



Full Length Article

Investing in forests Enhances ecosystem services and economic Growth in Cambodia: Evidence from the Integrated Economic-Environmental Modelling (IEEM) approach

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ARTICLE INFO

Keywords:

Integrated Economic-Environmental Model (IEEM)
Forest and Other Land Use (FOLU) sectors
Land use land cover change
Deforestation
Ecosystem services modeling
Carbon neutrality
Nationally Determined Contributions
Cambodia

ABSTRACT

Cambodia has one of the highest rates of deforestation in the world, which exacerbates local and global impacts of climate change while compromising the supply of critical ecosystem services that provide benefits to society. Cambodia's Long-Term Strategy for Carbon Neutrality and its Nationally Determined Contributions aim to mitigate climate change and enhance ecosystem service supply contributing to reducing erosion and flood hazards that jeopardize human lives and infrastructure. In this paper, we investigate the economic, social and ecosystem service impacts of these two policy packages by applying the Integrated Economic-Environmental Model (IEEM) for Cambodia linked with spatial Land Use Land Cover change and Ecosystem Services modeling. Focusing on Forest and Other Land Use policies within the Long-Term Strategy and Nationally Determined Contributions, our results show that these policies would reduce cumulative carbon dioxide emissions by 1.6 billion tons by 2050. Cumulative Gross Domestic Product and wealth impacts would be US\$3.576 billion and US\$118 billion, respectively. Implementation of the policies would enhance regulating and provisioning ecosystem service flows overall by US\$6.6 billion. The return on investment would be US\$31 billion, though not valuing changes in natural capital and environmental quality would realize only about 12% of this return (US\$3.7 billion). Our study demonstrates that working towards carbon neutrality is not only compatible with socioeconomic development but would effectively catalyze it. Further, we demonstrate that the most efficient and cost-effective strategy to meet Cambodia's emissions targets would be to eliminate deforestation more rapidly than outlined in the Long-Term Strategy, complemented by proactive measures for afforestation and forest restoration. The evidence presented in this study may be used to build the business case for government and private sector investment in achieving Cambodia's carbon neutrality goal by engaging Forest and Other Land Use sectors.

1. Introduction

Cambodia aspires to achieve upper-middle-income and high-income status by 2030 and 2050, respectively. In 2022, Cambodia's economy grew by 5.2 % and is forecast to grow by 6 % on average until 2026. Catalyzing economic momentum to reach income targets will require a focus on increasing labor and factor productivity and a shift toward

higher productivity industries and services (World Bank, 2024). Cambodia's strategies for achieving income targets are presented in its Rectangular Strategy for Growth, Employment, Equity and Efficiency (Royal Government of Cambodia, 2018) and the National Strategic Development Plan (Royal Government of Cambodia, 2019). The main elements of these strategies are transformative growth toward value-added and technological innovation, addressing the infrastructure gap

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<https://doi.org/10.1016/j.ecoser.2024.101695>

Received 13 March 2024; Received in revised form 19 December 2024; Accepted 29 December 2024

Available online 12 January 2025

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(water, sanitation, transport and energy), investing in human capital, economic diversification and the sustainable management of Cambodia's natural capital assets.

Climate change is creating a more challenging context for Cambodia to reach its income and development targets due to projected impacts on economic growth, trade, debt and poverty. In the absence of climate change action, Cambodia's Gross Domestic Product (GDP) could be between 3 % and 9 % lower by 2050 while poverty could increase by up to 6 % by 2040. Flooding is Cambodia's most prevalent natural disaster with the country ranked as the world's fourth most exposed. The populations residing along the Mekong and Tonle Sap floodplains are especially vulnerable and represent 80 % of Cambodia's population. Flooding can result in the loss of life, crops, productivity and agricultural land. Rainfall variability is also an emerging challenge with the annual probability of severe drought around 4 % in a given year (World Bank, 2023).

Deforestation is harshening the effects of climate change with Cambodia exhibiting one of the highest rates of deforestation in the world, losing 30 % (2.64 million hectares (ha)) of forest cover over the past two decades (Global Forest Watch, 2022). Although the annual rate of deforestation has declined slightly from 2 % in 2017 to 1.9 % in 2020, Cambodia's deforestation rate remains the highest among neighboring countries (Sachs et al., 2022). The primary drivers of deforestation are agrarian expansion (Davis et al., 2015; Johansson et al., 2020; Kong et al., 2019) and illegal logging (Ken et al., 2020a; Sasaki, 1998). Secondary drivers include exploitation of forests for fuelwood and charcoal, forest fires during the dry season aggravated by land clearing and climate change (Ken et al., 2020b; Sim et al., 2023), small-scale mining and the construction of hydropower dams and roads (Pacheco et al., 2021). In 2019, emissions from deforestation and Land Use Land Cover (LULC) change accounted for 44 % of Cambodia's total emissions (WRI, 2023).

While Cambodia has low absolute and per-capita greenhouse gas (GHG) emissions, its economy is among the most carbon-intensive in Southeast Asia (World Bank, 2023). Addressing climate change and building climate resilience presents an opportunity to achieve Cambodia's development vision while being compatible with the transition to low-carbon emissions and the mitigation of climate risks. Cambodia has made ambitious pledges in its Nationally Determined Contributions (NDCs) and Long-term Strategy for Carbon Neutrality (LTS4CN), which will require careful policy choices to leverage the development co-benefits of climate mitigation and adaptation measures.

Cambodia's NDCs aim to reduce GHG emissions by 64.6 million tons of carbon dioxide (mtCO₂) per year by 2030, from 155 mtCO₂ in a projected baseline to 90.5 mtCO₂. The LTS4CN was submitted to the Secretariat of the United Nations Framework Convention on Climate Change in December 2021 and targets carbon neutrality by 2050. The Forest and Other Land Use (FOLU) sector plays a pivotal role in the NDC and LTS4CN strategies, relying on it to act as a carbon sink for 50 MtCO₂ by 2050. Cambodia aims to achieve this through the implementation of the Reduced Emissions from Deforestation and Forest Degradation (REDD +) program in addition to forest sector reform. Specifically, the LTS4CN target is to eliminate deforestation, plant 1.6 million ha of forests and restore 1.1 million ha of vegetated areas to a natural forest state. Addressing the drivers of deforestation and planting and restoring forests will enable forests to make critical contributions to achieving carbon neutrality as well as to generate many important co-benefits that will contribute to climate change adaptation.

Forests in Cambodia provide valuable Ecosystem Services (ES) beyond climate regulation and include erosion mitigation, water and flood regulation and water purification. The quantification and valuation of these ES enables their use in informing public policy and decision making (Banerjee et al., 2020a; Mandle et al., 2021) and can broaden support for FOLU-driven strategies for climate change mitigation and adaptation. Moreover, rural communities directly depend on forests for food, medicine, clean water, building materials and goods for small

businesses (Chaplin-Kramer et al., 2019; Millennium Ecosystem Assessment, 2005; Persson et al., 2010; TEEB, 2010).

A number of ES assessment and valuation exercises have been conducted in Cambodia, many of which focus on a specific region of the country. For example, the valuation of the Veun Sai-Siem Pang National Park estimated the Park generated US\$129.84 million per year in value with air quality regulation ES as the primary contributor to value (Kibria et al., 2017). Various ES assessments were commissioned by the World Wide Fund for Nature (Watkins et al., 2016), for example, Hoy et al. (2015a,b) estimated water regulation services for Monduliri Province using the Natural Capital Project's Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) ES models (Natural Capital Project, 2023), though the authors did not estimate an economic value for these services. Trisurat et al. (2017) investigated how changes in water yield could affect rice production under different climate scenarios. Rawlins et al. (2020) estimated the economic value of the services provided by forests in Cambodia's Pursat basin. The authors estimated a net present value of US\$99 million per year (6 % opportunity cost of capital), equivalent to about five times more value than what conversion of forest to agriculture and charcoal extraction would yield. The analysis focused on the water provisioning and regulation ES (irrigation and energy), cultural and recreational ES and climate regulation (carbon storage) ES (Rawlins et al., 2020).

The objective of this paper is to evaluate the economic, social and ES impacts of the FOLU strategies in Cambodia's LTS4CN and NDCs. To do so, we apply the Integrated Economic-Environmental Modeling (IEEM) framework (Banerjee et al., 2016, 2019; Banerjee et al., 2020b). Given the importance of ES co-benefits that FOLU policies can generate, IEEM is linked to spatial LULC change and ES modeling (IEEM + ESM; Banerjee et al., 2022, 2023, 2024a) to quantify the market and non-market ES benefits of these strategies. The evidence generated in this paper can support policy makers in the operationalization of the LTS4CN and NDCs by developing a robust business case for domestic public, private and international financing of FOLU strategies and their ES co-benefits that extend beyond climate regulation.

2. Methods

2.1. Methods overview

IEEM is an economy-wide decision support tool for evidence-based public policy and investment design and analysis (see Supplementary Information (SI) Section 1 for a detailed overview of IEEM methods). IEEM has been applied by multilateral and government institutions including Ministries of Finance and Central Banks in future-looking analysis of hundreds of questions of public policy and investment in over 30 countries (Fig. 1). IEEM is a multi-purpose model that can be used to analyze policies across economic sectors and themes, including the environment, climate change, economic growth, labor markets, human development, poverty and inequality, fiscal policy and external shocks.

The IEEM + ESM modeling workflow is comprised of three models that interact through the transfer of data and results from one model to another Fig. 2. The first model is IEEM, a dynamic Computable General Equilibrium model at its core. An environmentally extended Social Accounting Matrix (Breisinger et al., 2009) underpins IEEM; this Social Accounting Matrix is a statistical representation of all sectors and transactions in an economy as well as land use dynamics for a specific base year. It is constructed based on a country's System of National Accounts, the internationally accepted framework for measuring economic activity and development (European Commission et al., 2009; an overview of Cambodia's economy from the perspective of the Social Accounting Matrix is provided in SI Section 2).

IEEM is dynamic, in other words, future looking, and is used to generate a business-as-usual or BASE projection of the economy in the absence of any new public policies and investments. Policy scenarios are

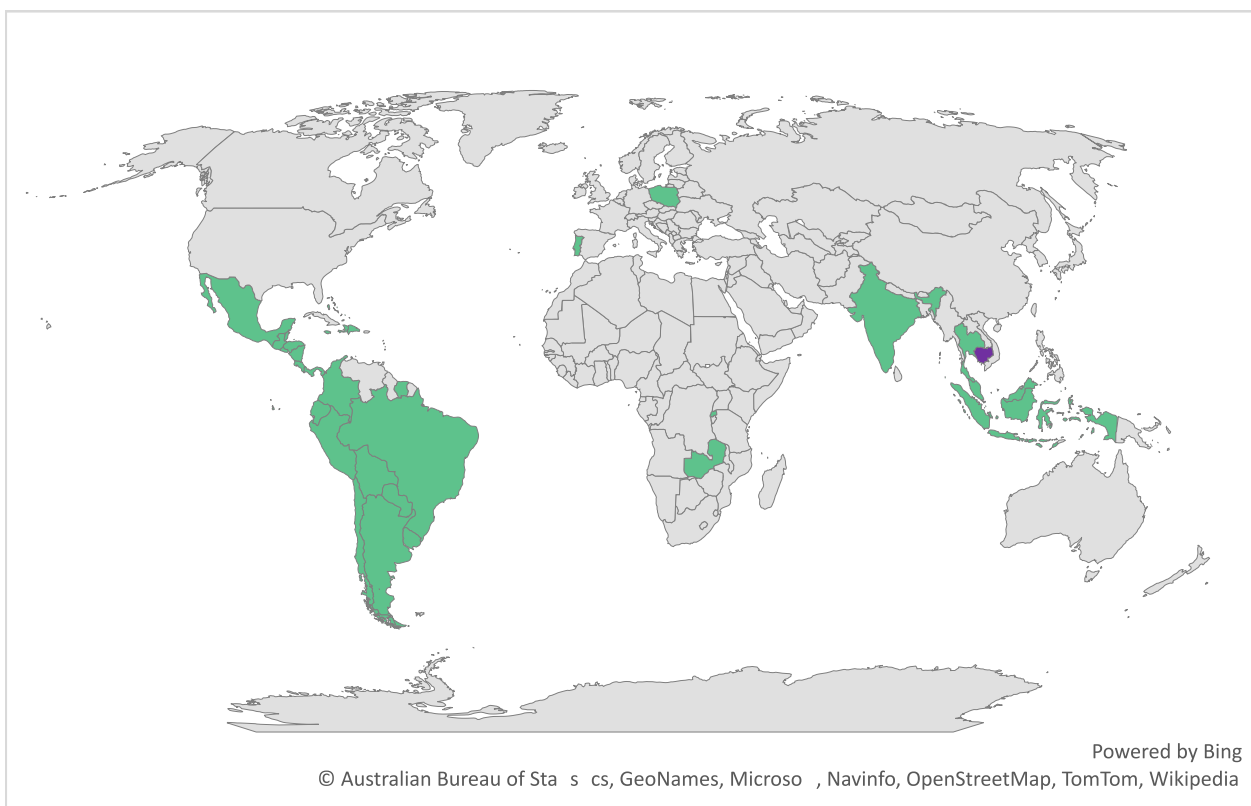


Fig. 1. IEEM + ESM countries indicated in green with Cambodia highlighted in purple. .
 Source: Authors' own elaboration based on above cited data



Fig. 2. Overview of the dynamic IEEM + ESM workflow applied to Cambodia. .
 Source: Authors' own elaboration

then implemented in IEEM which in the case of this study, represent key aspects of Cambodia's LTS4CN and NDC strategies.

To estimate policy impacts on future ES flows, LULC change modeling is a necessary bridge between the aspatial IEEM model¹ and spatial ES modeling. In the IEEM + ESM workflow, we use the IEEM-enhanced Dyna-CLUE LULC change model (Verburg et al., 2021). This LULC change model is calibrated with various biophysical (climate, topography, soils) and socioeconomic (distance to markets, transportation infrastructure, population density) geospatial layers to estimate the probability of a specific land use or land cover class occurring at each grid cell in a base map of the country (see SI Section 3 for a description of the LULC change modeling metadata). The LULC change model is linked to IEEM through IEEM-generated projections of demand for land and is used to spatially attribute this demand across the country.

Four InVEST ES models (Natural Capital Project, 2023) are used in

¹ While IEEM may be disaggregated to various levels, from national to state to municipal, IEEM does not operate at the grid cell level which is required for implementation of spatial ES modeling. For this reason, the LULC change model serves as the bridge between IEEM and the ES modeling by spatially allocating IEEM-projected demand for land which then serves as a direct input into the ES modeling.

this study, namely the carbon storage, erosion mitigation, water yield and water purification ES models (see SI Section 4 for ES modeling parameters and metadata). Climate regulation through carbon storage is a key ES in the context of the LTS4CN and NDCs. Erosion mitigation, water yield and water purification ES are critical co-benefits of the FOLU strategies with special importance to rural communities that rely heavily on the natural capital base for their well-being. The LULC maps produced by the LULC change model are the main variable of change used in the ES models. Each ES model is run to calculate changes in future ES flows for each policy scenario with respect to the business-as-usual BASE scenario.

In terms of the economic value of changes in ES flows, the implementation of IEEM without spatial modeling produces results in terms of impacts on the value of specific provisioning ES, namely plant-based food, meat and fish, timber and non-timber products, wood and pulp and paper. All of these provisioning ES are of importance to both rural and urban communities in enhancing food security and providing materials for construction. The spatial modeling of regulating ES, specifically, climate regulation through carbon storage, erosion mitigation, water yield and water purification ES, generates results in biophysical units at the level of grid cell.

Estimating the economic value of these regulating ES in a way that is

consistent with a country’s System of National Accounts is a frontier area in integrated economic-environmental modeling. In this application, we focus on erosion mitigation ES and its interaction with the economic system via agricultural productivity. Changes in erosion mitigation ES affect agricultural productivity (Panagos et al., 2018; Pimentel, 2006; Pimentel et al., 1995) which in turn have impacts on producer decisions, prices and supply and demand dynamics. Thus, this application of IEEM + ESM sheds light on how the LTS4CN and NDC policy portfolio affects not only standard economic indicators such as GDP and employment, but also the value of future market and non-market ES flows.

The OPEN IEEM Platform currently hosted by the Inter-American Development Bank (<https://openieem.iadb.org/>) provides many IEEM + ESM resources. On the Platform, IEEM model code (applicable to any country with the underpinning data) and ES datapackets (IDB, 2021) which render the carbon storage, water yield, water purification and erosion mitigation InVEST ES models essentially ‘plug-and-play’, are freely downloadable for most countries in Latin America and the Caribbean. In addition, an IEEM training course, User Guides for both IEEM and the IEEM-enhanced Dyna-CLUE model and numerous IEEM publications may be accessed. A parallel Platform (www.rmgeo.org) is under construction and will host IEEM resources for other regions and countries of the world including Cambodia. In terms of the ES models used, the Natural Capital Project maintains a comprehensive User Guide for all InVEST ES models (Natural Capital Project, 2023).

2.2. Policy Scenarios: Cambodia’s Long-Term Strategy for carbon neutrality and Nationally Determined Contributions

What follows is a description of the scenarios implemented in IEEM + ESM. These scenarios were designed to reflect the key FOLU strategies embodied in Cambodia’s LTS4CN and NDCs. As outlined in the LTS4CN, Cambodia will strive to achieve its NDC targets through the continued implementation of existing commitments in FOLU sectors, specifically, the REDD + Strategy and Investment Plan (REDD+ Task Force Secretariat., 2020). As detailed in these commitments, emissions reductions and carbon storage will be pursued through the elimination of deforestation and the afforestation and restoration of degraded forests.

BASE: This is the business-as-usual scenario that is used as the counterfactual reference scenario to which all other scenarios are compared. It presents the future trajectory of the Cambodian economy, projected until 2050, in the absence of any new large public policies and investments. The BASE projection of economic growth was sourced from the International Monetary Fund’s World Economic Outlook (IMF, 2022) while population projections were derived from the United Nations’ World Population Prospects (UN, 2018, 2022).

NODEFOR: This scenario simulates the reduction and eventual elimination of deforestation. Following the LTS4CN and REDD + Strategy, this scenario simulates the reduction in the rate of deforestation linearly beginning in 2023 by 50 % by 2030 and eliminating deforestation by 2045. The cost of reducing and eliminating deforestation was distributed across the implementation period proportionally under the assumption that enforcing policies to eliminate deforestation require ongoing expenditure. The annual cost of reducing and eventually eliminating deforestation is US\$1,017,857 (REDD+ Task Force Secretariat., 2020).²

AFFOR: This scenario simulates the afforestation of 1.6 million ha (Kingdom of Cambodia, 2021) with mixed species on already cleared and degraded lands that are currently not generating economic value. Afforestation will commence in 2023 with planting of 15 % of the total

area followed by 25 %, 35 % and 25 % in 2024, 2025 and 2026, respectively. The trees planted are assumed to reach maturity at 20 years of age after which no additional carbon would be stored. Twenty percent of the new forest plantations will be sustainably managed to produce timber and non-timber forest products and thus will generate economic value beginning 5 years after establishment. The cost of afforestation was estimated at US\$58.40/ha for a total of US\$93,440,000 (REDD+ Task Force Secretariat., 2020). This scenario also includes measures for eliminating deforestation as in NODEFOR.

RESTORE: This scenario simulates restoration of 1.1 million ha of degraded forests (Kingdom of Cambodia, 2021); the scenario accounts for the expectation that the carbon storage in restored forests will be enhanced. Restoration efforts will commence in 2023 with restoration of 15 % of the total area followed by 25 %, 35 % and 25 % in 2024, 2025 and 2026, respectively. Any trees planted are assumed to reach maturity at 20 years of age after which no additional carbon would be stored. Ten percent of the restored areas will be sustainably managed to produce timber and non-timber forest products and thus will generate economic value beginning 5 years after establishment. The cost of restoration was estimated as 50 % of the cost of afforestation equivalent to US\$29.20/ha for a total of US\$32,120,000 (REDD+ Task Force Secretariat., 2020). This scenario also includes measures for eliminating deforestation as in NODEFOR.

COMBI: This scenario is the simultaneous implementation of AFFOR and RESTORE.

***COMBI:** This scenario is the same as the COMBI scenario above but does not include ES impacts.

COMBI+: This scenario includes AFFOR and RESTORE as well as a more ambitious commitment to eliminating deforestation whereby the deforestation rate is reduced by 65 % by 2030, and deforestation is all together eliminated by 2035.

***COMBI+:** This scenario is the same as the COMBI + scenario above but does not include ES impacts.

3. IEEM results

3.1. Land Use land Cover change results

Fig. 3 presents the distribution of land in 2050, the final year of this analysis. With the eventual elimination of deforestation, natural forest cover and commercial forest plantations would increase in all scenarios, relative to the BASE. Twenty percent of afforested areas (AFFOR) and 10 % of restored forests (RESTORE) would be used for commercial sustainable forest management. Because of the elimination of deforestation (NODEFOR), there would be a small contraction in agricultural land supply, equivalent to 15 % of the area of avoided deforestation.

Fig. 4 shows LULC in the BASE (left) and the COMBI+ (right)

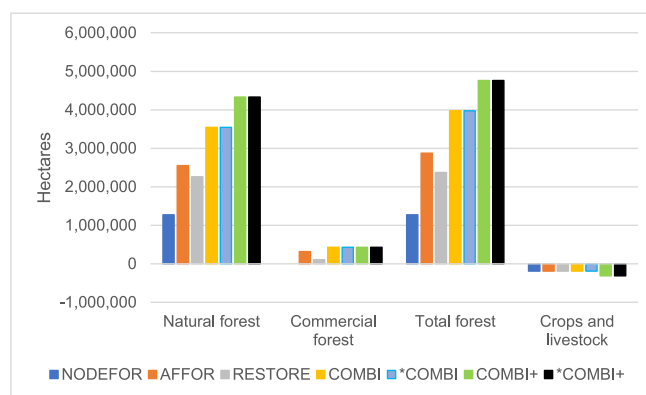


Fig. 3. Land Use Land Cover as a difference from BASE in 2050. . Source: IEEM+ESM results. Scenario names preceded by an “*” indicate that regulating ES were not included

² For all scenarios, investment costs were derived from the REDD+ Strategy and Investment Plan (REDD+ Task Force Secretariat, 2020) and were assumed to be financed by non-reimbursable grants (50%) and through international development loans (50%) with standard repayment terms.

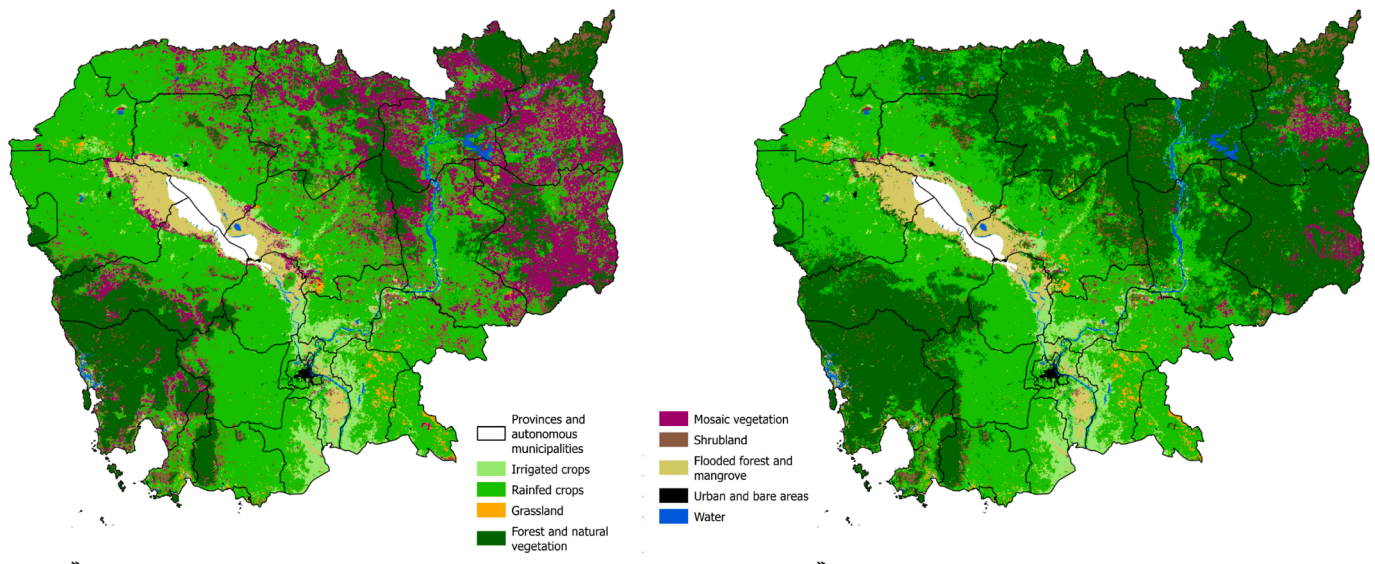


Fig. 4. BASE (left) and COMBI+ (right) Land Use Land Cover in 2050. .
Source: IEEM+ESM results

scenario in 2050. The effect of eliminating deforestation and the afforestation and restoration activities is pronounced and visible in the maps, particularly in the northeast of Cambodia. COMBI+, when compared with the BASE, shows important environmental improvements. Deforestation would be slowed and eventually eliminated while the area of Forest and Natural Vegetation would increase as Mosaic Vegetation would be converted to Forest through afforestation and forest restoration activities.

3.2. Ecosystem service results

What follows focuses on the COMBI + scenario, presenting results as a difference between COMBI + and the BASE in the year 2050. Fig. 5 (top) shows impacts on carbon storage ES where the greatest increases would be found in the provinces of Otdar Mean Chey, Preah Vihéar and Krachéh (71 %, 67 % and 66 %, respectively). The southeastern provinces would register lower levels of carbon accumulation while the western provinces would be closer to the average, in general, ranging from increases between 4 % and 23 % above the BASE in 2050. Erosion mitigation ES (Fig. 5, bottom) would improve across most of Cambodia's provinces with the greatest impacts in Mondól Kiri, Kaoh Kong and Krong Preah Sihanouk, increasing by 71 %, 49 % and 48 %, respectively as a difference from the BASE in 2050. Smaller impacts would be found in the southeastern provinces.

Water regulation ES (Fig. 6, top) would improve across Cambodia with the greatest positive impacts found in Preah Vihéar, Mondól Kiri and Stoeng Treng, by 54 %, 47 % and 34 %, respectively, as a difference from the BASE in 2050. Smaller impacts would be found in the southeast and provinces of Krong Pailin and Bantéay Méanchey. Water purification ES (Fig. 6, bottom) would improve markedly in Preah Vihéar and MondólKiri, by 49 % and 48 %, respectively, as a difference from the BASE in 2050. Smaller impacts would be found in the southeastern provinces and Krong Pailin and Banteay Meanchey.

The contribution of policy-driven changes in ES to the economy is shown in Table 1. Across scenarios, there would be a reduction in food provisioning services. Output of both unprocessed and processed forest products would increase due to measures for afforestation and forest restoration. In the case of COMBI+, there would be a US\$6.3 billion increase in unprocessed timber and non-timber forest products as the cumulative difference from BASE in 2050. Regulating ES, specifically, erosion mitigation ES would increase by US\$1.9 billion (cumulative impact by 2050). The net effect of most scenarios would be positive with

COMBI yielding the greatest net cumulative ES benefit of US\$6.7 billion by 2050 which is equivalent to 25 % of GDP in the base year (2018).

The trajectory of net CO₂ emissions is shown in Fig. 7 (left) while Fig. 7 (right) presents cumulative net CO₂ emissions as a difference from BASE in 2050. These figures include emissions from both fossil fuel consumption and LULC change. By 2050, the portfolio of policies for afforestation, restoration and the elimination of deforestation would reduce cumulative net emissions by 1.6 billion tons of CO₂ (COMBI). The more ambitious COMBI + would reduce emissions by 1.7 billion tons of CO₂. The elimination of deforestation on its own (NODEFOR) would reduce emissions by 703 million tons of CO₂ while the individual contributions of AFFOR and RESTORE would be 545 million and 374 million tons of removals of CO₂, respectively.

3.3. Economic results

Table 2 presents scenario impacts on key macroeconomic indicators. The elimination of deforestation would have a small negative impact on cumulative GDP as it would reduce agricultural land supply. Considering wealth, the more appropriate indicator of sustainable economic development, the cumulative impact of eliminating deforestation would be positive on the order of US\$74.453 billion by 2050 as a difference from BASE. Where elimination of deforestation is coupled with afforestation and restoration, both the GDP and wealth impacts would be positive. With a hastened pace in eliminating deforestation, coupled with afforestation and forest restoration, cumulative GDP and wealth would be bolstered by US\$3.576 billion and US\$118.844 billion, respectively. This GDP and wealth impact equates to 13 % and 441 % of GDP in the base year (2018) on a cumulative basis (impacts on macroeconomic indicators expressed as a percent difference from the BASE are reported in SI Section 5).

Fig. 8 (Panel A) presents the GDP trajectory of each scenario while Fig. 8 (Panel B) presents the wealth trajectory, both as a difference from BASE. NODEFOR and RESTORE would exhibit a slightly declining trend while the remaining scenarios would exhibit an increasing trend in GDP impacts. The wealth trajectory would present an upward trend with some convergence among scenarios around the year 2045 when deforestation would be eliminated.

Employment impacts are shown in Fig. 8 (Panel C) where the elimination of deforestation on its own would have a negative impact on employment (3,630 less jobs by 2050); the portfolio of policies represented by the COMBI scenario would result in an increase of 1,900 new

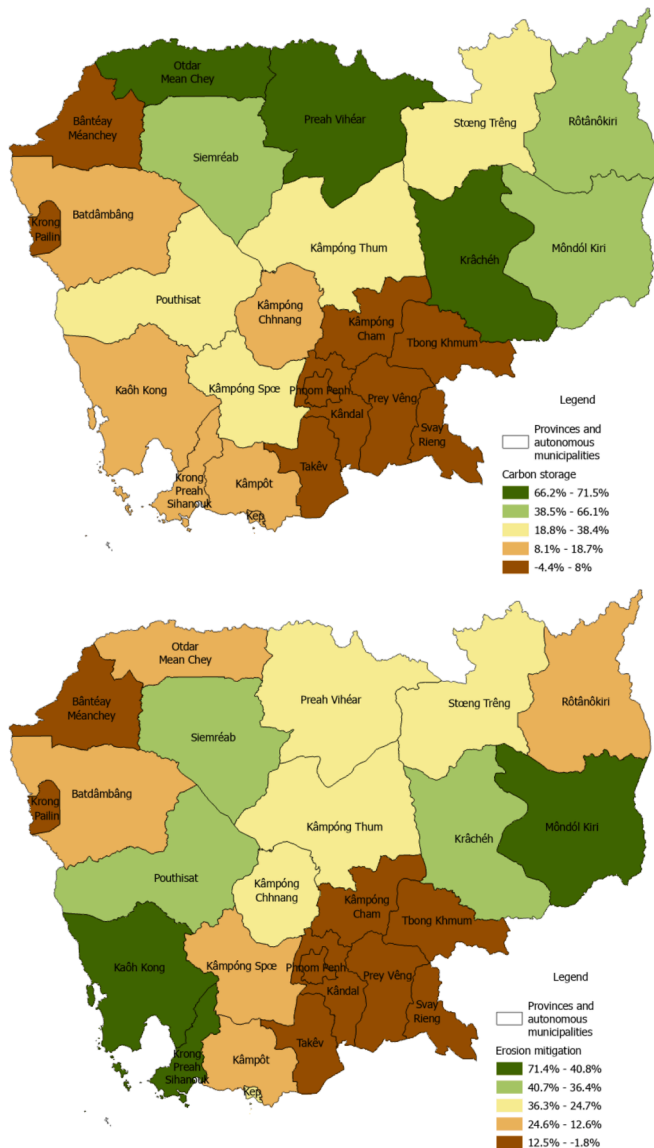


Fig. 5. COMBI + carbon storage climate mitigation (top) and erosion mitigation (bottom) ecosystem services in 2050 as a difference from BASE in percent. . Source: IEEM+ESM results

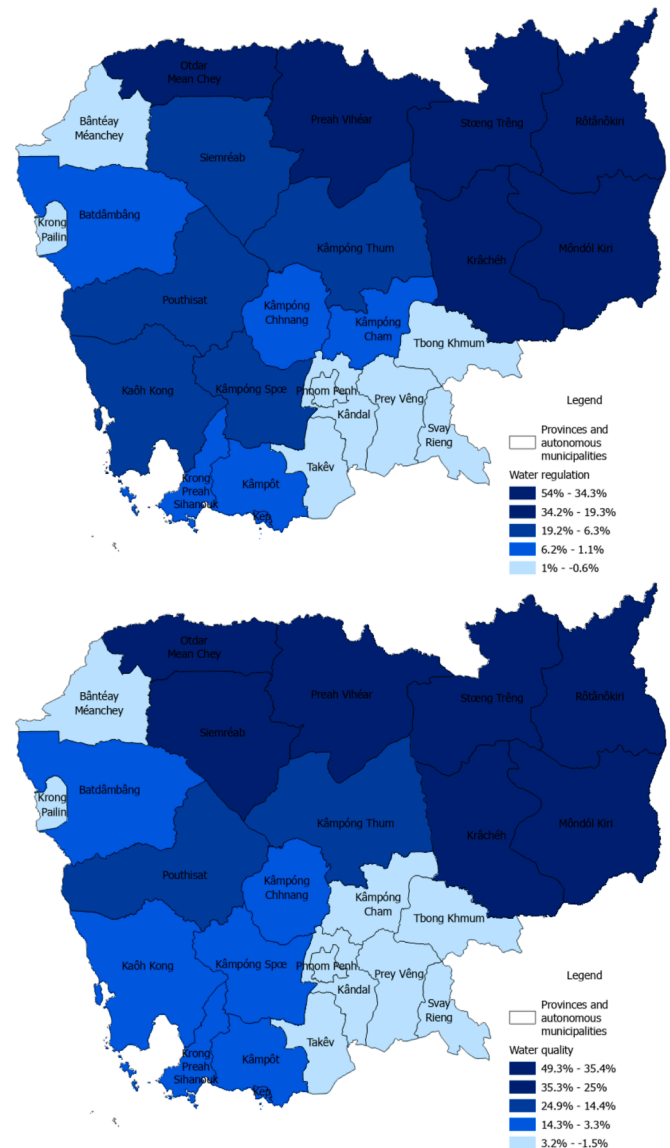


Fig. 6. COMBI + water regulation (top) and water purification (bottom) ecosystem services in 2050 as a difference from BASE in percent. . Source: IEEM+ESM results

jobs. Fig. 8 (Panel D) presents the Net Present Value of the investments with two discount rates (5 % and 10 %) and with and without the inclusion of changes in natural capital stocks and environmental quality. The more ambitious COMBI + would generate the greatest return on investment, equivalent to US\$30.7 billion while COMBI would come in at a close second at US\$29.3 billion, both considering a discount rate of 10 %. Using the lower discount rate of 5 % would almost double the return on investment.

4. Discussion and Conclusions

During the past two decades, Cambodia has experienced one of the most rapid rates of deforestation in the world. Deforestation is a major source of emissions, with tropical deforestation in particular responsible for approximately 25 % of total anthropogenic emissions (Kindermann et al., 2008). Deforestation exacerbates the impacts of climate change on ES that are critical for societal well-being (Millennium Ecosystem Assessment, 2003; Sangha et al., 2022). Cambodia’s LTS4CN and NDCs aim to mitigate and adapt to climate change, reduce damages due to erosion and floods and increase carbon storage by protecting, planting

and restoring forests, which would also contribute to preserving biodiversity and critical ES. This study applied the IEEM + ESM approach to investigate the economic, social and ES impacts of Cambodia’s LTS4CN and NDC strategies, focusing on the FOLU sector strategies.

The portfolio of policies embodied by the LTS4CN and NDC strategies (COMBI +) would generate positive GDP and wealth impacts on the order of US\$3.576 billion and US\$118 billion, respectively. The return on investment would be approximately US\$29.3 billion though not accounting for changes in natural capital stocks and environmental quality would result in a considerably smaller Net Present Value of US\$3.7 billion. Although the elimination of deforestation could constrain future agricultural land supply and food provisioning services, the reduction in erosion from afforestation and reforestation would positively impact agricultural productivity overall (Panagos et al., 2018; Pimentel et al., 1995) and potentially lower the need for fertilizers. In addition, output from timber and non-timber products, both of which are important for rural livelihoods (Chou, 2019; Ehara et al., 2016; Ender, 2016), would increase significantly with afforestation and restoration efforts. To mitigate any reductions in ES supply related to food security, measures to enhance agricultural productivity including agricultural

Table 1
Contribution of Ecosystem Services (ES) to the economy as a cumulative difference from BASE in 2050 in millions of USD.

ES Section	ES Class	Scenario							Code	
		NODEFOR	AFFOR	RESTORE	COMBI	*COMBI	COMBI+	*COMBI+	CICES	IPBES
Provision ecosystem services										
	Food (plant-based)	-1,918	-1,926	-1,918	-1,172	-1,933	-3,025	-3,935	1.1.1.1	12
	Meat (excluding fish)	11	-3	6	-2	-7	7	1	1.1.3.1	12
	Fish	81	-29	41	-52	-61	27	16	1.1.4.1	12
	Unprocessed timber and non-timber	3	4,846	1,765	6,323	6,321	6,331	6,328	1.1.1.2, 1.1.5.1, 1.1.5.2	12, 13, 14
	Processed wood and pulp/paper	5	46	23	55	54	61	59		
Regulating ecosystem services										
	Erosion mitigation				1,590		1,927		2.2.1.1, 2.2.1.2	9
Net effect on all ecosystem services considered		-1,818	2,934	-83	6,743	4,375	5,328	2,469		

Source: IEEM + ESM results. Scenario names preceded by an '*' indicate that regulating ES were not included.

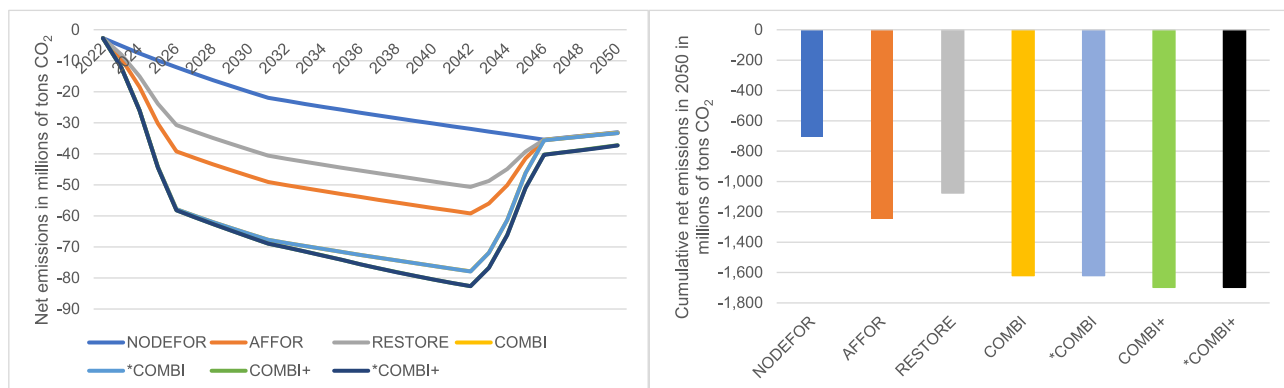


Fig. 7. Net emissions from the combustion of fossil fuels and Land Use Land Cover change (left) and cumulative net emissions from the combustion of fossil fuels and Land Use Land Cover change (right) in millions of tons of CO₂.

Source: IEEM+ESM results. Scenario names preceded by an '*' indicate that regulating ES were not included

Table 2
Impacts on macroeconomic indicators as a difference from BASE in 2050 or cumulative impact as indicated, in millions of USD.

	NODEFOR	AFFOR	RESTORE	COMBI	*COMBI	COMBI+	*COMBI+
GDP	-88	78	-8	304	105	307	69
Cumulative GDP	-943	1,819	177	4,134	2,544	3,576	1,649
Wealth	6,047	6,299	6,157	6,459	6,352	6,497	6,370
Cumulative wealth	74,453	99,831	90,025	1,14,315	1,13,522	1,18,844	1,17,874
Private consumption	-94	67	-27	270	110	257	67
Private investment	-16	10	8	57	0	60	-10
Exports	193	7	145	1	-74	175	82
Imports	193	29	152	27	-45	198	109

Source: IEEM + ESM results. Scenario names preceded by an '*' indicate that regulating ES were not included.

intensification on land that is poorly utilized would be advantageous (Bento de Souza Ferreira Filho et al., 2015; Byerlee et al., 2014; Garrett et al., 2018; Villoria et al., 2014).

Our analysis shows that the elimination of deforestation, afforestation of 1.6 million ha and restoration of 1.1 million ha would reduce emissions by a cumulative 1.698 billion tons of CO₂, net of any changes in emissions from fossil fuel combustion. Especially relevant co-benefits of emissions reductions given Cambodia's ranking as the 8th most vulnerable country to natural disasters is the simultaneous enhancement of water regulation and erosion mitigation ES, with the latter generating over US\$1.9 billion in additional economic value. Moreover, enhancing erosion mitigation and water regulation ES would result in more water being retained by forests, less run-off and rapid overland waterflow to streams and less hazard, damage and loss of human lives due to floods. Reducing erosion and sedimentation has important implications for hydropower generation (Kaura et al., 2019). The significant cost savings to the energy sector could potentially be used to finance the elimination

of deforestation as well as afforestation and restoration efforts.

The net economic impact of changes in future ES flows is estimated at US\$6.6 billion. With the tools developed in this study, specific ES could be spatially targeted across the landscape to maximize future ES flows while accommodating other land uses and socioeconomic constraints (Guo et al., 2020; Mokondoko et al., 2018; Wünschler et al., 2008). For instance, the identification of sites for afforestation should consider the impact on water regulation and water yield (Haas et al., 2024; Xiao et al., 2020; M. Zhang & Wei, 2021; X. Zhang et al., 2021) to ensure sufficient stream flow for current and future hydropower production, as well as potential competition for other land uses such as demand for land from new solar farms.

Generally, where landscapes with little or no vegetation are converted to forested ones, water yield is reduced relative to an unvegetated or degraded baseline condition (Farley et al., 2005; Li et al., 2021). While water yield may decline with afforestation due to higher rates of evapotranspiration from forests (exacerbated by the use of exotic tree

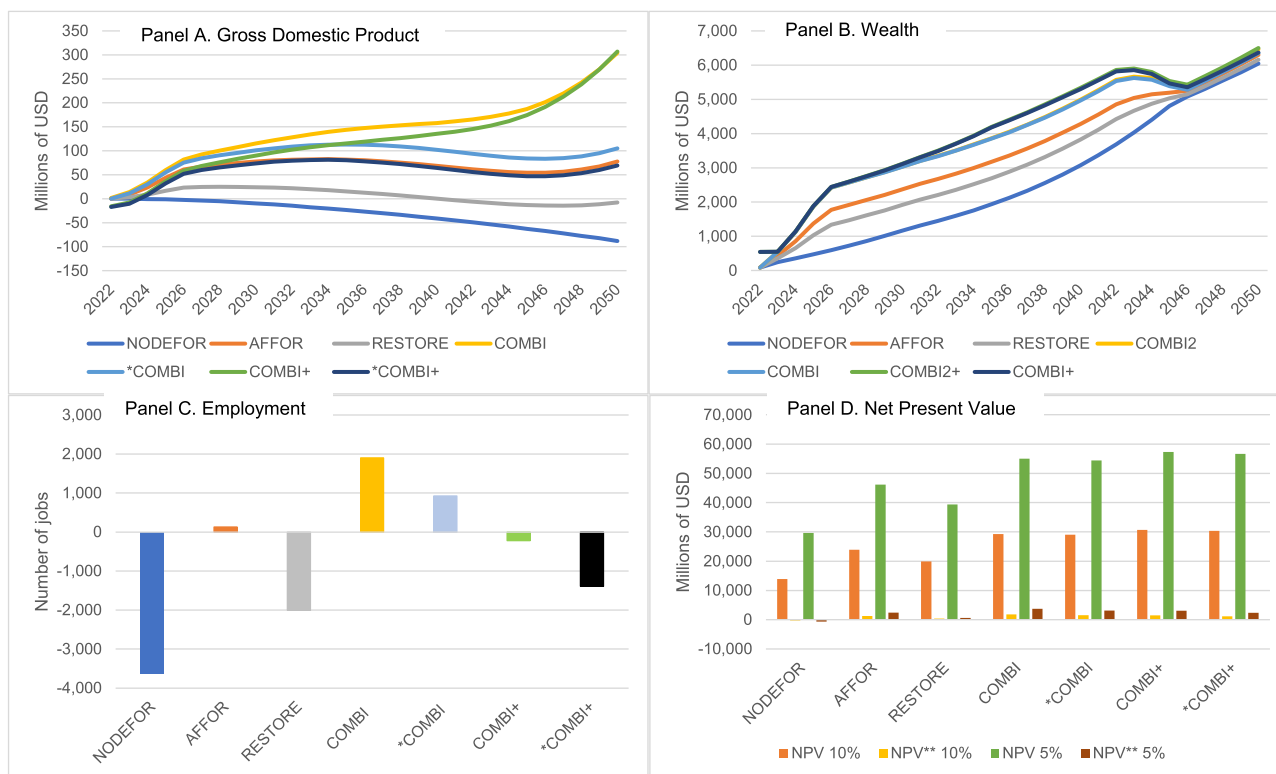


Fig. 8. Panel A and Panel B present the trajectory of Gross Domestic Product and Wealth, respectively, as a difference from BASE in millions of USD. Panel C presents employment impacts as a difference from BASE. Panel D presents Net Present Value with different discount rates in millions of USD. . Source: IEEM+ESM results. Net Present Value (Panel D) results without inclusion of changes in natural capital and environmental quality are identified with a double asterisk **

species (Seddon et al., 2020)), water regulation ES on the other hand may increase where more water would be maintained in the forested ecosystem, infiltration would increase, quick-flow would be reduced mitigating downstream flooding hazards (Dixit et al., 2022) and groundwater recharge may be enhanced.

An important issue of note with regard to afforestation and reforestation planning is that of timing. If emissions targets for FOLU strategies are set in the proximate future, the land required to meet those targets through afforestation and restoration would be larger than the land requirements of a more distant emissions target. Trees grow relatively slowly and thus accumulate carbon slowly. Consequently, the most efficient and cost-effective strategy to meet Cambodia’s emissions targets would be to eliminate deforestation more rapidly than planned in the LTS4CN, and as posed in the COMBI + scenario, complemented with afforestation and forest restoration measures with these activities undertaken over the course of a four-year period (as described in the COMBI + scenario).

This study has demonstrated that climate mitigation and adaptation goals can be achieved in ways that foster Cambodia’s socioeconomic development while reducing potential economic impacts of climate change (Adom & Amoani, 2021; Banerjee et al., 2024b; IPCC, 2014; Kahn et al., 2021; Millner & Dietz, 2015; Owen, 2020; World Bank, 2010). The policy package considered in this study was effective in meeting the emissions targets but also in catalyzing sustainable economic growth and building wealth which marks progress towards Cambodia’s upper-middle-income and eventually high-income status aspirations. Formulating a comprehensive policy framework that considers the interconnected benefits of aligning climate change action policies with other development priorities can promote a sustainable transition that meets multiple development objectives. Implementing Cambodia’s LTS4CN and NDCs will be critical for climate adaptation, mitigation and development goals and urgent reforms should be

prioritized with an emphasis on rigorous monitoring and evaluation of annual progress against targets (World Bank, 2023).

Scaling up investments in climate-smart agriculture and forest management and restoration will require stronger local governance, planning and management capacity as well as more stakeholder involvement and ownership (FAO, 2017). Successfully implementing forest policies could be supported by measures to reward climate-smart and resilient management of natural capital assets, as well as enabling the private sector to deliver market solutions for sustainable food systems. Community forests in Cambodia for example have been shown to contribute to maintaining forest cover and improve conservation outcomes (Poffenberger, 2009; Singh et al., 2018). Protected areas more generally and improving their management with reliable funding have also been proven to be effective in reducing deforestation (Black & Anthony, 2022).

Complementary policies and incentives can further enhance enabling conditions for the implementation of the LTS4CN and NDCs. Private sector participation in forest plantations and registration of private forests could be encouraged by disseminating the Guidelines on Private Forest Registration in Cambodia (AFoCO, 2021). Incentives for the private sector could also include the improvement of value chains and the development of new markets for sustainably harvested timber and non-timber forest products and nature-based tourism, or through direct payments for ES. Payment for ES in Cambodia has been effective in reducing deforestation in collectively owned forests (Chervier & Costedoat, 2017; Clements & Milner-Gulland, 2015).

Finally, aligning institutions and incentives and strengthening a climate change accountability mechanism are crucial to achieve Cambodia’s development, adaptation and mitigation objectives. Currently, climate adaptation and mitigation targets are not fully integrated into government ministries’ development plans, which results in a lack of clear ownership and responsibility. Incentives and monitoring could be

improved by incorporating climate-related expenditures in ministries' annual budgets and quantifying the efficacy of targeted climate interventions in a systematic way (World Bank, 2023). This study has provided evidence that climate change mitigation and sustainable economic development are not only compatible but self-reinforcing goals.

CRedit authorship contribution statement

Onil Banerjee: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martin Cicowiez:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis. **Erica Cristine Honeck:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Mani S. Muthukumara:** Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Funding acquisition, Conceptualization. **Katherine Anne Stapleton:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Acknowledgements

This study was funded by the World Bank. The writing of the paper was supported by RMGEO Consultants Inc. (Project: Globalizing IEEM + ESM Infrastructure and Analytics; Grant Agreement JS-2025) and the World Bank.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoser.2024.101695>.

Data availability

Data will be made available on request.

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