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Arresting environmental degradation to build wealth in Thailand

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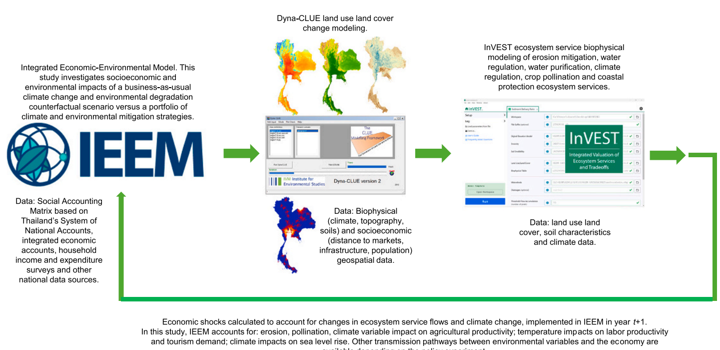
HIGHLIGHTS

- Thailand is aiming for high-income status but unabated environmental degradation and climate change pose challenges.
- We compare the costs of inaction with policies to arrest degradation and mitigate and adapt to climate change.
- The cost of inaction on GDP and ecosystem services is US$553 billion and US$177 billion.
- The policy intervention considered would partially offset GDP losses while enhancing wealth by US$54.5 billion.
- Of the policies considered, eliminating deforestation rapidly is most effective to reduce barriers to high-income status.

GRAPHICAL ABSTRACT



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ABSTRACT

Thailand aims to achieve high-income status by 2037 through the strategies developed in its 20-year National Strategy Preparation Act. Considerable friction is being generated through climate change and unsustainable natural resources management which are eroding Thailand's natural capital base, resilience and ability to generate wealth and progress toward its target. In this paper, we examine the impacts of ongoing environmental degradation including continued deforestation and climate change-induced impacts on flooding, productivity and sea-level rise. We contrast this future trajectory with the implementation of a policy package aligned with Thailand's National Strategy and Nationally Determined Contributions to counteract environmental degradation and adapt to and mitigate climate change. Where environmental degradation continues unchecked, Gross Domestic Product would decline by US$553 billion. Standing forest stock would be reduced from 8.25 million hectares to 5.43 million hectares and cumulative losses of Provisioning, Cultural and recreational and Regulating ecosystem services would be US$99 billion, US$61 billion and US$17 billion, respectively, by 2050. Policies to arrest environmental degradation would offset some but not all impacts with the loss in Gross Domestic Product

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32 % (US$174.9 billion) of what it would be without policy intervention. Wealth, the more appropriate metric of sustainable economic development, would increase by US$54.5 billion. The most effective measure to arrest environmental degradation and build wealth would be to eliminate deforestation. Doing so quickly would reduce ecosystem service losses, maintain carbon in forests and enhance water regulation ecosystem services which are critical for reducing flood hazards, loss of life and infrastructure damage. To advance an effective policy agenda for reaching high-income status, operational plans and cost estimations for mitigating and adapting to climate change and eliminating deforestation are necessary to guide the allocation of public and private investment to meet this formidable challenge.

1. Introduction

Thailand has made great strides in economic development, now categorized as an upper middle-income country with an economy and employment driven by agriculture, industry, services and tourism sectors. Through the principles of security, prosperity and sustainability, Thailand is implementing strategies to reach high-income status by 2037. Five key themes addressed by the National Strategy Preparation Act are: economic prosperity, environmental protection, social well-being, human resources empowerment and public sector governance (Kingdom of Thailand, 2019). There are challenges to overcome, however, as for over one decade now, the country has faced a deceleration of economic growth and declining investment.

Further exacerbating these challenges is Thailand's vulnerability to climate change. Thailand is the third most vulnerable country in Southeast Asia (World Bank, 2023c) and is especially at risk from increasing natural hazards including heavy rainfall, flood, drought and sea-level rise (World Bank and Asian Development Bank, 2021). Climate change and unsustainable natural resources management practices are eroding Thailand's natural capital base and hampering progress toward high-income status. Climate change is jeopardizing future flows of critical ecosystem services (ES), such as soil erosion mitigation, water regulation and coastal protection (MRC, 2021). Expansion of industrial activities without appropriate measures for environmental protection have reduced air quality, costing people their health and their lives with an associated economic cost of 6 % of GDP (World Bank, 2024b).

Temperature and precipitation patterns are changing (UNDP, 2017) and in many watersheds, dry season river flows are increasing while wet season flows are decreasing. Overall, projections show a trend of warming and a less certain though likely increase in precipitation. Thailand is vulnerable to drought and water shortages creating important challenges for the agricultural sector which accounts for approximately 9 % of GDP. Drought increases reliance on groundwater aquifers which comes with its own set of problems, especially land subsidence and sinking. In recent years, the Thai government has compensated farmers where drought has resulted in crop failure, paying farmers 0.15 % of GDP in compensation in 2019 and 0.36 % of GDP in additional measures to support farmers (World Bank, 2023c).

Thailand has an extremely high-risk exposure to flooding which includes riverine, flash and coastal flooding as well has a high level of exposure to tropical cyclones and related hazards (World Bank and Asian Development Bank, 2021). Average annual losses from flooding alone are projected to reach 0.5 % of GDP by 2030 (World Bank, 2024b). Climate change is estimated to impact the Thai economy between 1 % and 44 % of GDP by mid-century, though between 10 % and 20 % is viewed as a more probable range given experience in nearby countries (World Bank, 2023c).

Deforestation in Thailand is driven by rapid expansion of agriculture, infrastructure and tourism. Between 2001 and 2022, Thailand lost 2.41 ha (ha) of forest cover, emitting 1.36 gigatons of CO_2 equivalent. Persistent deforestation increases the risk and severity of floods which can have devastating consequences. Case in point, the 2011 flood affected more than 13 million people, destroyed 19,000 homes, displaced 2.5 million people (World Bank, 2016) and resulted in 12.6 % of GDP in damage and a reconstruction bill of about 3.4 % of GDP for the public sector (World Bank, 2023c). A one in fifty year flood similar to the 2011 flood could cost more than 10 % in GDP in forgone economic output (World Bank, 2024b). Shoreline erosion, saline water intrusion and subsidence are displacing people and reducing agricultural productivity. Sediment transport which is important for agricultural productivity and delta-forming processes, is declining due to the disruption of water flow by hydropower dams and commercial sand mining (Anthony et al., 2015; Eslami et al., 2021).

There have been some prior efforts to quantify changes in ES in Thailand. Arunyawat and Shrestha (2016, 2018) modeled how Land Use Land Cover (LULC) change from the expansion of rubber plantations and urban areas affected ES flows. Monprapussorn (2018) focused on the coastal province of Samutsakorn and found that sea level rise, temperature and precipitation change would degrade coastal ES and community resilience. Sea level rise alone is resulting in 2 km^2 per year of land loss equivalent to 0.04 % of GDP (World Bank, 2023c). Kaiser et al. (2013) modeled tsunami impacts on LULC change and ES in the Andaman Sea-facing province of Phang Nga. The authors found ES supply capacity loss in most LULC classes though discovered relatively fast recovery times for certain ecosystems such as beaches; mangroves and casuarina forests were found to require a few more years to recover.

Zhao et al. (2022) studied the effects of deforestation and changing precipitation patterns in the Upper Chao Phraya River Basin, an important water resource area for the country. The authors found that precipitation changes were responsible for much of the increase in streamflow as well as baseflow in some sub-basins. On the other hand, they found that deforestation was responsible for increased annual streamflow and baseflow in upstream sub-basins and increased sediment loads in specific sub-basins. Overall, a 1 % reduction in forest cover was found to increase annual streamflow by 1.9 %, with more pronounced effects in upstream sub-basins, and increase sediment loads by 8.7 %.

Climate change, environmental degradation and changes in ES supply are addressed at the highest level in Thailand's National Strategy and various sectoral development plans as well as the country's Nationally Determined Contributions (NDCs). This study quantifies the impacts of climate change, continued environmental degradation and ES loss and the costs of inaction and contrasts this future scenario with the implementation of a portfolio of policies and investments designed to mitigate and adapt to climate change and address the anthropogenic drivers of environmental degradation.

To do so, we implement the Integrated Economic-Environmental Model (IEEM; Banerjee et al., 2016; Banerjee et al., 2019) developed for Thailand and linked with spatial Land Use Land Cover (LULC) change and ES modeling (IEEM+ESM; Banerjee et al., 2020a; Banerjee et al., 2022b). The dynamic IEEM+ESM approach enables endogenous feedbacks between policy-induced changes in ES supply and the economy through time. This paper further builds on the dynamic IEEM+ESM approach by simultaneously integrating damage functions to account for broader climate change impacts on the economy and society.

The section that follows provides a brief overview of the study methodology and the business-as-usual and policy scenarios. Section 3 presents IEEM+ESM results and Section 4 concludes the study with a summary of key insights for informing policy and investment. This paper includes a detailed Supplementary Information (SI) component. SI Section 1 provides a detailed presentation of the IEEM+ESM methodology. SI Section 2 presents a view of the Thai economy from the perspective of the IEEM database. SI Section 3 presents ES modeling parameters while SI Section 4 presents details of the business-as-usual and policy scenarios. SI Section 5 presents detailed results and SI Section 6 presents the results of the systematic sensitivity analysis. SI Sections 7 and 8 present the ES and LULC geospatial metadata used, respectively.

2. Methods and scenario overview

2.1. Background on methods

Natural capital and ES that have a market price have been included in economy-wide Computable General Equilibrium (CGE) models for quite some time, though analyses have focused typically on the interaction between the economy and one natural capital asset or ES at a time (Banerjee et al., 2016). With the publication of the first internationally endorsed standard for environmental-economic statistics, the System of Environmental-Economic Accounting (SEEA) Central Framework (United Nations et al., 2014) which is consistent with a country's System of National Accounts (United Nations, 1993), it became possible to comprehensively integrate natural capital and market-based ES into CGE models and track how economic-environmental interactions affect natural capital stocks and their contribution to wealth. Banerjee et al. (2016) provides a review of the literature integrating natural capital and ES in macroeconomic models and developed proof of concept of the integration of SEEA in a CGE model which became known as IEEM.

With natural capital and market-based ES organized under the SEEA integrated in IEEM, the next challenge was to account for non-market ES, especially regulating ES which include erosion mitigation, crop pollination and water purification. Banerjee et al. (2020b) developed a blueprint for this integration in both national and global CGE models and addressed the challenge by linking spatial ES modeling with a CGE model using LULC change modeling as the bridge between the aspatial CGE model and the spatial ES modeling (Banerjee et al., 2020a). Significant advances have been made since then through: (i) the inclusion of additional regulating ES; (ii) the development of the dynamic IEEM+ESM workflow (described in the section that follows and in detail in SI section 1) which includes endogenous feedbacks between changes in ES supply and the economy through time (Banerjee et al., 2023b) and; (iii) in this study, the integration of climate damage functions to account for broader climate change impacts (described in Section 2.3).

2.2. The dynamic IEEM+ESM approach

The dynamic IEEM+ESM approach was applied in this study which is a methodological framework that simulates policy impacts on economic, social and environmental indicators (see Box 1). IEEM+ESM takes a whole-of-economy approach where all economic sectors interact through supply and demand relationships and factor (labor, capital and land) constraints and endowments. The IEEM+ESM framework links an economic model with spatial LULC and ES analytics to incorporate feedbacks between policy impacts on ES flows and the economy while maintaining consistency with a country's System of National Accounts. Consistency with the National Accounts ensures robustness of estimates and credibility with decision makers of Government including Ministries of Finance and Central Banks, which are responsible for developing the National Accounts.

At the core of IEEM is a recursive dynamic Computable General Equilibrium (CGE) model (see SI Section 1 for a detailed presentation of the IEEM+ESM methodology). CGE models are among the most well-documented models in the literature which has developed over the last four decades. Linked with IEEM is a LULC change model and 6 ES models. The widely used Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) LULC change model was calibrated for this application (Verburg et al., 1999, 2008; Verburg and Overmars, 2009; see SI Section 1 and 8). The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) ES models (Sharp et al., 2020) were used in this study and parameterized with national data where available (see SI Section 1, 3 and 7). The ES models applied were the Sediment Delivery Ratio, Annual Water Yield, Nutrient Retention, Carbon Storage, Crop Pollination and Coastal Vulnerability ES models (see SI Section 3 and 7).

In the dynamic IEEM+ESM approach, modeled changes in LULC and ES have consequences for the economy. In this workflow, economic shocks accounting for changes in erosion mitigation and crop pollination were estimated and implemented in IEEM. This approach enables estimation of the marginal value of regulating ES which generally do not have a market price. At the time of writing, the dynamic IEEM+ESM workflow is the only modeling framework in the peer reviewed literature that integrates dynamic endogenous feedbacks between changes in ES and the economy in this way.

2.3. Advancing the dynamic IEEM+ESM approach: integration of climate change damage functions

Building on the dynamic IEEM+ESM approach, we integrate climate damage functions in IEEM to capture some of the main impact channels of climate change. The integration of damage functions in a CGE model enables estimation of climate change impacts on economic trajectories with and without policy intervention (Roson and Sartori, 2016) and is the principal approach used in the World Bank's flagship report series "Country Climate and Development Reports" (see for example: World Bank (2023b, 2023a, 2024a, 2024b). Our approach accounts for how national policy affects future LULC and ES supply as well as projected global climate change impacts where in general, large scale global coordinated action would be required to avoid specific impacts such as sea level or temperature rise.

The implementation of climate damage functions in IEEM+ESM and how it integrates with the modeling components is presented in Fig. 1. The box on the left presents some of the primary climate damage functions, for different Relative Concentration Pathway (RCP) projections, which are implemented directly in IEEM. The result of this is that economic agents in IEEM adjust their production and consumption decisions to adapt to the various dimensions of the climate change impacts simulated. This in turn affects demand for land and subsequent LULC projections which are a key input into the ES modeling. Future ES flows are thus also affected by climate impacts in a business-as-usual scenario and policy and investment scenarios. The pathways through which changes in a specific ES flow in turn affect the economy are presented in the text embedded in the arrows in Fig. 1. For example, changes in erosion mitigation ES affect agricultural productivity, hydropower production potential and dredging costs related to hydropower and navigation.

In this study, we include climate change damage functions for coastal and inland flooding, catastrophic flooding, agricultural land productivity, agricultural labor productivity, construction sector labor productivity, tourism demand and sea level rise for RCP 4.5 and 8.5 (Markandya, 2023). Briefly, temperature effects on labor productivity and flooding impacts were based on data and methods from Climate Analytics (2024) and the World Bank (2012). Agricultural productivity impacts were based on projections from IFPRI (2019) and Rosegrant et al. (2017). Tourism sector impacts were based on the work of Hamilton et al. (2005) and Roson and Sartori (2016). Sea level rise impacts were based on the approach implemented in World Bank (2022) and estimates from Lincke and Hinkel (2018). Additional details are presented in SI section 4.

2.4. Scenario overview

We implement a business-as-usual baseline (BASE) and two main scenarios in IEEM+ESM to simulate continued environmental degradation and climate change (DEGRADE scenario) and policies designed to

Box 1 IEEMESM methods summary.

The IEEM+ESM modeling workflow is comprised of three models that interact through the transfer of data and results from one model to another. The first model is IEEM, a CGE model at its core, which is constructed based on a country's National Accounts, the internationally accepted framework for measuring economic activity and development. A Social Accounting Matrix underpins IEEM which is a statistical representation of all sectors and transactions in an economy as well as land use dynamics for a specific base year. IEEM is dynamic, in other words, future looking, and is used to generate a business-as-usual or a BASE projection of the economy in the absence of any new public policies and investments. Policy scenarios are then implemented in IEEM which in the case of this study, represent: (i) a suite of scenarios of continued environmental degradation and; (ii) a portfolio of policies to arrest this degradation.

Linked to IEEM is the Dyna-CLUE LULC change model. This model is calibrated with biophysical (climate, topography, soils) and socioeconomic (distance to markets, transportation infrastructure, population density) geospatial layers to estimate the probability of a specific LULC occurring at each grid cell in a base map of the country. The LULC model is linked to IEEM through projections of demand for land. Deforestation generates cleared land used by the agricultural sector. The LULC change model is used to spatially attribute demand for land across the country.

The InVEST ES models use the LULC maps generated by the LULC change model as inputs to calculate erosion mitigation, water regulation, water purification, climate regulation, crop pollination and coastal protection ES. ES model runs calculate changes in future ES flows for each policy scenario with respect to the business-as-usual scenario. These results are used to calculate economic shocks that account for changes in ES flows (both increases and decreases) which are subsequently implemented in IEEM to generate the final results presented in Section 3.

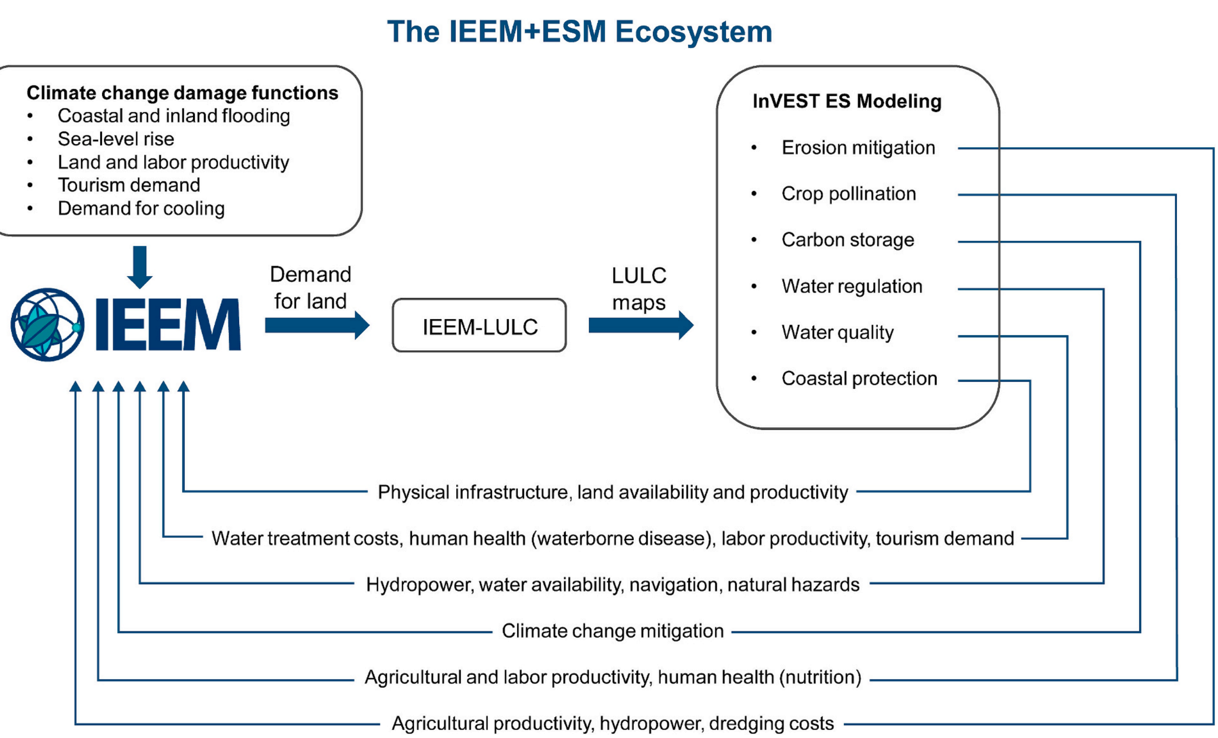

Fig. 1. The IEEM+ESM Ecosystem integrating climate damage functions with IEEM and spatial Land Use Land Cover Change and Ecosystem Services Modeling. Source: IEEM+ESM.

counteract this degradation and mitigate and adapt to climate change impacts (POLICY scenario). The business-as-usual scenario is used as the counterfactual reference scenario to which all other scenarios are compared. It presents the future trajectory of Thailand's economy, until 2050, in the absence of any new large public policies and investments and without further acceleration in the degradation of the natural capital base.

The DEGRADE scenario represents the main aspects of climate change-accelerated environmental degradation. The comparison between the business-as-usual BASE and DEGRADE scenario reveals the economic, wealth, natural capital and ES costs of policy inaction. The DEGRADE scenario is comprised of various subscenarios that simulate more rapid and destructive deforestation, increased coastal and inland flooding, two catastrophic floods of greater intensity than that of Thailand's devastating 2011 flood[1], reduced agricultural land productivity, reduced agricultural and construction sector labor productivity, stagnating tourism demand, sea level rise, increased soil erosion and reduced crop pollination (see SI section 4 for details of the subscenarios).

For a number of the DEGRADE subscenarios, RCP 8.5 and 4.5 projections were used in the estimation of climate damage functions

[1] These floods were projected to occur in 2029 and 2047 through a random number draw.

(Markandya, 2023). In IEEM, the effects determined by the damage functions are implemented in each subscenario and are modeled as changes in levels of productivity, output and costs depending on the specific scenario and damage function. In turn, the implementation of IEEM generates results that include direct, indirect and general equilibrium impacts of climate change-driven environmental degradation.

The POLICY scenario represents public policies and investments aimed at arresting further environmental degradation and adapting to climate change and mitigating its impacts. The results reported reveal the economic benefits of investing in enhancing natural capital and resilience and contributing to economic recovery, as well as trade-offs that may exist between economic, social and environmental outcomes. The POLICY scenario is comprised of various subscenarios that were designed to counteract the effects of the DEGRADE subscenarios (see SI section 4 for details of the subscenarios).

The POLICY scenario includes measures to reduce the damage caused by coastal and inland flooding and cyclones through the implementation of early warning and monitoring systems as well as physical infrastructure (Azarnivand and Malekian, 2016; Malekian and Azarnivand, 2016). This scenario assumes global cooperation in that all countries implement their NDCs and that these NDCs are effective in mitigating climate change and thus mitigating storm damage and slowing sea-level rise. These measures are assumed to be effective in offsetting climate change impacts on agricultural output, agricultural land and agricultural and construction sector labor productivity. Global cooperation and global implementation of NDCs is assumed to mitigate sea-level rise impacts and temperature effects on tourism demand. Finally, the POLICY scenario includes the elimination of deforestation by 2037 and measures for afforestation (1,806,400 ha) and the restoration of degraded forests (2,558,400 ha). These measures are consistent with Thailand's National Strategy (Kingdom of Thailand, 2019).

3. Results

In this section, we begin with a summary presentation of the results (Box 2). Next, LULC change and ES impacts are presented. Section 3.3 concludes the presentation of results focusing on the economic impacts of unabated degradation and climate change versus a portfolio of mitigation and adaptation strategies.

3.1. Land use land cover change impacts

Fig. 2 presents LULC change in 2050 for the BASE, DEGRADE and POLICY scenarios, respectively.

The BASE projection shows continued forest loss throughout the analytical period while DEGRADE presents an accelerated rate of deforestation which would eliminate most of Thailand's forests outside of protected areas. The POLICY scenario on the other hand includes measures for afforestation (1,806,400 ha) and restoration of degraded forests (2,558,400 ha) as well as the elimination of deforestation. Deforestation is reduced beginning in 2024 and altogether eliminated by 2037. Note that while the magnitudes of changes in LULC are defined by the scenarios themselves, the LULC change modeling spatially allocates this change as shown in Fig. 2 and according to the suitability analysis undertaken in the LULC change modeling exercise (see SI Section 1 for more details).

3.2. Ecosystem service impacts

ES impacts are presented as the difference between the DEGRADE and POLICY scenarios with respect to the BASE in 2050 for each of Thailand's 6 regions. Fig. 3 Panel A shows impacts on carbon climate mitigation ES for the DEGRADE scenario where the greatest declines would be found in the north, south and west (−16 %, −11 % and − 5 %, respectively). In the POLICY scenario (Fig. 3, Panel B), carbon storage would increase the most in the north, south and west (41 %, 35 % and 15 %, respectively).

Erosion mitigation ES would largely decline across most of Thailand as environmental degradation continues unchecked, from 16 % in the east, 11 % in the west and 5 % in the south (Fig. 3, Panel C). With policy intervention, erosion mitigation ES would improve notably, by 20 % in the north and 17 % in the west and east (Fig. 3, Panel D).

Fig. 4 (Panel A) presents the impacts of continued environmental degradation on water regulation ES. Impacts would be negative, particularly for the north, south and west of Thailand (−13 %, −7 % and −3 %, respectively). With policy intervention, on the other hand, water regulation ES would be markedly improved, especially in the north, south and west of the country (Fig. 4 Panel B). With regards to water purification ES, the DEGRADE scenario would have severe impacts, particularly in the north, south and west of the country (−36 %, −26 % and −9 %, respectively; Fig. 4 Panel C). With policy intervention, impacts would be strongly mitigated with the greatest effects in the north, south and west (33 %, 23 % and 10 %, respectively; Fig. 4 Panel D).

Finally, environmental degradation would affect crop pollination ES as presented in Fig. 5, Panel A. Impacts would be negative across the country, with the greatest impacts experienced in the north, south and west of Thailand (−8 %, −5 % and −3 %, respectively). With policy intervention, these negative impacts would be largely offset with the greatest impacts in the north, south and west of the country (39 %, 35 % and 15 %, respectively; Fig. 5, Panel B).

The bottom of Error! Reference source not found. Fig. 5(Panel C) presents a preliminary assessment of coastal vulnerability in the business-as-usual BASE scenario. Thailand's eastern coastline and gulf region east of Bangkok are the areas exhibiting the highest levels of

Box 2 Results overview.

In the absence of mitigation measures, results show that Thailand would lose most of its unprotected forest, a loss of over 2.8 million hectares. Deterioration of ecosystems and their capacity to produce ES would be compromised, resulting in a net loss of US$177.6 billion. Cumulative GDP would decline by US$553.7 billion by 2050. Approximately 4.3 million jobs would be lost with an additional 46,510 people facing poverty.

The proposed mitigation and adaptation policies on the other hand would eliminate deforestation by 2037 and increase afforestation and restored forests by 1.8 million and 2.56 million hectares, respectively. The resulting ES impacts would be highly positive when compared with the business-as-usual scenario, increasing climate regulation, erosion mitigation, water regulation and crop pollination ES with especially positive outcomes in the north, south and west of Thailand. In particular, crop pollination and erosion mitigation ES would contribute over US$18 billion to economic growth. The policies would serve to mitigate some of the negative GDP impact while they would increase wealth by US$54 billion. Employment and poverty impacts would also be moderated, though additional policy measures would be necessary to completely reverse the momentum of negative impacts driven by climate change and environmental degradation.

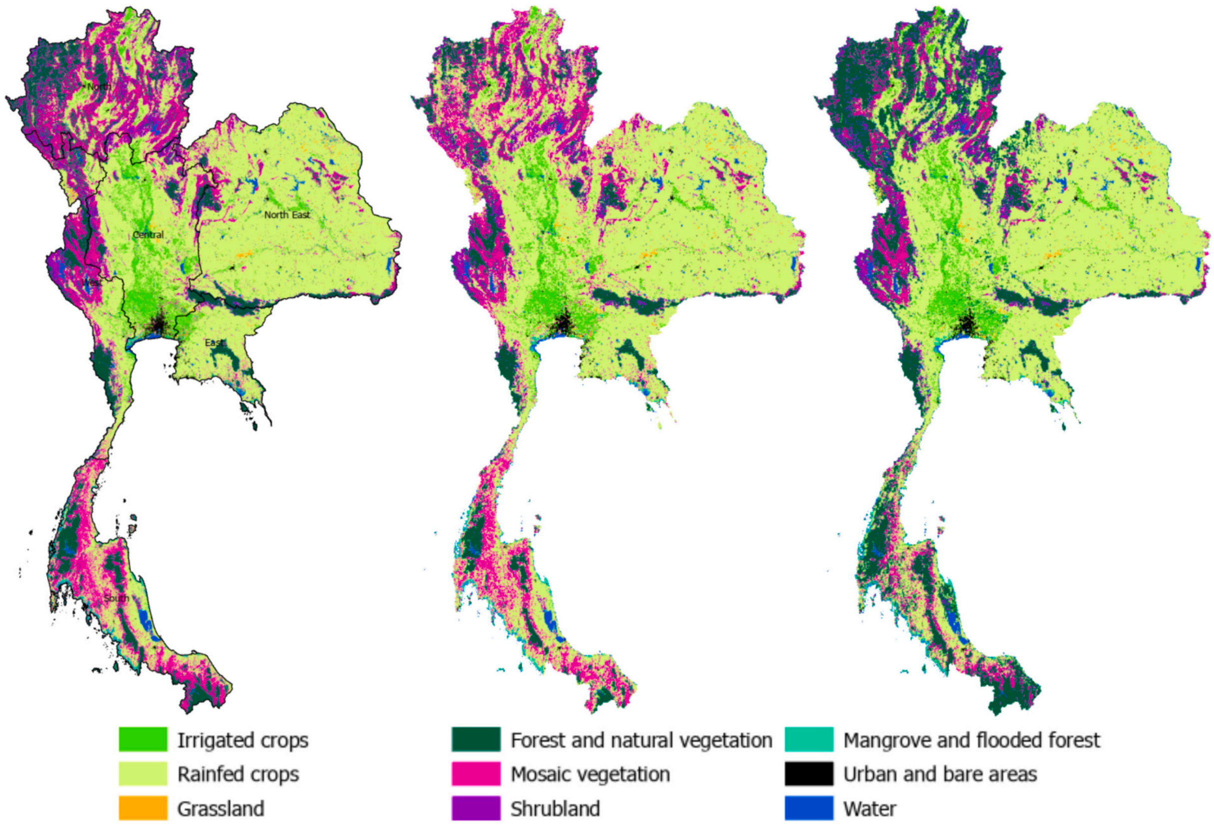

Fig. 2. BASE (left) DEGRADE_PES+ (middle) and POLICY (right) Land Use Land Cover Change Map in 2050. (Source: IEEM+ESM results. Note: scenario names that terminate in PES+ use the RCP8.5 pathway projection.)

exposure. Future applications of the modeling framework developed in this study could consider policy scenarios that affect specific coastal vulnerability variables such as the presence of mangroves, coral reefs and other natural or built features.

3.3. Economic impacts

Table 1 presents the scenario impacts on ES and key macroeconomic indicators. In these results, scenario names that terminate in OPT consider the RCP4.5 pathway while scenario names that terminate in PES+ use the RCP8.5 pathway projection. Focusing first on ES, the ES presented in.

Table 1 are categorized according to the Common International Classification of Ecosystem Services (CICES; Haines-Young and Potschin (2018)) which identifies the categories of Provisioning, Cultural and recreational, and Regulating ES. Cultural and recreational ES would experience the greatest decline with continued environmental degradation. As would be expected, impacts of scenarios that use RCP4.5 projections versus RCP8.5 projections would be milder, though negative, nonetheless. Energy ES would be next in terms of negative impacts followed by food provisioning ES. Crop pollination and erosion mitigation ES would also decline by US$7.5 billion and US$9.9 billion, respectively.

ES losses should environmental degradation continue unabated would translate into an overall net loss of US$177.6 billion in economic value (DEGRADE_PES+). Policy intervention would mitigate some of these losses. Regulating ES would make positive contributions, but some losses would still be incurred through a reduction in Provisioning and Cultural and recreational ES. The net impact of policy implementation (POLICY_PES+) would be US$39 billion. Finally, while not reported in.

Table 1, the elimination of deforestation would result in a net 189-million-ton increase in CO_2 storage. Afforestation and forest restoration activities which are components of the POLICY scenario would store an additional 1913 million tons of CO_2.

Table 1 presents scenario impacts on key macroeconomic indicators. Considering DEGRADE_PES+, the cumulative GDP impact would be a loss of US$553.7 billion by 2050. Policy intervention would reduce these losses significantly though the impact would still be negative (US$174.9 billion). With the elimination of deforestation as well as the implementation of afforestation and forest restoration activities, the policy interventions to arrest environmental degradation would enhance cumulative wealth by US$54 billion. The systematic sensitivity analysis presented in SI section 6 demonstrates that it is almost certain that cumulative wealth would be between $56.7 billion and US$57.2 billion, given variations in key IEEM+ESM model parameters.

Fig. 6 presents the GDP (left) and wealth (right) trajectory of each scenario as a difference from BASE. The 'steps' visually evident in both these figures are the result of the impacts of catastrophic flood events occurring in the years 2029 and 2047.

Fig. 7 presents sector-level impacts of the DEGRADE and POLICY scenarios. Those sectors most affected by continued environmental degradation and climate change would be the Crop, Machinery and equipment, Vehicles, Trade, Hotel and restaurants and Other services sectors. In the Policy scenario, impacts would be mitigated to some degree but not entirely. Relatively strong positive impacts would be found in the Public administration and Construction sectors.

Employment in DEGRADE_PES+ would be reduced by over 4.3 million jobs (Fig. 8, left). Policy intervention would mitigate much of this impact though 931 thousand jobs would still be lost. The DEGRADE_PES+ scenario would result in 46,510 more people living in poverty while policy intervention would reduce this impact to 35,227 individuals (Fig. 8, right).

A benefit-cost analysis was undertaken to estimate the net present value of the investments with a discount rate of 2.5 % and 10 %. The

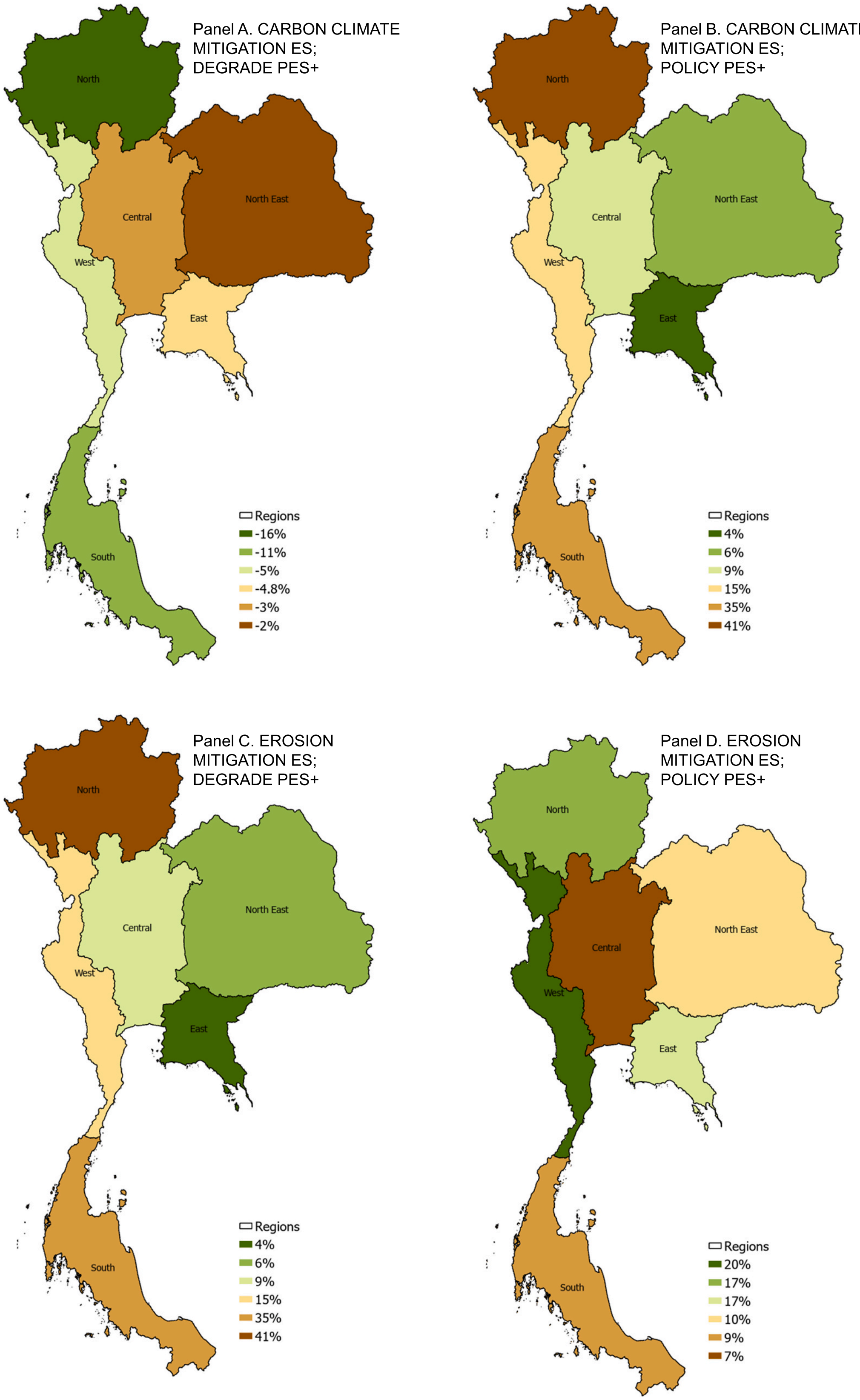

Fig. 3. DEGRADE PES+ and POLICY PES+ carbon storage mitigation ecosystem services (Panel A and B, respectively) and; DEGRADE PES+ and POLICY PES+ erosion mitigation ecosystem services (Panel C and D, respectively). All figures expressed as a percent difference from BASE. Source: IEEM+ESM.

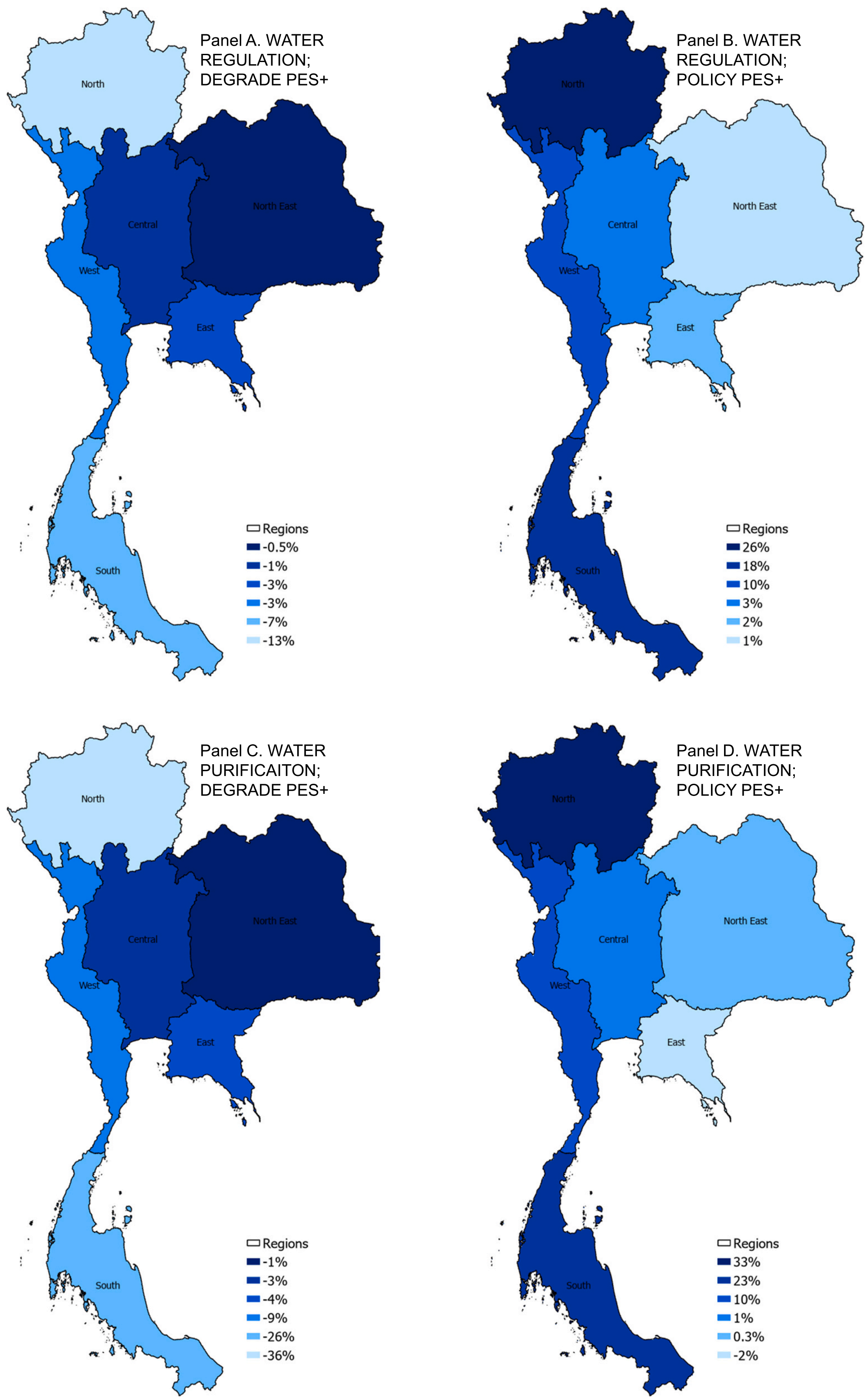

Fig. 4. DEGRADE PES+ and POLICY PES+ water regulation ecosystem services (Panel A and B, respectively) and; DEGRADE PES+ and POLICY PES+ water purification ecosystem services (Panel C and D, respectively). All figures in 2050 as a percent difference from BASE. Source: IEEM+ESM results.

POLICY_OPT scenario would result in a negative return of US$32,277 million with a 2.5 % opportunity cost of capital and a negative US$8365 million return with a 10 % opportunity cost of capital.

4. Discussion and conclusions

This study evaluated the economic, social and environmental impacts of ongoing environmental degradation and climate change in

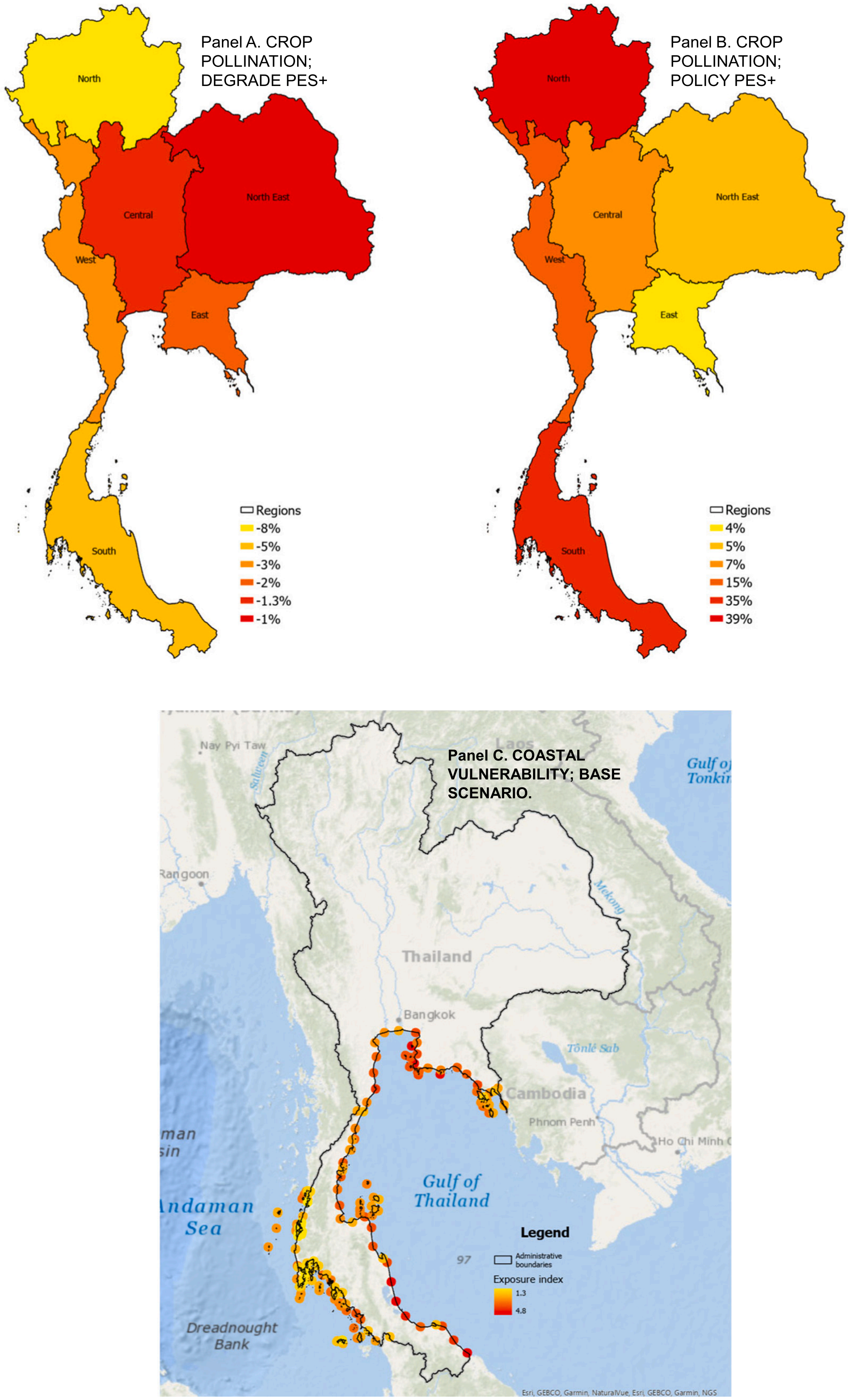

Fig. 5. DEGRADE PES+ and POLICY PES+ (Panel A and B, respectively) crop pollination ecosystem services as a difference from BASE in percent. Panel C: BASE coastal vulnerability, index value between 1 (very low exposure) to 5 (very high exposure). Source: IEEM+ESM results.

Table 1
Scenario impacts on the value of ecosystem service flows and key macroeconomic indicators. Impacts on ecosystem service flows are reported as a cumulative difference from BASE in 2050. Impacts on macroeconomic indicators are reported as a difference from BASE in 2050 or cumulative impact as indicated. All values reported in millions of USD.

	DEGRADE_OPT	DEGRADE_PES+	POLICY_OPT	POLICY_PES+
Impacts on ecosystem services				
Provision ecosystem services				
Food (plant-based)	−6834	−79,786	−7074	−22,477
Meat (excluding fish)	−1335	−7672	−1895	−3159
Fish	−1845	−2996	−4786	−1138
Timber and non-timber	499	3224	−4786	−3631
Abiotic subsurface minerals	−15,257	−10,361	−11,402	−9525
Abiotic subsurface non-mineral energy	−1641	−1454	541	814
Cultural and recreational ecosystem services				
Culture, recreation and tourism	−26,256	−61,156	−5103	−17,930
Regulating ecosystem services				
Crop pollination		−7508		17,749
Erosion mitigation		−9871		285
Impacts on macroeconomic indicators				
GDP	−36,442	−46,878	−7658	−14,548
Cumulative GDP	−423,101	−553,708	−80,056	−174,902
Wealth	−6564	−6888	−1649	2669
Cumulative wealth	−75,420	−80,530	−18,238	54,490
Private consumption	−27,392	−39,652	−5515	−11,143
Private investment	−11,999	−11,287	−2674	−4217
Exports	−34,314	−37,279	−25,383	−24,324
Imports	−32,551	−35,136	−3721	−5129

Source: IEEM+ESM results. Note: scenario names that terminate in OPT use the RCP4.5 pathway projection while those that terminate in PES+ use the RCP8.5 pathway projection.

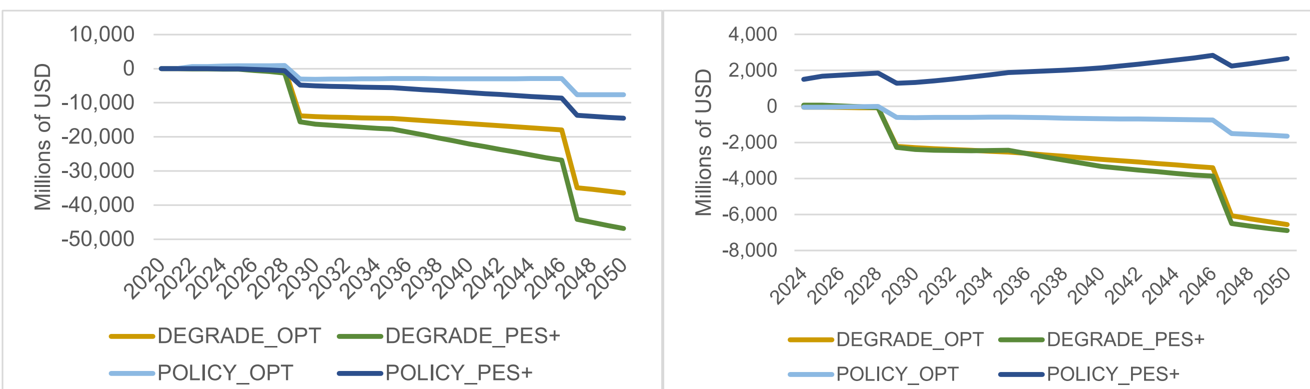

Fig. 6. GDP (left) and wealth (right) trajectory as a difference from BASE in millions of USD. (Source: IEEM+ESM results. Note: scenario names that terminate in OPT use the RCP4.5 pathway while those that terminate in PES use the RCP8.5 pathway projection.)

Thailand and strategies to arrest this degradation and mitigate climate change impacts. Two main scenarios were considered with the first simulating the impacts of more rapid and destructive deforestation, increased coastal and inland flooding, catastrophic floods, reduced agricultural land and labor productivity, stagnating tourism demand, sea level rise, increased erosion and reduced crop pollination. The policy interventions considered included strategies to reduce environmental degradation and adapt to and mitigate climate change impacts.

Unabated environmental degradation with an accelerated rate of deforestation would reduce the standing forest stock from 8.25 million ha to 5.43 million ha by 2050. This change in forest cover would strongly affect the future flow of ES including reductions in climate change mitigation, erosion mitigation, water regulation, water quality and crop pollination ES. Results show that the cumulative net impacts on Provisioning ES would be about US$99 billion by 2050, the largest of the impacts of the ES categories considered. Cultural and recreational ES would also be affected given the relationship between tourism demand and climate change-induced temperature rise with impacts on the order of about US$61 billion by 2050. Losses in Regulating ES, primarily due to accelerated deforestation and LULC change, would reduce erosion mitigation and crop pollination ES by US$17.4 billion by 2050.

The effective implementation of the policies to mitigate and adapt to climate change and arrest environmental degradation would contribute to reducing future economic, environmental and social impacts. In interpreting the results, it is important to note that we did not consider all possible measures for arresting environmental degradation and mitigating and adapting to climate change; instead, we focus on some of the specific measures that are being considered by the Thai Government. As such, there is no a priori expectation that the measures considered would completely offset the environmental degradation observed in the DEGRADE scenario. Indeed, the results of the analysis show that while the strategies considered go a long way to mitigate impacts of environmental degradation, they are insufficient to entirely offset economic, environmental and social losses.

Beginning with ES impacts, Provisioning ES would be reduced to 39 % of the losses that would be experienced without policy intervention. In the case of Cultural and recreational ES, losses would be reduced by 29 %. With the elimination of deforestation combined with afforestation

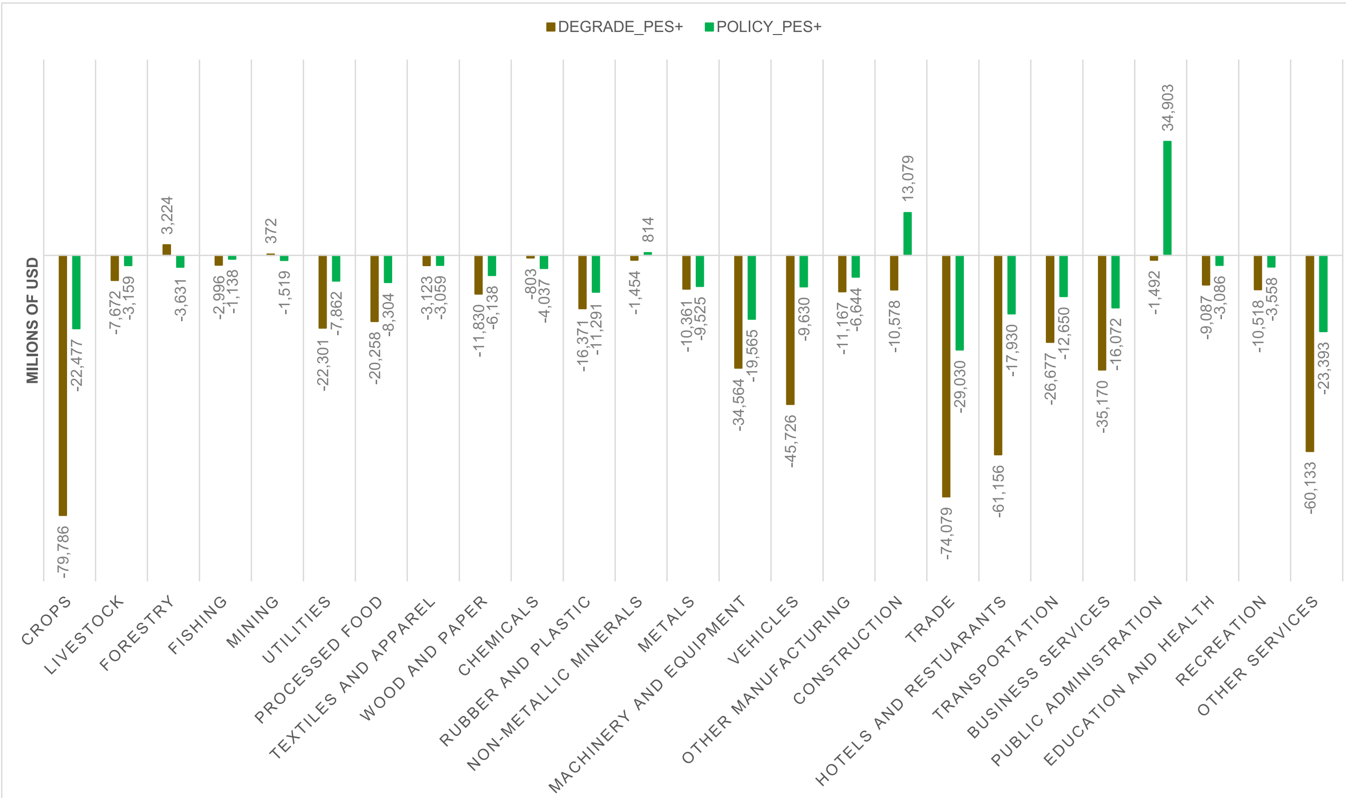

Fig. 7. Value added impacts of DEGRADE and POLICY scenarios in millions of USD. Source: IEEM+ESM results.

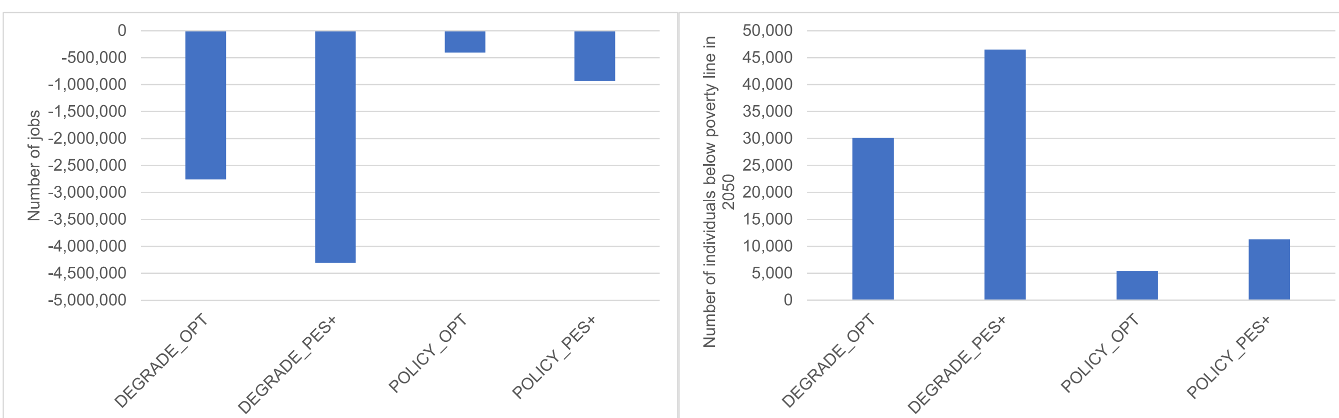

Fig. 8. Scenario impacts on employment as a difference from BASE in 2050. (Source: IEEM+ESM results. Note: scenario names that terminate in OPT use the RCP4.5 pathway while those that terminate in PES use the RCP8.5 pathway projection.)

and forest restoration, the standing forest stock would increase with respect to the business-as-usual case. This implies: increased carbon storage for climate change mitigation; increased erosion mitigation and crop pollination ES, which would positively impact agricultural productivity and potentially lower the need for the application of fertilizers; enhanced water regulation ES resulting in more water retained in forests, reduced quick flow and reduced flood hazard risks and damage which would save lives and generate positive economic co-benefits and; improved water purification services which could be further enhanced through reduced fertilizer use as a result of increased erosion mitigation ES.

While overall, ES flows would increase relative to the baseline because of the policies considered, the results presented demonstrate that the pattern of ES impacts would be spatially heterogenous across Thailand with the greatest benefits perceived in the north, south and west of the country. These regions are the country's most forested and thus are also the regions that would experience the greatest loss of ES should environmental degradation continue unabated.

With regards to water regulation services, the siting of new forested areas should be considered in conjunction with impacts on water regulation ES to ensure sufficient stream flow for hydropower generation and navigation in some cases. Future consideration of stream flow is critical since increasing Thailand's hydropower capacity forms part of its strategy for reducing emissions. Also important in determining where to establish new forests is consideration of competition for land from other uses, particularly for establishing new solar farms. With the tools developed in this study, ES could be spatially targeted across the landscape to maximize future ES flows while accommodating other land uses subject to biophysical and socioeconomic opportunities and constraints (Blackman et al., 2019; Crossman et al., 2013; Guo et al., 2020; Mokondoko et al., 2018; Ribeiro de Souza et al., 2021).

Where climate regulation ES are concerned, the portfolio of policies would result in a net 189-million-ton increase in CO_2 storage. Afforestation and forest restoration activities which are components of the POLICY scenario would result in the storage of an additional 1913 million tons of CO_2. If one were to assume a US$20 per ton damage cost of carbon following World Bank (2021) and the World Bank Flagship reports "Changing Wealth of Nations", the portfolio of policies would generate additional carbon storage that would be worth over US$42 billion.

A preliminary coastal vulnerability analysis was conducted, demonstrating that Thailand's eastern coastline and gulf region east of Bangkok has the highest levels of exposure to natural hazard risk. Bangkok is situated less than 2 m above sea level and rests on what was once marshland. These features along with high-rise development and unsustainable groundwater usage has Bangkok slowly sinking below sea level. Without preventative measures, it has been projected that Bangkok could become submerged by 2050 or sooner (Kulp and Strauss, 2019), displacing over 12 million people many of which are already living in poverty (World Bank, 2024b).

Future analysis with IEEM+ESM could explore scenarios designed to protect and enhance the resilience of coastal areas and reduce vulnerability around Bangkok and in other vulnerable regions of the Thai coastline. Policy measures could include the planting of mangroves and seagrasses and coral reef restoration among other nature-based solutions. These measures could be evaluated in a benefit-cost framework to assess benefits and trade-offs compared with conventional investments in coastal protection. This information could be used to develop a business case for investment and design the appropriate combination of nature-based and conventional interventions as well as inform the targeting of these interventions to maximize returns. There are clear linkages between tourism demand and the health of coastal ecosystems which could be included in this analysis.

The overall economic impact of continued environmental degradation would result in cumulative GDP losses of about US$553 billion by 2050 which is about US$5 billion greater than Thailand's GDP in 2019. This loss represents the cumulative effect of unabated deforestation along with the climate change impacts embodied in the DEGRADE scenario. The GDP loss is driven primarily by changes in factor productivity and investment. Focusing on the scenario of continued environmental degradation and climate change (DEGRADE) with respect to the BASE: (i) agricultural total factor productivity is adversely affected by climate change, specifically through temperature and precipitation effects as well as some loss of agricultural land due to sea level rise; (ii) agricultural as well as construction sector labor productivity is reduced due to climate change impacts; (iii) increased coastal and inland flooding due to climate change reduces the stock of capital.

These climate change impacts affect economic sectors in various ways, primarily: (i) Agricultural sector output declines due to the impacts noted above; (ii) Processed food activity as well as the Hotel and restaurant sector activity decline due to the input-output relationships with the agricultural sector; (iii) the Machinery and equipment and Vehicle sectors are closely linked to investment and the Construction sector. Again, input-output relationships are important as the Construction sector contracts due to climate change impacts on labor productivity. Finally, the Transport and Commerce sectors are closely linked to the overall level of economic activity. With climate change slowing economic growth, these sectors would also suffer contraction.

Other macroeconomic indicators including private consumption, investment, exports and imports would be negatively impacted. With the portfolio of policy measures considered to arrest environmental degradation and mitigate climate change impacts, GDP losses would be reduced to 32 % (US$174.9 billion) of what they would be without policy intervention. Wealth impacts on the other hand would be reversed and Thailand would experience a net gain in cumulative wealth by 2050 on the order of US$54.5 billion.

Fig. 7 elucidates the degree to which the policy interventions would offset the negative impacts of continued environmental degradation and climate change on a sector-by-sector basis. In most cases, negative impacts would be offset by more than half. Negative impacts on the Construction and Public Administration sectors would be reversed, showing growth. This is explained by the stimulus the policy interventions would create in terms of new infrastructure and thus Construction-sector expansion as well as the implementation of the overall investment package by the government, in other words, the Public Administration sector in this context.

Continued environmental degradation and climate change would result in about 4.3 million less jobs and poverty would increase by 46,520 individuals by 2050. The policy measures considered would mitigate an important share of these losses though not completely offset them with 931,188 less jobs and 11,283 more poor by 2050. Finally, the return on the investment of the portfolio of policies would be a negative return of US$8365 million with a 10 % discount rate. Additional policy measures to arrest environmental degradation and mitigate climate change impacts beyond those considered in this study could tip the balance in favor of a positive return. Consideration of additional ES including the value of carbon storage and air quality regulation ES as well as health and quality of life impacts of enhanced environmental conditions would contribute positively to the returns on investment.

One counterintuitive result compared with other studies (Banerjee et al., 2021; Banerjee et al., 2022a; Banerjee et al., 2023a) is that the elimination of deforestation would boost GDP growth in the medium term. This result is counterintuitive since deforestation is linked with the supply of future agricultural land and thus its elimination would restrict future supply. In the case of Thailand, this finding is explained by the fact that the elimination of deforestation causes a reallocation of labor to higher yielding activities thus more than offsetting any negative impact caused by a reduction in future agricultural land supply.

The main limitation of this study relates to the policy scenarios considered. While Thailand has the broad brushstrokes of strategies to reduce environmental degradation and adapt to and mitigate climate change impacts, including its National Strategy and updated NDCs (Kingdom of Cambodia, 2020; Kingdom of Thailand, 2019), the country lacks operational plans for the implementation of these strategies. Specifically, there are very few details of these strategies published and a complete absence of cost estimates even at the aggregate level at which they are presented. As a result, the policy strategies considered in this study are inferred from broader strategic documents while cost estimates from other studies and from the literature were used. In addition, evidence on the effectiveness of policy measures in mitigating and adapting to climate change as well as mitigating damages is sorely lacking. This is a concern, however, that applies to many countries, not only Thailand.

As Thailand begins to carefully consider the social, environmental and economic impacts of environmental degradation, it will need to develop detailed operational plans for implementing climate change mitigation and adaptation strategies. The operationalization of these plans will require large amounts of public and private finance and government budgets will need to be adjusted accordingly. International funding is available through various mechanisms and studies such as this one can be used to present a business case for investing in specific measures for climate change mitigation and adaptation. Accessing those financing mechanisms, however, will require detailed budgets as well as robust evidence of the effectiveness of the proposed policies.

Thailand has lost 12 % of its tree cover since the year 2000. If deforestation continues unchecked, its forest area could be reduced to 5.43 million ha of its current extent (66 %). The most effective measure Thailand can take to reduce barriers to reaching high-income status and reduce future loss of ES flows including climate regulation is to eliminate deforestation and to do it quickly. Furthermore, reforestation and forest restoration are relatively low-cost measures that have demonstrated effectiveness for enhancing ES flows; the science is unambiguous on this question. The effect of forests on water regulation ES are particularly important for a country like Thailand that is subject to severe and catastrophic flooding.

Of all the climate change impacts considered, Thailand is most susceptible to the devastating impacts of inland and coastal flooding. With the intensity and frequency of catastrophic floods expected to increase with climate change, the country faces enormous future risks in the absence of policies that enhance the ES that regulate the impacts of flooding. Putting this in perspective, the catastrophic floods considered in this study were responsible for over 74 % of the total climate change-induced economic impacts.

With complex environmental thresholds, the interaction of specific variables, magnitudes and timing determines the outcomes and potential damage that may occur when they are approached. Even in the case of those thresholds that have been most studied in the literature, for example, environmental thresholds in the Amazon basin (Banerjee et al., 2022b; Lovejoy and Nobre, 2019; Nepstad et al., 2008), when these thresholds may be reached and its impacts remain largely unknown due to non-linearities in causes and effects. This holds true in the case of Thailand.

With the evidence presented in this study, what can be stated with confidence is that Thailand's current trajectory is severely degrading its natural capital base, compromising its resilience to environmental shocks and reducing the flow of critical ES, particularly those that reduce natural hazards and their impacts. The value of these ES in protecting Thailand's society and natural capital base is increasing as climate change advances. Fully accounting for these ES in economic decision-making using frameworks such as IEEM+ESM will improve public policy and investment decisions and will contribute to Thailand arresting environmental degradation and its consequences.

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, Methodology, Investigation, Formal analysis, Data curation. **Erica Cristine Honeck:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Rattanyu Dechjejaruwat:** Validation, Data curation. **Anil Markandya:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Hector Pollitt:** Investigation, Formal analysis, Data curation. **Mani S. Muthukumara:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.177386.

Data availability

Data will be made available on request.

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