbon sequestration potential of mangroves following restoration. Song et al (2023) estimated a global average of carbon storage in the aboveground and belowground biomass and sediments of reforested mangroves over a 40-year period, at 305.6 Mg C /ha[20], which is equivalent to 7.64 Mg C /ha per annum or 28 Mg C /ha per annum. This estimate may be conservative for Sri Lanka because the sample of mangrove reforestation sites from which the average was drawn were located between the altitudes 38 degrees South and 28 degrees North and carbon storage in all three carbon pools is highest near the equator (Song et al. 2023) while Sri Lanka is located roughly between 9 and 5 degrees North.

Costs

Direct Costs

In 2024, the Sri Lanka Forest Department indicated the direct costs of mangrove restoration as US$ 800 / ha per hectare in upfront expenditure and the after-care costs as US$ 100/ha per hectare for 6 years after planting. These 2024 values are equivalent to US$ (2020) 689/ha and US$ (2020) 86 respectively.

Opportunity Costs

[19] Loss of mangroves would lead to emission of carbon stored in the three carbon pools. Perera et al (2024) measured total organic carbon stored in aboveground and below ground biomass and sediments (up to one meter depth) in mangrove forests in 7 study areas along the coastal belt. They estimated the average carbon sequestration capacity of Sri Lankan mangrove ecosystems at 524.25 tC/ha. Pendleton et al (2012) report that conversion of coastal ecosystems to agriculture result in loss of biomass as well as sediments of at least one meter depth.

[20] +/- 28.5 Mg C /ha for a 95% confidence interval.

Jakovac et al. (2020) estimate the NPV of opportunity cost of Sri Lankan mangroves at US$ (2019) 6,738/ha. The annualized equivalent in 2020 constant US$ is US$ (2020) 398/ha. In the BAU scenario, we multiply this amount with the projected annual cumulative mangrove area converted. In the restoration scenario, we multiply the same with the planned annual cumulative restored mangrove area. Table 11 presents both streams.

Table 11 presents the streams of annual benefits and costs in the BAU and restoration scenarios.

Table 11. Stream of annual benefits, costs, and carbon emissions/sequestration under BAU and restoration scenarios

A) BAU Scenario

Year	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**…**	**2040**	**…**	**2045**	**…**	**2050**
Cumulative mangrove lost (ha)	236	472	707	943	1,179	1,415	1,650	1,886	2,122	2,358	2,593		3,772		4,951		6,130
Additional expected damages to coastal assets from coastal flooding (1,000 US$ 2020)	385	770	1,155	1,540	1,925	2,310	2,695	3,080	3,466	3,851	4,236		6,161		8,086		10,012
Expected damages to coastal assets from coastal flooding (1,000 US$ 2020)	164,901	165,286	165,672	166,057	166,442	166,827	167,212	167,597	167,982	168,367	168,752		170,677		172,603		174,528
Loss of fisheries and resource extraction (1,000 US$ 2020)	(20)	(40)	(60)	(80)	(100)	(120)	(140)	(160)	(180)	(200)	(220)		(320)		(420)		(520)
Benefits from economic uses after mangrove land conversion (1,000 US$ 2020)	94	188	281	375	469	563	657	750	844	938	1,032		1,501		1,970		2,439
Emissions of stored carbon (1,000 t CO2e)	62	72	82	90	95	101	106	111	116	122	127		141		151		157

B) RESTORATION Scenario

Year	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**		**2040**		**2045**		**2050**
Cumulative mangrove extent restored (ha)	800	1,000	1,500	2,000	2,250	2,500	3,500	3,500	3,500	3,500	3,500		3,500		3,500		3,500
Reduction in expected damages to coastal assets from coastal flooding (1,000 US$ 2020)	(288)	(360)	(540)	(720)	(810)	(900)	(1,260)	(1,260)	(1,260)	(1,260)	(1,260)		(1,260)		(1,260)		(1,260)
Fisheries and resource extraction (1,000 US$ 2020)	220	275	413	551	620	689	964	964	964	964	964		964		964		964
Direct costs of restoration (1,000 US$ 2020)	(551)	(207)	(431)	(500)	(370)	(370)	(909)	(302)	(215)	(172)	(129)		0		0		0
Opportunity cost of restoration (1,000 US$ 2020)	(318)	(398)	(597)	(796)	(895)	(995)	(1,392)	(1,392)	(1,392)	(1,392)	(1,392)		(1,392)		(1,392)		(1,392)
Additional carbon sequestration (1,000 t CO2e)	6.11	7.64	11.46	15.28	17.19	19.10	26.74	26.74	26.74	26.74	26.74		26.74		26.74		26.74

Incorporation of Benefits and Costs in MFMod Sri Lanka

Mangroves are integrated into MFMod through two channels. First is the reduction in expected damages to coastal assets from coastal flooding. The treatment of asset damages from natural disasters are discussed in Burns et al. (2021). The production function of each MFMod country model is written as:

$$Y_t = A_t N_t^{\alpha} K_{t-1}^{1-\alpha}$$

Where Y is potential GDP, A is total factor productivity (TFP), N is structural employment, K is total capital stock and α is the share of labor in total value-added.

Capital stock accounts for damages as follows:

$$K_t = \left(1 - \frac{DS_t}{\widetilde{K_t}}\right)^{\frac{1}{1-\alpha}} \widetilde{K_t}$$

DS is the stock of destroyed capital and $\widetilde{K}$ is the remaining capital. Mangroves reduce DS and limit the capital stock destruction.

The second channel of integration is through TFP. Mangrove restoration generates benefits for fisheries and sustainable resource extraction. This is productivity enhancing and enters as a positive TFP shock to the model. On the other hand, mangrove restoration creates an opportunity cost, which is a negative TFP shock.

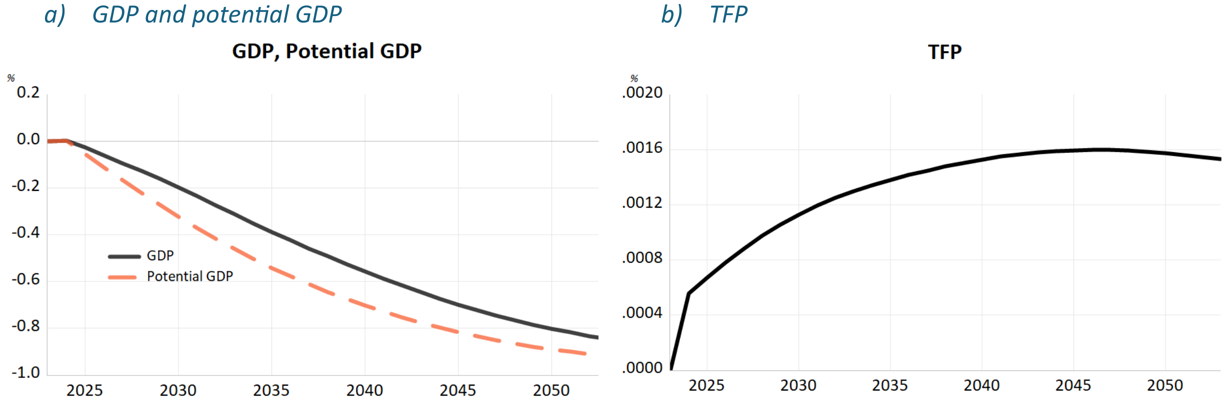
In no restoration scenario, the expected shock to capital stock is the baseline annual expected damages to coastal assets in 2020 plus reduced coastal protection benefits due to mangrove loss. At the same time, there are two TFP shocks hitting the economy. First is the loss of fisheries and resource extraction, a negative TFP shock and the second is the benefits from alternative economic uses after mangrove land conversion, a positive TFP shock.

Results

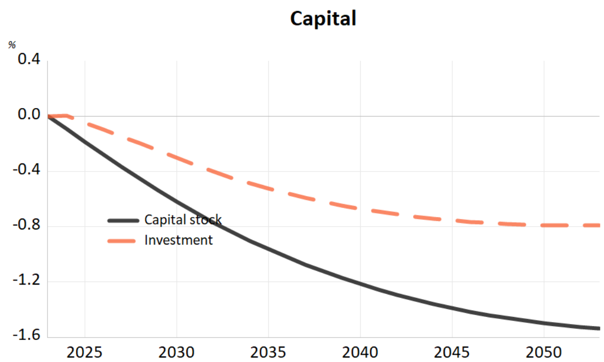
Figure 5 shows that, in the BAU scenario, both potential and actual GDP would decline with capital stock destruction due to rising coastal flooding damage due to mangrove loss. TFP rises with economic benefits after land conversion, but capital damage dominates the macro responses. On the labor market, employment goes up because of the positive output gap and decline in real wages.

Figure 5. BAU scenario simulation results

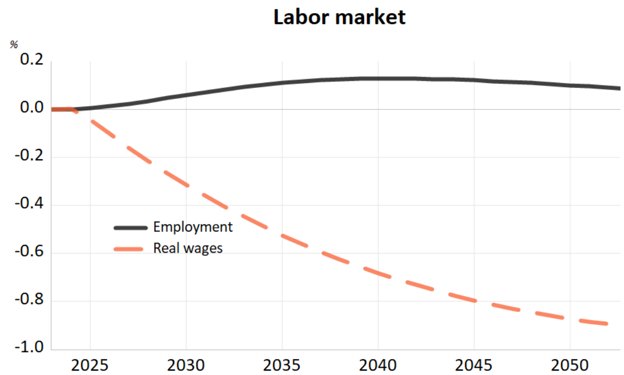
a) GDP and potential GDP *b) TFP*



c) Capital



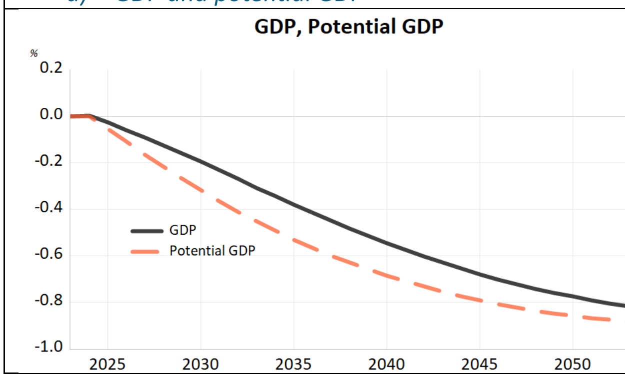
d) Labor market



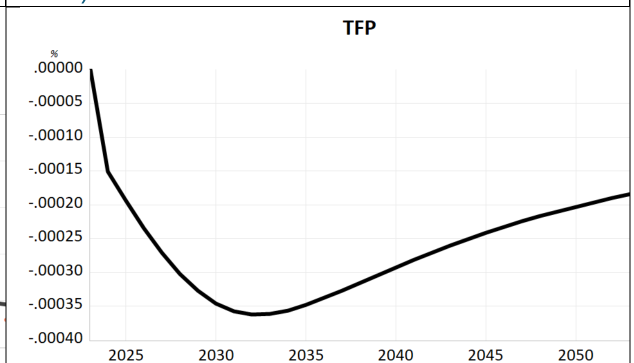
In the restoration scenario, expected coastal flooding damage goes down due to mangrove restoration. The cost is restoration spending, which is modeled as additional public investment. This investment is productive and increases TFP by the amount of increase in fisheries and sustainable resource extraction, but the opportunity cost of restoring mangroves enters as a negative TFP shock to the model. Figure 6 shows restoration outcomes with respect to the baseline. Public investment rises with restoration spending, but this does not enter capital stock; instead, it increases TFP, but the opportunity cost of restoration dominates this effect, and TFP goes down with respect to baseline. Restoration also reduces expected coastal flooding damage and limits capital stock destruction.

Figure 6. Restoration scenario simulation results

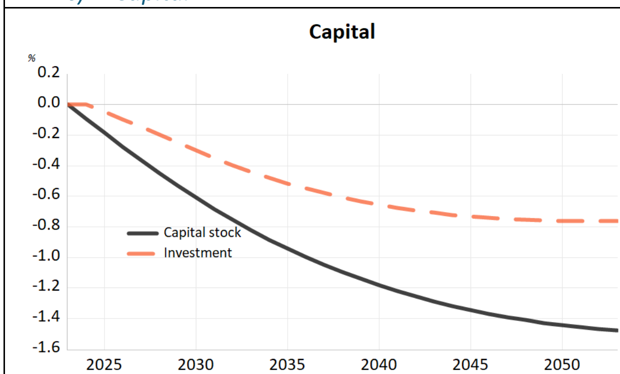
a) GDP and potential GDP



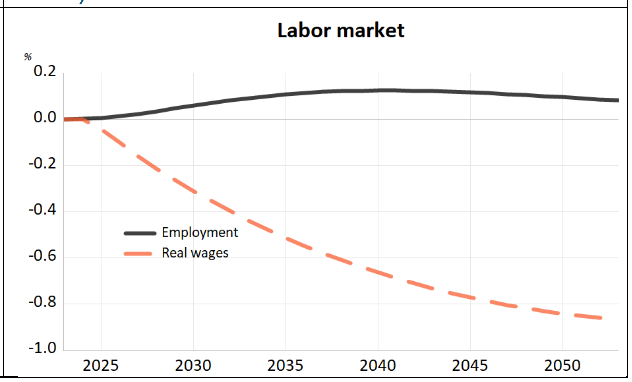
b) TFP



c) Capital



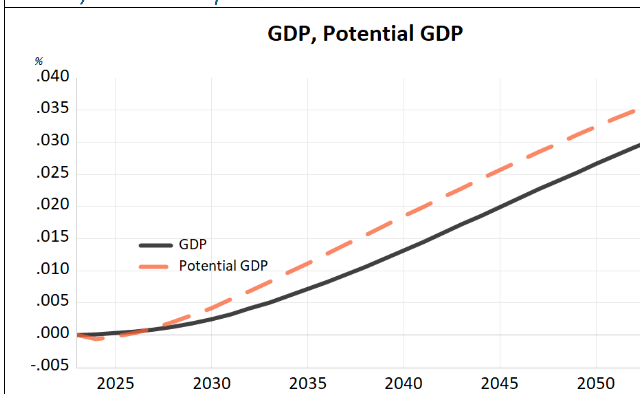
d) Labor market



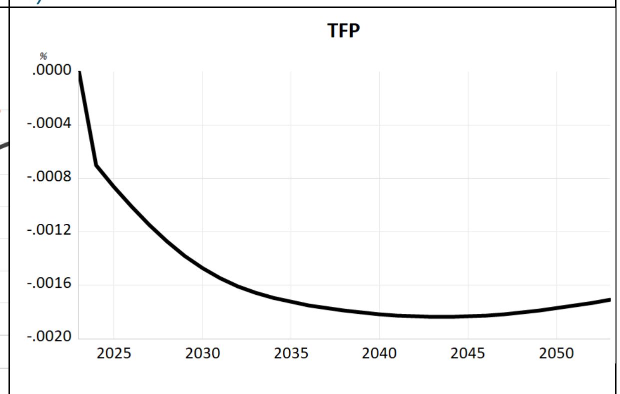
Presenting the restoration scenario results as deviations from the BAU scenario, figure 7 shows that capital stock is higher, because of the avoided asset damages. Higher capital stock increases potential GDP, which then pulls actual GDP upwards. Negative TFP shock reduces potential initially, but is then dominated by the capital stock response. In the labor market, negative output gap and higher real wages slightly reduce employment. Although government restoration projects might increase labor demand in specific sectors, aggregate labor demand declines with higher real wages and insufficient aggregate demand.

Figure 7. Macroeconomic results in the restoration scenario, as deviations from BAU scenario

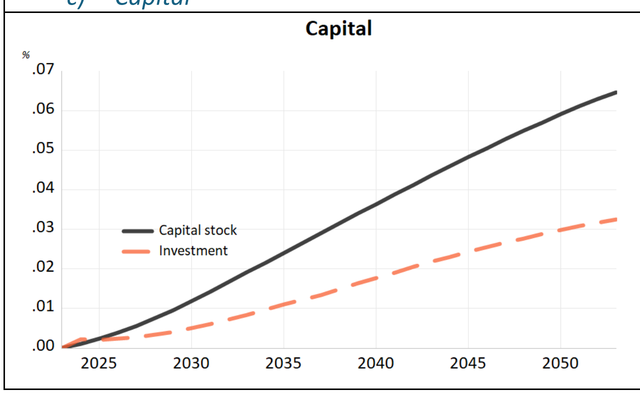
a) GDP and potential GDP



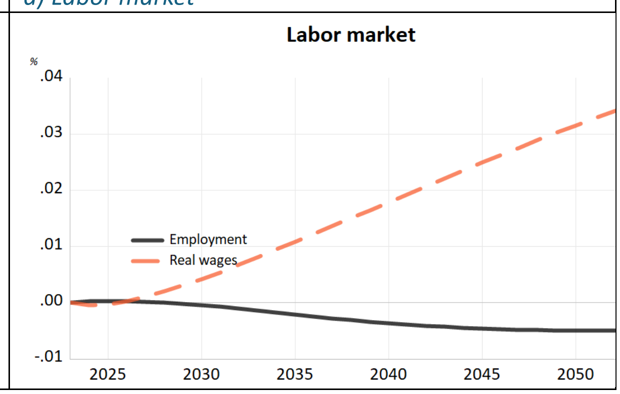
b) TFP



c) Capital



d) Labor market



In the BAU scenario, stored capital emissions due to loss of mangroves are estimated to reach nearly 160,000 tons of CO_2 equivalent per year by 2050. In the restoration scenario, these emissions are avoided, with an additional sequestration of about 27,000 tons of CO_2 equivalent per year. The sum of avoided emissions and new sequestrations amount to a reduction of approximately 0.6 percent of baseline emissions by mid-century, contributing to the mitigation of residual emissions under a net zero scenario (World Bank 2025).

Discussion

[This section is to be enhanced. Suggestions from peer reviewers would be welcomed.]

Mangroves are invaluable to coastal ecosystems, providing a broad array of ecosystem services that are crucial for both human and environmental health. These services include habitat provision for diverse species, coastal protection from erosion and storm surges, and the sequestration of blue carbon. Additionally, mangroves offer numerous provisioning services for nearby communities, such as timber, fuelwood, and non-wood forest products. Given their extensive benefits, it is critical to integrate mangroves into nature-aware macroeconomic models to better assess their contributions to the economy and inform policy decisions.

The pilot study in India offers useful insights into the value of integrating coastal protection services provided by mangroves into macroeconomic models. The significant benefits identified in states like Gujarat and Maharashtra underscore the economic importance of mangrove restoration efforts, especially in areas with dense coastal populations and significant capital stock.

The next steps for mainstreaming these methods involve addressing the remaining gaps in data and methodology for other mangrove ecosystem services, including coastal protection from erosion reduction as opposed to just flood reduction.

References

Bayraktarov, E., Saunders, M. I., Abdullah, S., Mills, M., Beher, J., Possingham, H. P., ... & Lovelock, C. E. 2016. The cost and feasibility of marine coastal restoration. Ecological applications, 26(4), 1055-1074.

Beck, Michael W, Nadine Heck, Siddharth Narayan, Pelayo Menendez, Borja G. Reguero, Stephan Bitterwolf, Saul Torres-Ortega, Glenn-Marie Lange, Kerstin Pfliegner, Valerie Pietsch McNulty, Iñigo J. Losada. 2022.Return on investment for mangrove and reef flood protection. *Ecosystem Services*, 56 (2022) 101440. https://doi.org/10.1016/j.ecoser.2022.101440

Burns, A, Jooste, C, and Schwerhoff, G. (2021). Macroeconomic Modeling of Managing Hurricane Damage in the Caribbean.

FAO. 2020. *Global Forest Resources Assessment 2020*: Main report. Rome. https://doi.org/10.4060/ca9825en

GFDDR. 2024. NBS Opportunity Scan. Coastal Zones Sri Lanka.

Himes-Cornell, A., Grose, S. O., & L. Pendleton. 2018. Mangrove ecosystem service values and methodological approaches to valuation: where do we stand?. *Frontiers in Marine Science*, *5*, 376.

IPCC. 2014. 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T.G., eds. IPCC, Switzerland.

Jakovac, C.C., A.E. Latawiec, E. Lacerda, I. Leite Lucas, K. A. Korys, A. Iribarrem, G. A. Malaguti, R. K. Turner, T. Luisetti, B. B. Neves Strassburg. 2020. Costs and Carbon Benefits of Mangrove Conservation and Restoration: A Global Analysis. *Ecological Economics*. Volume 176, October 2020, 106758 https://doi.org/10.1016/j.ecolecon.2020.106758

Johnson, J.A., U. Baldos, T. Hertel, J. Liu, C. Nootenboom, S. Polasky, and T. Roxburgh. 2020. Global Futures: modelling the global economic impacts of environmental change to support policy-making. Technical Report, January 2020. https://www.wwf.org.uk/globalfutures

Leal, M and Spalding M D (editors), 2024 The State of the World's Mangroves 2024.Global Mangrove Alliance. DOI: https://doi.org/10.5479/10088/119867

Menéndez, P., I. J. Losada, S. Torres-Ortega, S. Narayan, & M. W. Beck. 2020. The global flood protection benefits of mangroves. *Scientific reports*, *10*(1), 1-11

Murray BC, L. Pendleton, W.A. Jenkins, S. Sifleet. 2011. *Green payments for blue carbon: Economic incentives for protecting threatened coastal habitats.* Report NI R 11-04, Nicholas Institute for Environmental Policy Solutions, Duke University, Durham.

Narayan S., MW Beck, B.G. Reguero, I.J. Losada, B. van Wesenbeeck, N. Pontee, et al. (2016) The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defenses. PLoS ONE 11(5): e0154735. https://doi.org/10.1371/journal.pone.0154735

Pendleton L., D.C. Donato, B.C. Murray, Crooks S, Jenkins WA, et al. (2012) Estimating Global "Blue Carbon" Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems. PLOS ONE 7(9): e43542. https://doi.org/10.1371/journal.pone.0043542

Perera, K.A.R.S., W. de Silva, M.D. Amarasinghe. 2024. "Carbon Stocks in mangrove ecosystems of Sri Lanka: contributions and determinants of sequestration potential." *Ocean and Coastal Management* 257 (2024) 107357.

Rutebuka, E. and E. Frimpong Asamoah. 2025. *Methodological report focusing on Land use and land cover change and restoration scenario development of Sri Lanka.* Unpublished technical background document. World Bank South Asia Environment Department

Sanderman, J., Hengl, T., Fiske, G., Solvik, K., Adame, M.F., Benson, L., ... Landis, E. 2018. "A Global Map of Mangrove Forest Soil Carbon at 30 m Spatial Resolution." *Environmental Research Letters* 055002.

Simard, M., Fatoyinbo, L., Smetanka, C., RiveraMonroy, V. H., Castañeda- Moya, E., Thomas, N., and Van der Stocken, T. 2019. "Mangrove Canopy Height Globally Related to Precipitation, Temperature and Cyclone Frequency." *Nature Geoscience* 12 (1): 40–45.

Song, S., Ding, Y., Li, W. et al. Mangrove reforestation provides greater blue carbon benefit than afforestation for mitigating global climate change. *Nat Commun* 14, 756 (2023). https://doi.org/10.1038/s41467-023-36477-1

Sri Lanka 30 x 30. 2024. "Restore degraded forest and mangrove habitats. Program information brochure." *Conservation and Prosperity for Nature and People*. https://srilanka30x30.com/restoration/

Taillardat P., DA Friess, M. Lupascu. 2018 Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale. *Biol. Lett*. 14: 20180251. https://doi.org/10.1098/rsbl.2018.0251

van Zanten, B.T., Gutierrez Goizueta, Gonzalo; Brander, Luke Mckinnon; Gonzalez Reguero, Borja; Griffin, Robert; Macleod, Kavita Kapur; Alves Beloqui, Alida Ivana; Midgley, Amelia; L.D. Herrera Garcia, B. Jongman. 2023. *Assessing the Benefits and Costs of Nature-Based Solutions for Climate Resilience: A Guideline for Project Developers.* © World Bank. http://hdl.handle.net/10986/39811

World Bank. 2024a. *The Changing Wealth of Nations 2024. Revisiting the Measurement of Comprehensive Wealth*. World Bank Publications. Washington, DC. https://documents1.worldbank.org/curated/en/099100824155021548/pdf/P17844617dfe6e0241ad25120b1320904c2.pdf

World Bank. 2024b. *The Changing Wealth of Nations 2024. Building Resilience with Mangroves: The Contribution of Natural Flood Defenses to the Changing Wealth of Nations*. Technical Report. https://documents1.worldbank.org/curated/en/099101124150015562/pdf/P17844613fd9760e31a55510ba9e7e43371.pdf

World Bank. 2024c. *The Nature-Based Solutions Opportunity Scan: Leveraging Earth Observation Data to Identify Investment Opportunities in NBS for Climate Resilience in Cities and Coasts across the World.* © World Bank, Washington, DC.

World Bank. 2024d. The Changing Wealth of Nations - Estimating Global Carbon Storage of Mangrove Ecosystems: Technical Report (English). Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/099101024134013399

World Bank Group. 2025. Sri Lanka Country Climate and Development Report. Draft.

zu Ermgassen P.S.E., N. Mukherjee, T.A. Worthington, A. Acosta, A.R. da Rocha Araujo, C.M. Beitl, G.A. Castellanos-Galindo, M. Cunha-Lignon, F. Dahdouh-Guebas, K. Diele, et al. Fishers who rely on mangroves: Modelling and mapping the global intensity of mangrove-associated fisheries. *Estuar. Coast. Shelf Sci.,* 247 (2020), p. 106975. https://doi.org/10.1016/j.ecss.2020.106975