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## Land use strategies for achieving Chile's nationally determined contributions

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## PAPER

# Land use strategies for achieving Chile's nationally determined contributions

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Supplementary material for this article is available [online](#)

## Abstract

Chile's Nationally determined contributions (NDCs) commit to carbon neutrality by 2050, with measures to reduce emissions and natural hazards while enhancing water security. The Forestry and Other Land Uses (FOLU) sectors are critical to Chile's goal of carbon neutrality, as they serve as a net carbon sink. In this paper, we conduct policy scenario analysis focusing on FOLU strategies for meeting the NDCs. We implement the Integrated Economic-Environmental Modeling framework linked with spatial Land Use-Land Cover and Ecosystem Services (ES) Modeling (IEEM + ESM) to assess impacts on economic, environmental and social indicators. Our results show that the implementation of Chile's FOLU strategies would reduce emissions, enhance wealth and economic growth and increase future flows of ES. Carbon dioxide emissions would be reduced (by 151 million tons by 2050) to levels that would be considerably better than current Government expectations. Gross Domestic Product and wealth would be bolstered by US\$16 065 million and US\$22 731 million, respectively. Water-related ES would improve including the quality of potable water, while more water would be maintained within forested ecosystems, thereby reducing the future risk of natural hazards such as landslides and floods. The FOLU strategies would create 72 800 new jobs and reduce poverty by 15 586 individuals. Analysis with IEEM + ESM demonstrates that reducing wildfire-driven forest loss would have outsized impacts and be the most effective and expedient way to contribute to meeting NDC targets. The IEEM + ESM approach is an example of an analytical framework that is meeting growing demand from Government institutions and multilateral development banks for understanding the effects and transition pathways of NDC strategies on economic, social and environmental outcomes.

## 1. Introduction

Chile's updated Nationally determined contributions (NDCs) and Framework Law on Climate Change are aligned with its international commitments under the Paris Agreement to limit global temperature rise to 1.5 degrees Celsius. The country has the unconditional goal of reducing emissions to 95 MtCO<sub>2</sub> by 2030,

representing a 30% reduction in its greenhouse gas emissions relative to baseline emissions in 2016, and of achieving carbon neutrality by 2050. Chile's energy sector, through the use of coal for electricity and diesel for transportation, was responsible for 78% of total emissions in 2016. Forestry and Other Land Uses (FOLU) sectors are the only sectors that have served as a carbon sink since data collection began in 1990 (Government of Chile 2020). In 2020, the FOLU sectors offset 53% of Chile's greenhouse gas emissions (Climate Watch 2023).

Climate change is expected to impact Chile through higher temperatures, especially in the more arid north and in its mountainous regions. Precipitation is projected to decrease, causing more severe and frequent droughts, especially between the Atacama and Los Lagos regions, which are Chile's most agriculturally productive and densely populated regions. Additional climate change impacts include increasing frequency and intensity of extreme events such as floods, mass erosion, forest fires, storm surge and ocean acidification (Government of Chile 2020). Less precipitation also translates into reduced snowpack in mountainous regions with important cumulative effects on stream flow and water availability for consumptive and environmental uses (Vicuña *et al* 2011, Alvarez-Garreton *et al* 2021, Salazar *et al* 2024).

The National Strategy for Climate Change is Chile's main policy instrument focused on addressing climate change, desertification, drought and land degradation through Land Use-Land Cover (LULC) management (MINAGRI 2017). The Strategy contributes to Chile's NDCs and includes measures to reduce deforestation and degradation while promoting sustainable management, afforestation and forest restoration. Chile has committed to the sustainable management and recovery of 200 000 hectares (ha) of native forest, which is expected to capture 0.9–1.2 MtCO<sub>2</sub> yr<sup>-1</sup> by 2030. In addition, Chile will afforest 200 000 ha of degraded land thereby sequestering approximately 3.0–3.4 MtCO<sub>2</sub> yr<sup>-1</sup> by 2030 (Government of Chile 2020, MINAGRI and MMA 2021). The policy scenarios examined in this paper are based on key interventions proposed in this National Strategy.

In considering FOLU strategies for meeting Chile's NDCs, historical land-use practices are relevant given their implications for biodiversity and ecosystem services (ES). Historically, where native forest clearing took place, the expansion of forest plantations led to net biodiversity losses with little change in above ground carbon storage (Heilmayr *et al* 2020). By 2020, Chile had 2.595 million ha of planted forest (Richter *et al* 2024). With large areas of degraded native forest, particularly in Chile's southern-central area, there are significant opportunities for forest restoration to enhance carbon storage and biodiversity while generating socioeconomic co-benefits (Donoso and Romero 2020). As demand for timber increases, Chile can continue to meet this demand from its planted forests while generating many co-benefits by planting mixed species stands to approximate the ecological functioning of native forests in addition to enhancing biodiversity and pest resilience (Gómez-González *et al* 2022).

In this paper, we investigate the economic, social and environmental impacts of implementing Chile's FOLU strategies for meeting its NDCs. To understand the full range of impacts of the proposed strategies, we apply the Integrated Economic-Environmental Modeling framework (IEEM; Banerjee *et al* 2016b, Banerjee *et al* 2019) for Chile linked with spatial LULC and ES modeling (IEEM + ESM; Banerjee *et al* 2022, 2024a). IEEM + ESM modeling infrastructure has been constructed for over 30 countries and is being applied around the world by a diverse set of user groups including multilateral development banks, government, the private sector and academia. An important feature of this methodology is its ability to reveal policy impacts on both market and non-market ES for which market prices do not exist, all in a manner consistent with a country's System of National Accounts (European Commission *et al* 2009), the internationally accepted framework for reporting economic output.

While there are no previous analyses that investigate Chile's NDCs in an integrated economic-environmental way, there are a handful of studies that evaluate the economic impacts of NDCs or apply ES modeling to investigate impacts of LULC management. With respect to economic impacts, O'Ryan *et al* (2023) assessed the potential contribution of a carbon tax to reaching the country's NDCs. Nasirov *et al* (2020) examined the macroeconomic effects of phasing out the use of coal to generate energy. Finally, O'Ryan *et al* (2020) examined different emissions baselines for the Chilean economy with and without structural change. With respect to ES analytics, Locher-Krause *et al* (2017) examined spatial and temporal changes in ES flows in four Chilean regions to generate insights into appropriate landscape management practices. Benra *et al* (2021) evaluated how well water regulation ES models compared with water monitoring records in numerous catchments in southern Chile.

This paper has the dual objective of contributing policy insights to an important area of discourse for the Chilean Government as well as to advancing integrated economic-environmental methods. On the policy front, the policy scenario analysis we conduct is based on key components of The National Strategy for Climate Change, focusing on FOLU sectors. Results of this analysis shed light on trade-offs, where they exist, between economic, social and environmental outcomes and can provide insights into the relative contribution and effectiveness of individual FOLU strategies that comprise the policy intervention.

Moreover, this policy analysis contributes to one of the charges of The Network for Greening the Financial System (NGFS), a network of Central Banks collaborating to create an enabling environment for low-carbon development, which is to identify interactions between national economies and changes in natural capital assets and future ES flows to reduce physical and transition risks (NGFS 2023).

Methodologically, the IEEM + ESM approach continues to evolve and in this paper, three notable advances are made. First, we integrate crop pollination in the dynamic, integrated framework where feedbacks between changes in ES flows and agent behavior are captured. Second, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) Seasonal water yield (SWY) model (Natural Capital Project 2023) is particularly data demanding, requiring datasets that are usually unavailable in many developing country contexts. To address this challenge, we develop a step-by-step approach to parameterizing the SWY model based on readily accessible global datasets and information. Third, we develop a new LULC change modeling tool which enables modeling of larger datasets, along with more rapid resolution and enhanced error detection compared with other available tools.

What follows is an overview of the IEEM + ESM approach and policy scenarios. Section 3 presents the results. Section 4 concludes the paper with a discussion of the results and policy insights offered through the application of integrated analytical approaches such as IEEM + ESM. This paper includes a detailed supplementary information (SI) component with the relevant sections of the SI referenced in the main text.

## 2. Methods and scenario overview

### 2.1. The IEEM and methods overview

In this study, we applied the dynamic IEEM + ESM approach to policy scenario impact analysis (see box 1; see SI1 for a detailed presentation of IEEM + ESM methods). IEEM is an economy-wide model where all economic sectors interact through supply and demand relationships and labor, capital and land factor constraints and endowments. IEEM is linked with spatial LULC and ES modeling (IEEM + ESM) and incorporates feedbacks between policy impacts on ES flows and the economy. Our approach is rigorous in maintaining consistency with a country's System of National Accounts, ensuring robustness of estimates and credibility with key decision makers within governments, including Ministries of Finance and Central Banks.

At the core of IEEM is a recursive dynamic Computable general equilibrium (CGE) model. The bridge between the aspatial CGE model and the spatial ES modeling is a LULC change model. We apply the IEEM-LULC model, which closely follows the theoretical underpinnings of the widely used Dynamic Conversion of Land Use and its Effects model (Verburg *et al* 1999, 2008, Verburg and Overmars 2009; see SI section 1 (section 2) for a detailed presentation of the IEEM-LULC model including a sample of geospatial driving factors for LULC change and LULC probability maps). The InVEST ES models (Natural Capital Project 2023) were used and parameterized with national data where available, specifically, the erosion mitigation, carbon storage, annual water yield, SWY, water purification and crop pollination models (see SI section 1, subsection 3, for an overview of the models used and SI section 2 for ES Model Parameters).

In our dynamic IEEM + ESM workflow, we account for how future changes in ES flows affect the economy. Focusing on erosion mitigation and crop pollination ES, this approach enables estimation of the marginal value of regulating ES, which generally do not have a market price. At the time of publication, the dynamic IEEM + ESM workflow is the only framework in the peer reviewed literature that integrates dynamic feedbacks between changes in ES and the economy in this way. Access to many of these models, data, manuals and capacity-building resources will be provided at [www.rmgeo.org](http://www.rmgeo.org) by mid-2025.

#### Box. 1. Overview of IEEM + ESM Methods.

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 is the database that underpins IEEM and is a statistical representation of all sectors and transactions in an economy as well as land-use dynamics for a specific base year (see SI section 3 for an overview of the Chilean economy from the perspective of IEEM's Social Accounting Matrix). 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 key FOLU strategies for meeting Chile's NDCs, including reducing forest loss to fire, afforestation and forest restoration.

Linked to IEEM is the IEEM-LULC change model. This model is parameterized with biophysical (climate, topography, soils) and socioeconomic (distance to markets, transportation infrastructure, population density) geospatial layers to estimate the probability of a specific LULC transition (e.g. from forest to cropland) 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. Forest lost due to fire generates cleared land where 17% of this area is converted to a productive use including commercial forest plantations, agriculture or urban development (Acuña 2023). The IEEM-LULC model is used to spatially attribute demand for land across the country. The InVEST ES models use the LULC maps generated by IEEM-LULC as inputs to calculate erosion mitigation, water regulation, SWY, water purification, crop pollination and carbon storage ES. ES model runs calculate changes in future ES flows for each policy scenario with respect to the business-as-usual scenario. For erosion mitigation and crop pollination, 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.

## 2.2. The IEEM-LULC model

LULC change modeling is the necessary bridge between IEEM and spatial ES modeling. IEEM-LULC is used to spatially allocate IEEM-projected LULC change across a grid for the baseline and scenarios using empirical relationships between land use and location-specific driving factors. In IEEM-LULC, driving factors are responsible for the distribution of LULC across the landscape. In this application, 15 drivers were used and comprised of climate, topographic, edaphic and socioeconomic variables. To allocate LULC for each grid cell, IEEM-LULC calculates probability maps for each land use type, which reflect the probability of each land use class occurring at each grid cell. This suitability analysis is performed as a binomial logit step-wise regression for each land use and set of explanatory variables (Verburg *et al* 2021). SI section 1 (section 2) provides additional details of IEEM-LULC, the driving factors and the allocation algorithm.

## 2.3. Crop pollination in the dynamic IEEM + ESM approach

We implement the InVEST crop pollination model (Natural Capital Project 2023) and use the results to create a linkage between changes in this ES and economic outcomes in IEEM. Changes in pollinator abundance can affect crop yields depending on a given crop's dependence on pollination by insects. The dependence of specific agricultural crops and the crop yield impacts related to the presence or absence of pollinators was based on a seminal paper by Klein *et al* (2007). Our analysis focuses on Chilean regions that produce the greatest share of pollinator dependent crops and thus while we exclude Chile's 4 northernmost and 2 southernmost regions (see figure 3 (right) for a map of Chile's 16 regions), we capture more than 97% of Chile's pollination-dependent crop output.

We develop an economic shock to describe the relationship between crop pollinator abundance and crop yield as described in equation (1).

$$CPC_r = D_r \cdot (A_r \cdot Y_{r,vh} \cdot V_{r,vh} \cdot W_{r,vh} + A_r \cdot Y_{r,h} \cdot V_{r,h} \cdot W_{r,h} + A_r \cdot Y_{r,m} \cdot V_{r,m} \cdot W_{r,m} + A_r \cdot Y_{r,l} \cdot V_{r,l} \cdot W_{r,l}). \quad (1)$$

Where:

- $CPC_r$  is the crop productivity impact for subscript region  $r$  of Chile;
- $D_r$  is a pollinator adjustment factor representing current pollinator abundance relative to full potential abundance;
- $A_r$  is pollinator abundance in subscript region  $r$  of Chile;
- $Y_{r,vh}$  is the yield impact in region  $r$  for very highly pollinator dependent crops (subscript vh);
- $V_{r,vh}$  is the value of crop output in region  $r$  for very highly pollinator dependent crops (subscript vh);
- $W_{r,vh}$  is the weight of the value of very highly pollinator dependent crops (subscript vh) in Chile's total crop output value and;
- Subscripts  $h$ ,  $m$  and  $l$  refer to high, medium and low dependent pollinator crops (see Klein *et al* 2007 and SI table 3).

Pollinator abundance is calculated with the InVEST crop pollination model using the BASE and FOLU scenario maps generated with IEEM-LULC. The pollinator adjustment factor, accounting for pollinator decline driven by pesticide use, climate change, drought and other factors, was conservatively estimated based on the literature (Goulson *et al* 2015, Chaudhary and Chand 2017, Sponsler *et al* 2019, Pérez-Méndez *et al* 2020). Yield impacts are derived from Klein *et al* (2007) and mapped to Chile's crop output from FAOSTAT crop data and the IEEM database. FAOSTAT crop data (FAO 2025) is used for its greater level of

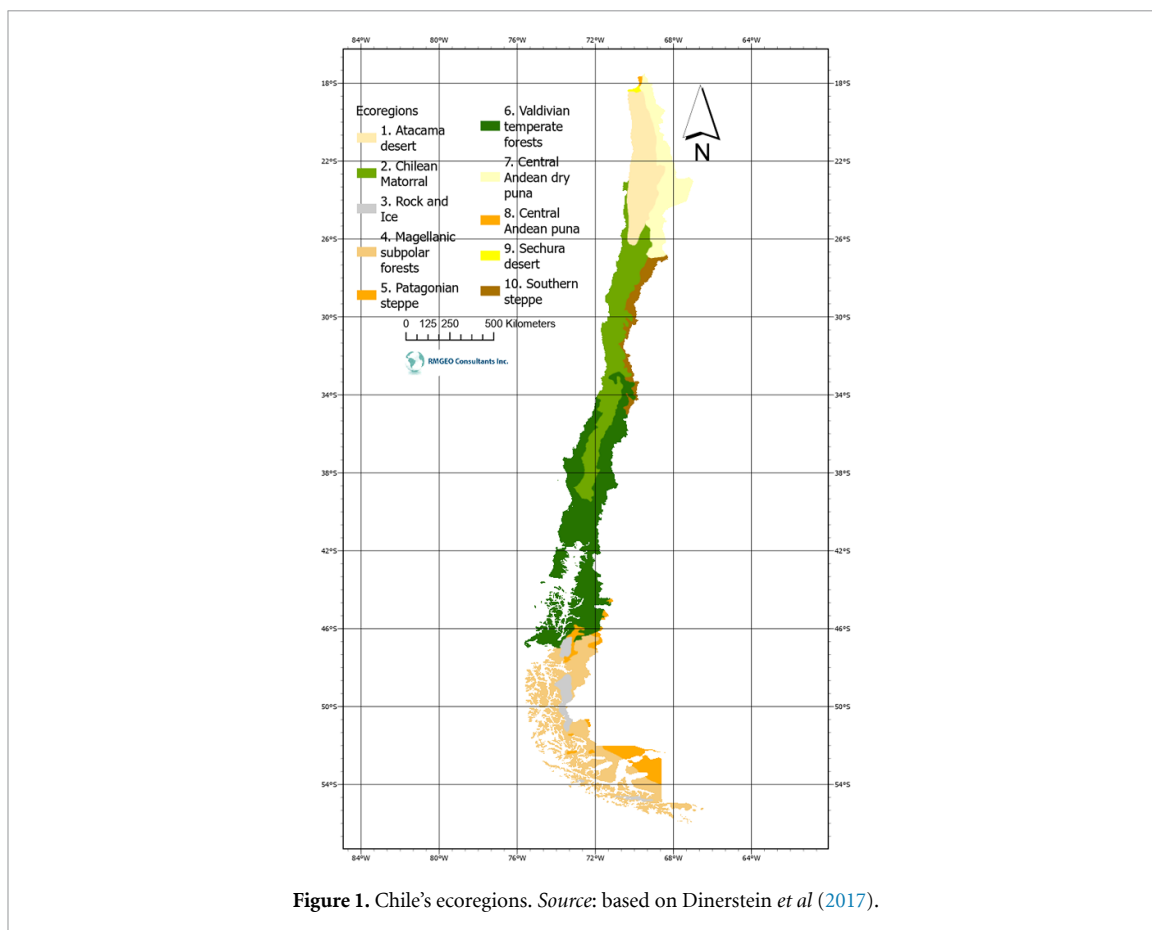


Figure 1. Chile's ecoregions. Source: based on Dinerstein *et al* (2017).

disaggregation with respect to crop type. The crop output value and weights are calculated from FAOSTAT data.

The crop productivity ( $CPC_r$ ) shock is implemented in IEEM in the dynamic IEEM + ESM workflow where all three models (IEEM, IEEM-LULC and the InVEST crop pollination model) are run iteratively in 5 year time steps. In this way, changes in crop pollination ES are transmitted to the national economy through crop productivity channels (see SI 1 sections 4 and 6 for additional details). These changes in productivity affect producer decisions which are captured in subsequent time periods ( $t + 5$ ) over which IEEM + ESM is implemented.

#### 2.4. Parameterization of the InVEST SWY model

The InVEST SWY model generates information on seasonal water flow, specifically, the monthly partitioning of quickflow (flow that occurs during or shortly after rainfall events) and baseflow (flow maintained by groundwater discharge) which can be important for managing water resources and reducing natural hazard risks (Natural Capital Project 2023). The approach we develop in this paper to parameterize the SWY model uses openly accessible global databases and accounts for regional variation in the number of rain events and ecological considerations in the estimation of crop evapotranspiration coefficients (i.e. Kc values). Given the complexity of the data processing and parameterization process, only a brief overview of the approach is provided here while SI section 2, subsection 5, presents all relevant details of data processing, model inputs and the parametrization algorithm.

Key data inputs into the SWY model that require processing are: (i) a climate zone table indicating rain events by month for each of the country's climatic zones; (ii) Kc values for each LULC class and month and; (iii) Curve number values for each combination of soil group and LULC class. These inputs are discussed in turn. To generate a climate zone table, we obtained data from the Global Historical Climatology Network daily; Menne *et al* 2012), which is a database of daily climate summaries from land surface stations globally. To estimate rain events by climate zone, we rely on the ecoregions defined by Dinerstein *et al* (2017; figure 1) and intersect these two data layers.

To estimate Kc values for each LULC class, we rely on the multivariate linear regression models developed in Liu *et al* (2017). The authors estimated models to calculate monthly Kc values for seven broad land cover types—shrubland, cropland, grassland, deciduous broad leaf forest, evergreen needle leaf forest, evergreen

broad leaf forest and mixed forest across 81 sites globally. The independent variables used in the estimation are (i) monthly average Leaf Area Index (LAI); (ii) monthly average precipitation and; (iii) median latitude. Some data processing is required to prepare each of these input datasets for the independent variables used in the estimation.

For the first, we use the spatial LAI dataset from Liu *et al* (2012), which provides a consistent global LAI product calculated from 1981 to 2011 through quantitative fusion of Moderate Resolution Imaging Spectroradiometer and historical Advanced Very High-Resolution Radiometer data with an 8 km resolution. With some pre-processing, we extracted monthly LAI for each ecoregion. For (ii), we extracted monthly precipitation by ecoregion from WorldClim data (Fick and Hijmans 2017). Finally, for (iii), we estimated the absolute value of mean latitude for each ecoregion using ArcGIS Pro (Version 3.4.3).

In implementing the Liu *et al* (2017) regressions, we associated our LULC classes with the closest corresponding LULC class in Liu *et al* (2017). The regressions were run and a table was prepared with a Kc value for each LULC class and month. To complete the biophysical table required for SWY implementation, we sourced curve numbers for each LULC class from Zeng *et al* (2017) for different hydrological soil groups. In the final step prior to SWY Implementation, we generated a new LULC map, which includes all possible combinations of LULC classes and ecoregions.

## 2.5. Scenarios implemented in IEEM + ESM

We implement a business-as-usual baseline (BASE) and four scenarios in IEEM + ESM to simulate Chile's FOLU strategies for meeting its NDCs. For all scenarios, investment costs were assumed to be 50% financed by a non-reimbursable grant and 50% by a loan from a multilateral development bank with standard repayment terms.

**BASE:** This is the BASE scenario that is used as the counterfactual reference scenario to which all other scenarios are compared. It presents the future trajectory of the Chilean economy, projected until 2050, in the absence of any new large public policies and investments. The BASE projection of economic growth was provided by the Central Bank of Chile while population projections were derived from the United Nations' World Population Prospects (UN 2022). The BASE scenario includes a projection of forest cover loss which was extrapolated forward based on the historical trend between 2001 and 2013 (Hansen *et al* 2013, Harris *et al* 2021). Forest cover loss in Chile is primarily due to wildfires and other secondary drivers. In general, the areas where forests are lost to fire are converted to commercial forest plantations (17%) and unproductive cleared land (83%; Acuña 2023).

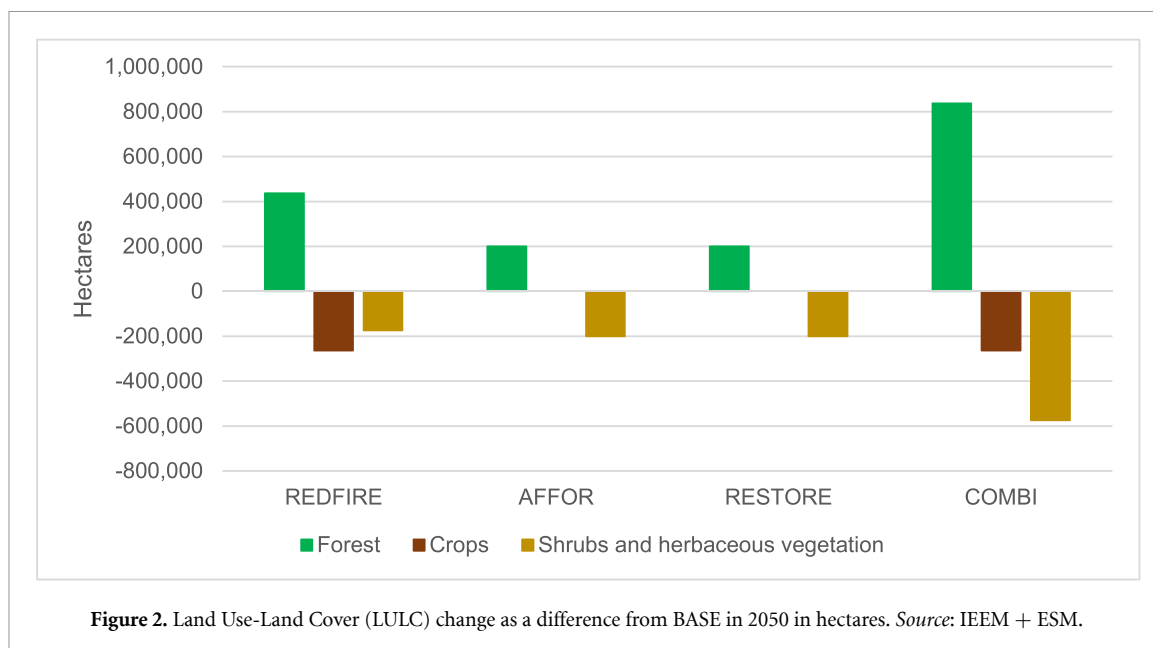
**REDFIRE:** This scenario simulates the Government of Chile's commitment to reduce forest cover loss by 25% by 2030 with respect to the BASE (Government of Chile 2020)<sup>9</sup>. The rate of forest cover loss is reduced linearly beginning in 2023 until reaching a 25% reduction in 2030, which is maintained until 2050. This implies reducing the average rate of forest cover loss of 0.70% (the calculated rate of forest cover loss between 2001 and 2013) to 0.53%<sup>10</sup>. The total and per hectare cost of implementation of REDFIRE measures is US\$3831 798 596 and US\$539.70 (2022 prices), respectively (Consultant for the World Bank 2022).

The cost of reducing forest cover loss from fire is distributed equally from 2023 to 2050 under the assumption that maintaining and enforcing policies to reduce wildfires requires recurrent expenditure. Reducing forest cover loss to fire is achieved through: (i) expanding the network of well-trained and equipped fire brigades to suppress accidental wildfires; (ii) developing climate-smart, fire-free land management systems to minimize fire ignition sources; (iii) implementing command-and-control enforcement to stop deforestation and prevent wildfires from escaping; (iv) improving fire early warning systems to help guide prevention and suppression efforts, and efficiently allocating resources months before the fire season starts and; (v) investing in fire prevention to protect vulnerable areas through fire breaks, implementing controlled burns to reduce fuel loads and coordinating with local communities.

**AFFOR:** This scenario simulates the Government of Chile's commitment to establish 200 000 ha of forest plantations in unproductive land (Government of Chile 2020). Afforestation will commence in 2023 with the

<sup>9</sup> In order to fulfill this broader commitment to reducing forest loss from all drivers of deforestation and degradation, the following actions proposed in the National Strategy on Climate Change were considered: (i) strengthen management models in forest wildfire prevention and restoration of burned areas; (ii) strengthen sustainable management models on the use of natural resources; (iii) apply management models to reconcile livestock with conservation forest; (iv) strengthen phytosanitary protection of native plant resources; (v) adapt land use management practices to climate change, desertification, land degradation and drought; (vi) implement regulatory adjustment and agricultural development compatible with existing vegetation and; (vi) support the forestry sector (Government of Chile 2020).

<sup>10</sup> The expenditure on reducing forest cover loss is modeled as a 90% recurrent government expenditure and 10% government investment. The increase in government recurrent spending is allocated to the 'Other Services' sector instead of Public Administration because the production of Other Services is less intensive in the use of skilled labor compared with the Public Administration sector.



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 25 years of age after which no additional carbon would be stored. Fifty percent of the new forest plantations will be sustainably managed for the production of forest products, both timber and non-timber, and will begin to generate economic value 12 years after establishment. The cost of afforestation was estimated based on Cardenas Moll (2016). The total and per hectare cost of implementation of AFFOR measures is US\$309 904 471 and US\$1,549.50, respectively, and is consistent with the costs reported in CONAF (2011).

**RESTORE:** This scenario simulates the restoration of 200 000 ha of degraded and unproductive areas by 2030 (Government of Chile 2020). Forest restoration will commence in 2023, restoring 12.5% of this area per year and concluding in 2030. The trees planted are assumed to reach maturity at 30 years of age after which no additional carbon would be stored. One hundred percent of the new forest plantations will be sustainably managed for the production of forest products, both timber and non-timber and will generate economic value beginning 12 years after establishment. The cost of restoration was estimated at 50% of the cost of afforestation and thus the total and per hectare cost of implementation is US\$154 952 235 and US\$774.80, respectively.

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

### 3. IEEM results

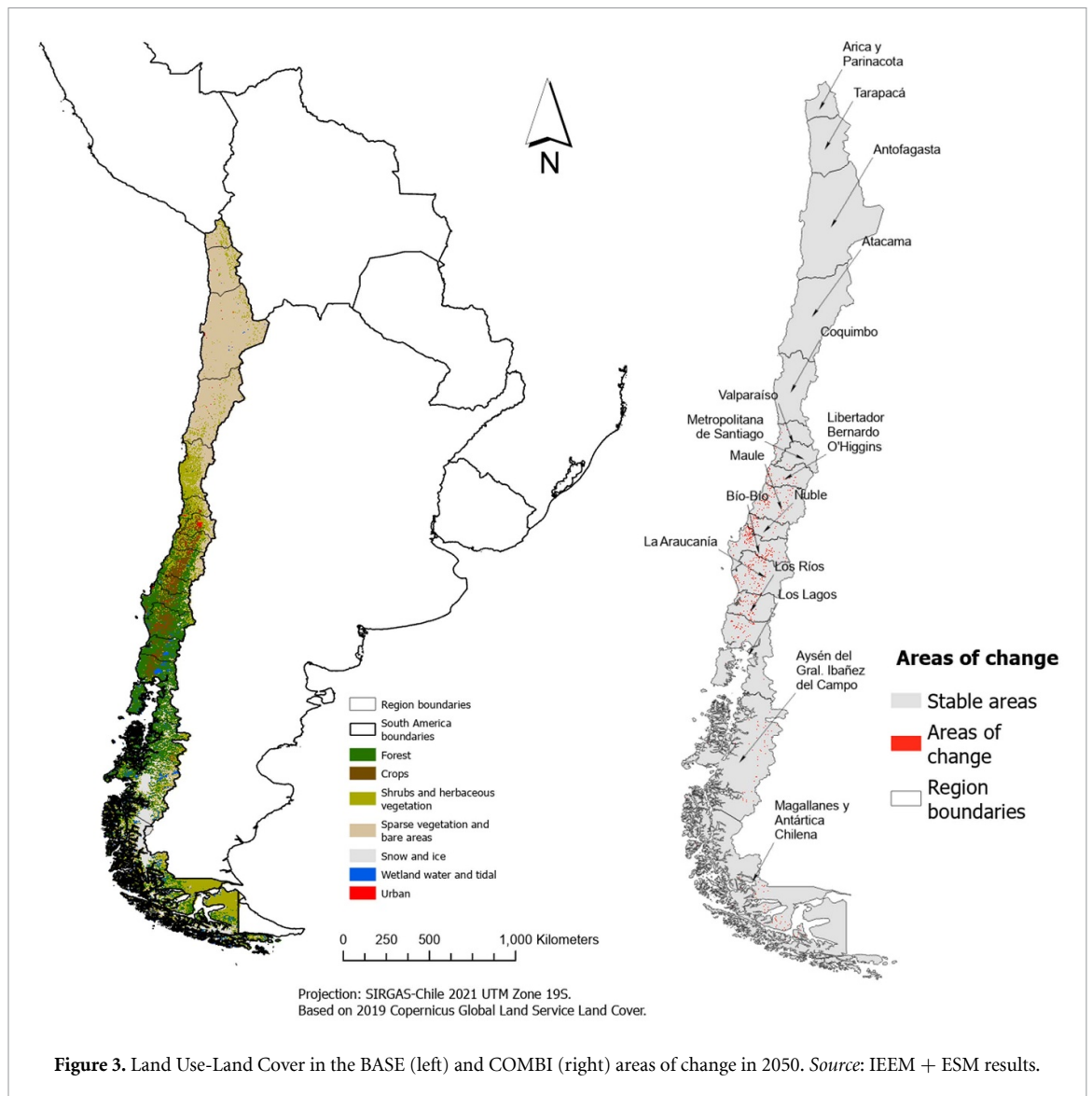
#### 3.1. LULC change impacts

By 2050, REDFIRE would maintain 436 595 ha more forest compared with the BASE (business-as-usual) projection. COMBI, which includes afforestation and forest restoration activities, would result in 836 595 ha more forest as compared to the BASE (figure 2).

Figure 3 presents LULC in the BASE (left) and stable areas and areas of change in COMBI as a difference from BASE in 2050 (right). In COMBI, much of the LULC change occurs in the mid-section of the country, in Región de los Lagos, Región de los Ríos, Región de la Araucanía, Región del Bío-Bío, Región de Nuble, Región del Maule and Región del Libertador Bernardo O'Higgins.

#### 3.2. Ecosystem service impacts

What follows are the estimated ES impacts focusing on the COMBI scenario, presenting results as a percent difference from BASE in 2050 (SI section 4 presents ES modeling results in biophysical units in tabular format). From left to right, figure 4 presents scenario impacts on carbon storage, erosion mitigation and crop pollination ES. At the national level, the COMBI scenario would store an additional 59 million tons of carbon, 3.6% above baseline levels in 2050. The greatest increases in carbon storage would occur in Región del Libertador Bernardo O'Higgins (14%), Región del Maule (9.6%), Región del Bío-Bío (9.5%) and Region



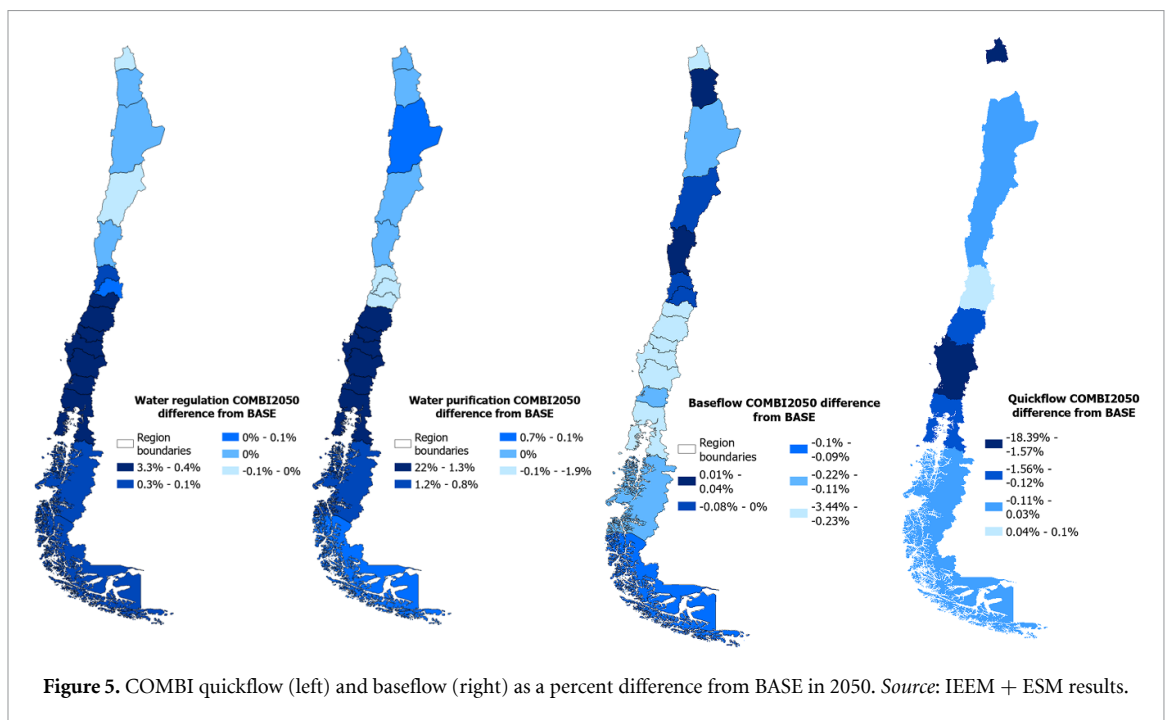
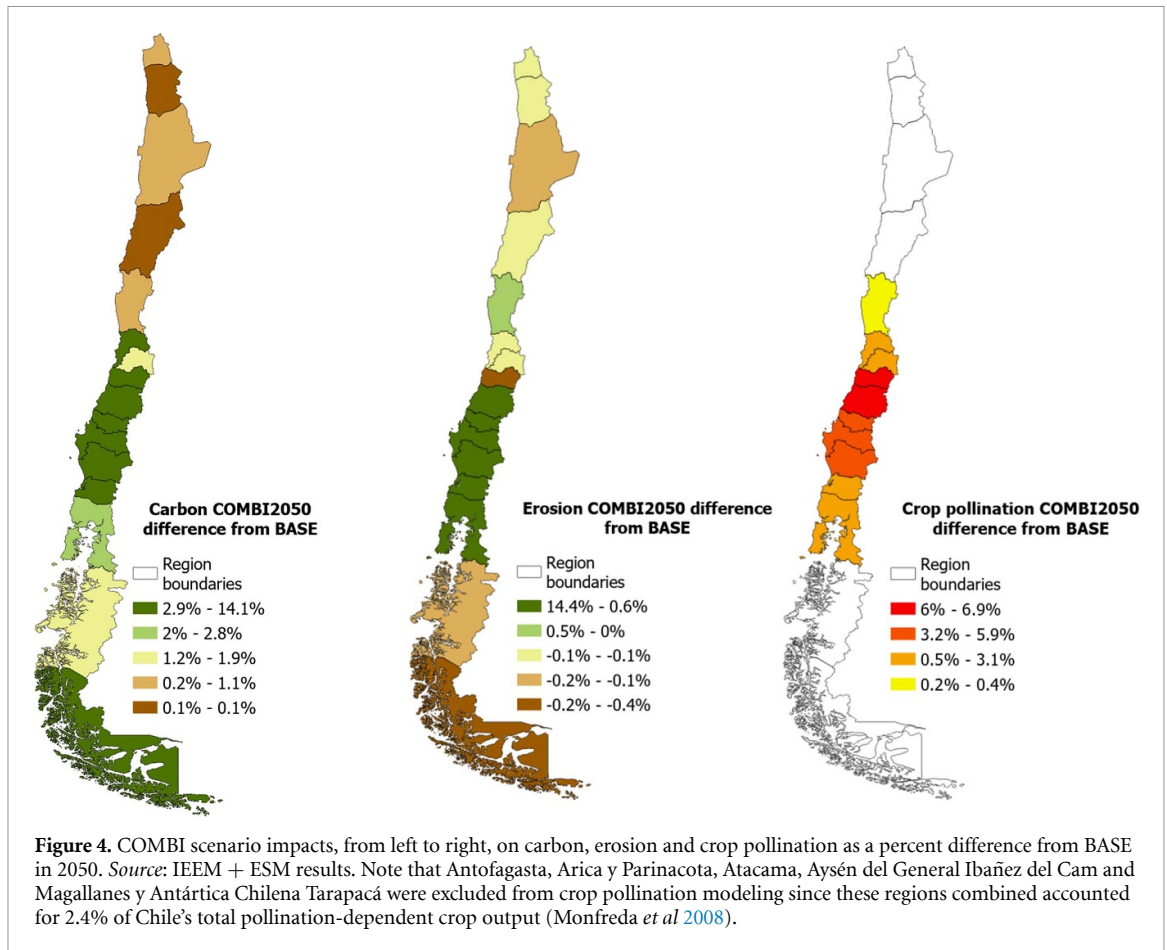
de Ñuble (7.9%). The regions least impacted would be those in the north of the country (Regiones de Atacama, Tarapacá, Antofagasta and Arica y Parinacota).

At the national level, COMBI would reduce soil loss by 10 million tons (0.3%) compared to the BASE in 2050. Erosion mitigation ES would increase the most in the Región de Los Ríos (14.5%), Región de La Araucanía (8.7%) and Región del Bío-Bío (7.7%). Erosion mitigation ES would be least affected in Región del Libertador Bernardo O'Higgins (0.4%), Región de Magallanes y Antártica Chilena (0.3%), Región de Aysén del Gral. Ibañez del Campo (0.1%) and Región de Antofagasta (0.1%).

At the national level, COMBI would enhance pollinator abundance by 3.4% by 2050 compared with the BASE. Pollinator abundance would increase the most in Región del Libertador Bernardo O'Higgins (6.9%), Región del Maule (6.4%), Región del Bío-Bío (5.9%) and Región de Ñuble (4.7%). Smaller increases would be found in Región Metropolitana de Santiago (0.4%) and Región de Coquimbo (0.1%).

Figure 5, from left to right, presents water regulation and water purification ES as well as baseflow and quickflow for the COMBI scenario in 2050 as a percent difference from BASE. At the national level, COMBI would improve water regulation by 0.5% compared to the BASE in 2050. Water regulation ES would improve the most in Región del Maule (3.4%), Región del Bío-Bío (3.4%), Región del Libertador Bernardo O'Higgins (2.8%) and Región de Ñuble (2.4%). Water regulation would be almost unaffected in Región de Tarapacá, Región de Arica y Parinacota and Región de Atacama.

At the national level, COMBI would improve water purification ES by 9.2% compared to the BASE in 2050. Water purification dynamics would improve the most in Región de Los Ríos (22.1%), Región del Bío-Bío (14.3%), Región de Los Lagos (14.0%) and Región de La Araucanía (11.9%). Small negative impacts would be found in Región Metropolitana de Santiago (−0.7%), Región del Libertador Bernardo O'Higgins (−1.8%) and Región de Valparaíso (−1.9%).



With regard to baseflow and quickflow, results show that in general, both would tend to decline where afforestation and forest restoration activities occur. Baseflow would decline the most in Región del Maule (−3.4%), región del Bío-Bío (−2.8%), región del Libertador Bernardo O’Higgins (−2.7%) and Región de Ñuble (−2.7%). Quickflow would decline the most in Región de Los Ríos (−2.4%), región del Bío-Bío (−2.1%) and Región de La Araucanía (−1.6%).

**Table 1.** Contribution of ecosystem services (ES) to the economy as a cumulative difference from BASE in 2050 in millions of USD (December 2022 USD).

ES Section	ES Class	Scenario			Code		
		REDFIRE	AFFOR	RESTORE	COMBI	CICES	IPBES
Provisioning ecosystem services							
	Food (plant-based)	676	176	125	1,817	1.1.1.1	12
	Meat (excluding fish)	-10	4	2	-3	1.1.3.1	12
	Fish	-21	2	0	-16	1.1.4.1	12
	Timber and non-timber	1,369	311	232	1,648	1.1.1.2, 1.1.5.1, 1.1.5.2	12, 13, 14
	Abiotic subsurface minerals	-504	45	6	-521	4.3.1.3	
	Abiotic subsurface non-mineral energy	13	7	4	28	4.3.2.2	
Cultural and recreational ecosystem services							
	Culture, recreation and tourism	122	49	27	239	3.1.1.1	6, 16
Regulating ecosystem services							
	Crop pollination				1,109	2.2.2.1	2
	Erosion mitigation				656	2.2.1.1, 2.2.1.2	9

Source: IEEM + ESM results. The CICES column refers to the CICES and the IPBES column refers to The IPBES classification.

The contribution of ES to the economy is shown in table 1 along with their corresponding Common International Classification of Ecosystem Services (CICES) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) reference classification codes (Díaz *et al* 2015, European Environment Agency 2018). Focusing on the results from COMBI, food provisioning ES would increase by US\$1,817 million. Timber and non-timber provisioning ES would increase by US\$1,648 million. Cultural and recreational ES would increase by US\$239 million. Regulating ES would make an important contribution to economic outcomes, with a US\$1,109 million increase in crop pollination ES and a US\$656 million increase in erosion mitigation ES. The cumulative impact in 2050 for provisioning, cultural and recreational and regulating ES would be US\$2,954 million, US\$239 million and US\$1,765 million, respectively.

While not reported in this table, focusing on LULC change, the COMBI scenario would store an additional 215 million tons of CO<sub>2</sub> as compared to BASE in 2050. In the COMBI scenario, emissions from fossil fuel combustion would equate to a cumulative 63.5 million-ton increase over the BASE in 2050. The net effect would be a 151 million-ton reduction in CO<sub>2</sub> emissions by 2050.

### 3.3. Economic impacts

Table 2 presents scenario impacts on key macroeconomic indicators. To provide a frame of reference for the interpretation of these results, Chile's GDP in 2020 was US\$254 billion. The COMBI scenario would result in a US\$16 065 million impact on cumulative GDP by 2050 and a US\$22 731 million impact on cumulative wealth. The difference between COMBI and COMBI\* reveals the contribution of regulating ES (comprised of crop pollination and erosion mitigation ES, in this application) to each of these indicators, which would be non-trivial quantitatively. All scenarios would generate positive impacts with the REDFIRE scenario presenting the greatest benefits, enhancing cumulative GDP and wealth by US\$10 679 million and US\$19 113 million, respectively.

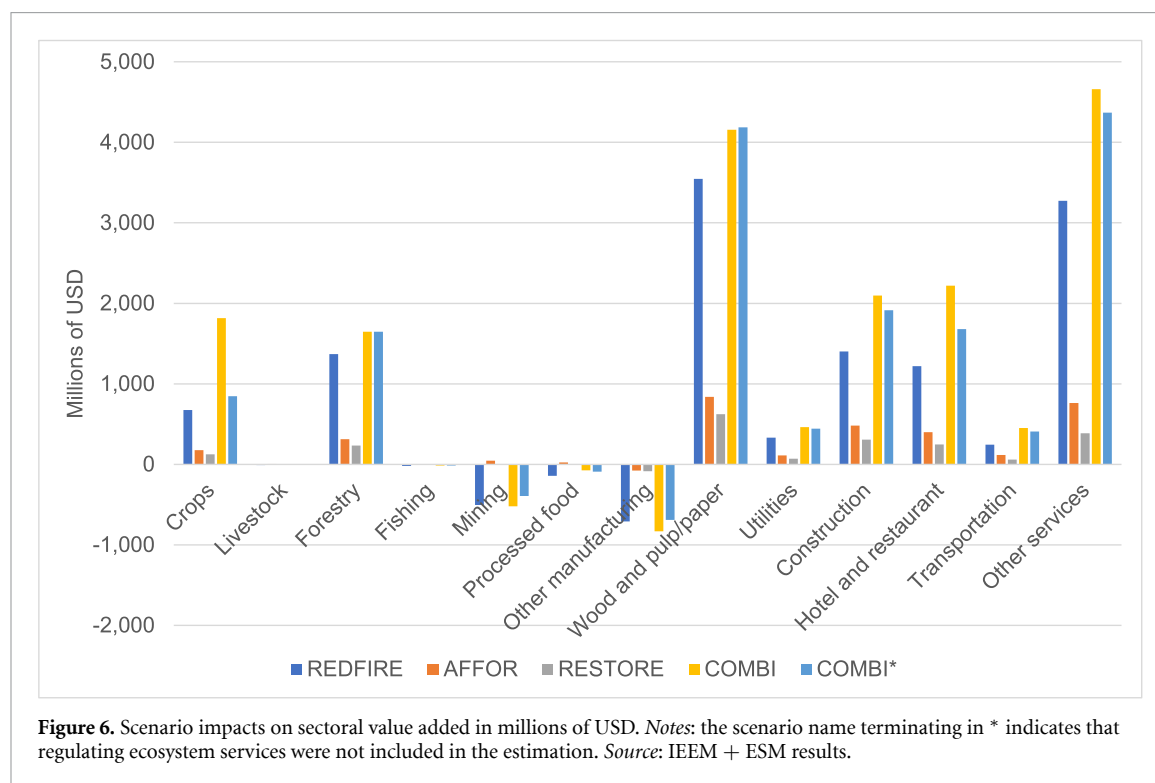
Figure 6 presents scenario impacts on sectoral value added. With the enhanced economic growth that the portfolio of policies would generate, impacts across most sectors would be positive, with the Wood and pulp and paper sectors as well as the Other services sectors having outsized gains (Other sectors includes trade which is where the gains are stemming from in this case). Those sectors showing a small contraction are those that lack strong linkages with sectors most affected by the policies implemented, as well as due to a reallocation of factors of production toward targeted sectors.

**Table 2.** Impacts on macroeconomic indicators as a difference from BASE in 2050 or cumulative impact as indicated in millions of USD (December 2022 USD).

	REDFIRE	AFFOR	RESTORE	COMBI	COMBI*
GDP	1,440	492	418	2,089	1,956
Cumulative GDP	10 679	3,196	1,978	16 065	14 302
Wealth	2,194	833	819	2,648	2,587
Cumulative wealth	19 113	5,246	3,840	22 731	22 015
Private consumption	862	322	271	1,299	1,199
Private investment	766	291	261	1,080	1,022
Exports	652	268	238	962	906
Imports	693	233	206	964	916

Notes: the scenario name terminating in \* indicates that regulating ES were not included in the estimation.

Source: IEEM + ESM results.



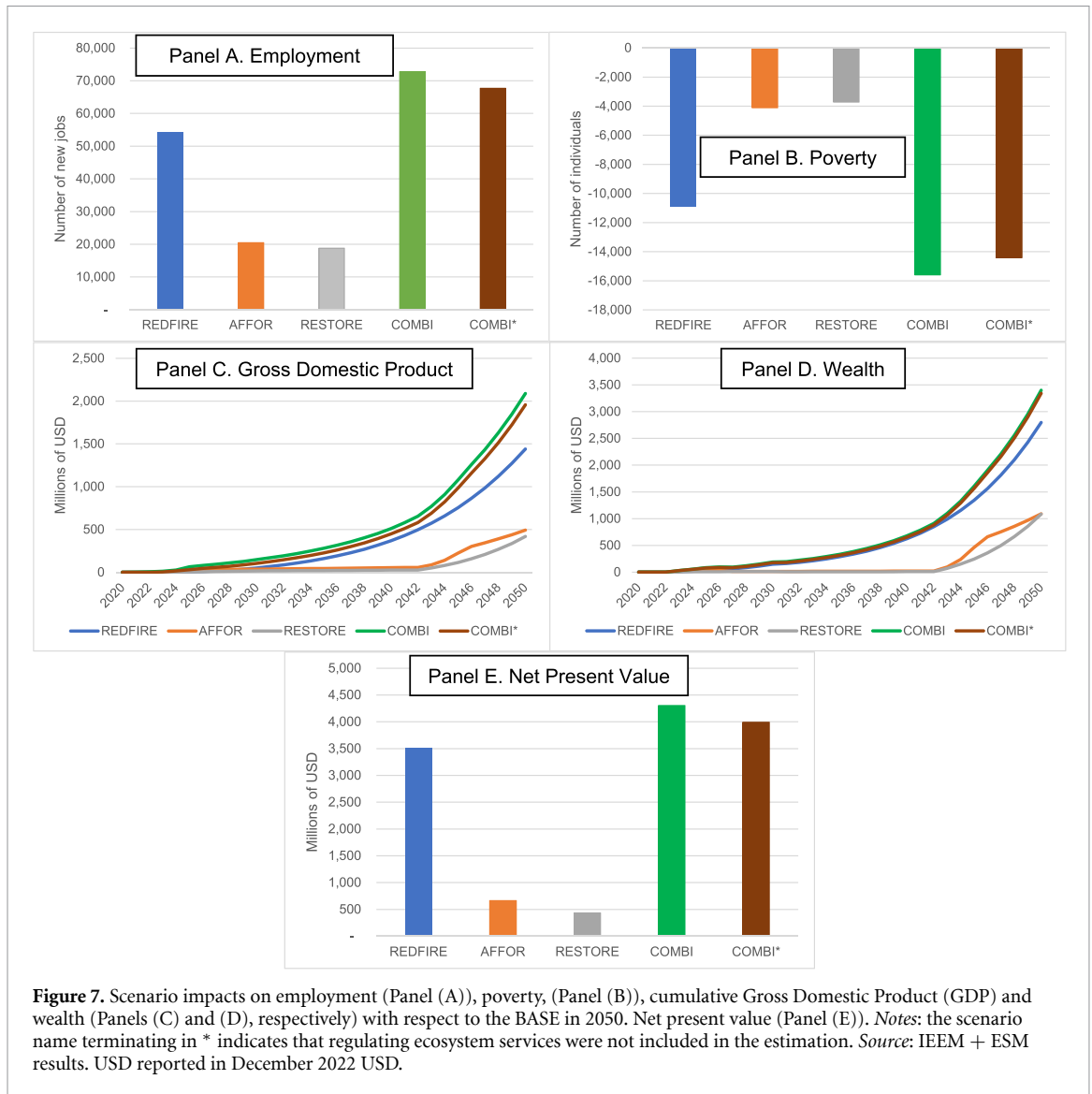
**Figure 6.** Scenario impacts on sectoral value added in millions of USD. Notes: the scenario name terminating in \* indicates that regulating ecosystem services were not included in the estimation. Source: IEEM + ESM results.

Figure 7 presents the scenario impacts on employment (Panel (A)), poverty, (Panel (B)), cumulative GDP and wealth (Panels (C) and (D), respectively) and Net Present Value (Panel (E)). All scenarios would create new jobs and reduce poverty. The COMBI scenario would result in an increase in employment of about 72 800 new jobs by 2050. The REDFIRE scenario on its own would generate an additional 54 170 new jobs. REDFIRE would reduce poverty by 10 881 individuals by 2050 while COMBI would reduce poverty by 15 586 individuals.

The Net Present Value of the investments was evaluated using a 10% opportunity cost of capital, similar to the rate used by some multilateral development banks (Banerjee *et al* 2016a); the temporal horizon for the analysis was until the year 2050. REDFIRE would present a strong return, valued at US\$3,505 million while the portfolio of FOLU strategies embodied by the COMBI scenario would generate US\$4,303 million in returns. The difference between COMBI\* and COMBI represents the contribution of ES to economic returns, equivalent to US\$247 million.

#### 4. Discussion and concluding remarks

This study evaluated the economic, social and environmental impacts of Chile's FOLU strategies to meet its NDC targets. Results were strongly positive across the indicators considered. Considering the portfolio of NDC strategies, erosion mitigation ES would be enhanced across most regions with an overall impact of 10 million tons less soil loss. Scenario-driven changes in ES flows are spatially heterogeneous, though in general, impacts would be greatest in Chile's forested regions, for example, the Valdivian Temperate Forests



ecoregion (figure 1). Less erosion would translate into greater soil fertility, less sedimentation of waterways and a more sustainable and resilient agricultural sector, contributing US\$656 million to GDP. Pollinator abundance would increase by 3.4% at the national level, valued at US\$1,109 million, contributing to increased agricultural output of pollinator-dependent crops as well as agricultural sector resilience.

Water regulating services would improve with policy implementation, thereby maintaining more water within forested ecosystems. Water purification services would be positively impacted, by 9.2% at the national level, which is an important outcome affecting the quality of surface water extracted for various consumptive purposes. Increasing the species diversity of the newly planted forests would further enhance water regulation services (Esquivel *et al* 2020). SWY modeling indicates that quickflow would be reduced, which can contribute to reducing natural hazards including landslides and flooding. Afforestation and forest restoration would reduce baseflow to a small degree, though it is expected that the seasonal variability of baseflow would also be reduced, which would be a positive outcome (Brown *et al* 2005).

New forests affect the water balance in watersheds in various ways, especially through rainfall interception and slowed percolation due to new understory vegetation and organic debris. This is counter-balanced by the increased evapotranspiration from forests, which can reduce baseflow. Considering effects beyond the local microclimate, at the macroscale, newly planted forests often enhance rainfall recycling. Rainfall recycling is usually beneficial in drier regions such as those considered here (Keys *et al* 2024), though this phenomenon is challenging to quantify.

The policy portfolio's impact on carbon emissions and carbon storage are of special importance to this study. Considering CO<sub>2</sub> emissions from fossil fuel combustion and the FOLU strategies and their impact on LULC, the net effect would be a 151 million-ton reduction in emissions by 2050. Considering emissions from fossil fuel combustion independently, due to more rapid economic growth, the portfolio of FOLU policies

embodied in the COMBI scenario would increase CO<sub>2</sub> emissions in the absence of policies and investments to mitigate emissions outside of the FOLU sector. This finding is consistent with other country analyses of NDCs (Banerjee *et al* 2024b, 2025) in the absence of mitigation measures beyond FOLU sectors. The FOLU strategies simulated, on the other hand, would store an additional 215 million tons of CO<sub>2</sub>. This carbon storage is greater than the Chilean government's target capture rates of 0.9–1.2 MtCO<sub>2</sub> yr<sup>-1</sup> from forest restoration and 3.0–3.4 MtCO<sub>2</sub> yr<sup>-1</sup> from afforestation (Government of Chile 2020), thus presenting an advantage over current carbon storage expectations.

ES would make not only important environmental contributions but also economic ones. The FOLU strategies considered would enhance the value of provisioning ES by US\$2,954 million while cultural and recreational and regulating ES would increase by US\$239 million and US\$1,765 million, respectively. The contribution of changes in future ES flows to returns on investment with a 10% opportunity cost of capital would be US\$247 million.

Economic impacts would be positive, with the FOLU strategies boosting cumulative GDP and wealth by US\$16 065 million and US\$22 731 million, respectively. The reduction in forest loss from fire would be especially impactful, on its own enhancing cumulative GDP and wealth by US\$10 679 million and US\$19 113 million, respectively. This intervention is thus an especially significant component of Chile's National Strategy for Climate Change and it could be beneficial to consider its prioritization. The Net Present Value of the portfolio of FOLU strategies would be US\$4,303 million. Finally, in terms of employment and poverty impacts, the portfolio of policies would generate 72 800 new jobs and reduce poverty by 15 586 individuals.

What drives our results? With REDFIRE producing most of the economic gains, the reduction of fire in this scenario would result in less commercially managed forests being lost to fire since, of the annual forest area lost to fire, 40% is commercially managed for timber and non-timber forest products (CONAF 2022). In the presence of fire, these future returns to timber and non-timber forest products would be lost; fire suppression activities under REDFIRE would protect 436 595 ha of commercial forests. The AFFOR and RESTORE scenarios would also increase the area of forest managed for timber and non-timber forest products, which would drive gains across economic indicators. In all scenarios considered, the increase in standing stock of forests would positively effect natural capital assets and thus national wealth, which would be further bolstered by increased net national savings arising from greater economic growth.

From a methodological perspective, the integrated economic-environmental analytical approach embodied by IEEM + ESM, with its consistency with a country's System of National Accounts, is increasingly being adopted and institutionalized by Government institutions including Central Banks, Ministries of Finance and various line ministries (Banerjee *et al* 2019, World Bank 2023a, 2023b). Central Banks, for example, require forward-looking analytical tools to fulfill their mandates. In a context of accelerated environmental degradation and where governments are implementing policies to achieve NDCs and a green transition, there is increasing demand for tools that account for the macroeconomic impacts of the changes in natural capital assets and ES flows. Understanding the transition effects of NDC strategies is also important for guiding policies to mitigate short-run negative impacts, including increased emissions from economic growth. The results presented in this application demonstrate how IEEM + ESM and similar frameworks that integrate large scale economic models with spatial environmental and ES analytics are fit to meet this demand.

The application of the IEEM + ESM framework by a diverse set of user groups, including multilateral development banks, government, academia and the private sector, continues to grow with modeling infrastructure developed for over 30 countries (SI figure 1). The range of applied policy and investment themes analyzed with IEEM + ESM is broadening in scope to include sector-specific policies such as infrastructure, tourism and forestry, to thematic areas such as the NDCs, green growth, ecological thresholds, fiscal policy and technological transformation, among others. The IEEM + ESM framework continues to evolve with advances, for example, in the LULC modeling to increase the spatial resolution of LULC change, as well as in the integration of an increasing number of ES. The current application to Chile integrates crop pollination in the dynamic, integrated framework, capturing feedbacks between changes in ES flows and agent behavior. The SWY modeling is particularly data demanding, and the approach developed in this paper demonstrates how the model may be parameterized based on global datasets and information. In another IEEM + ESM application, work is underway to integrate feedbacks between water purification ES and IEEM.

The NGFS is intimately aware of the need to incorporate natural capital and ES into economic analysis that extends beyond climate change. The NGFS has recently recommended that Central Banks begin working to identify the channels by which the degradation of natural capital and ES can threaten macroeconomic and financial stability (NGFS 2023). In particular, the NGFS advises Central Banks to identify exposures and dependencies of economic activities arising from physical and transition risks in moving toward carbon-neutral economies.

Regarding physical risks, the decline in the supply of ES can lead to losses of agricultural and labor productivity, damage to assets, or disruption of processes, while transition risks can induce reallocation of resources due to adaptation and mitigation policies (e.g. investment in low-emissions technologies). In addition, this disruption can provoke changes in interest rates due to the large amount of new investment required to implement those policies, which can have impacts on investment and consumption, both with important macro-financial implications. This paper demonstrates how an integrated framework such as IEEM + ESM can be implemented to address these kinds of questions and provides guidance on robust approaches to integrating natural capital and ES into economic analytical frameworks and toolkits.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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