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The integrated economic-environmental modelling framework: An illustration with Guatemala's forest and fuelwood sectors

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THE INTEGRATED ECONOMIC- ENVIRONMENTAL MODELLING FRAMEWORK

An Illustration with Guatemala's Forest and Fuelwood
Sectors

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Martin Cicowiez
Renato Vargas
Mark Horridge

Inter-American Development Bank
Climate Change and Sustainability Sector/Environment, Rural
Development and Disaster Risk Management Division

November 2016

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The Integrated Economic-Environmental Modelling Framework: An Illustration with Guatemala's Forest and Fuelwood Sector

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Abstract

This paper develops and operationalizes the Integrated Economic-Environmental Modelling (IEEM) platform which integrates environmental data organized under the first international standard for environmental-economic accounting with a powerful economy-wide modelling approach. IEEM enables the ex-ante economic analysis of public policies and investment on the economy and the environment in a quantitative, comprehensive and consistent framework. IEEM elucidates the two-way interrelationships between the economy and environment, considering how economic activities depend on the environment as a source of inputs and as a sink for its outputs. In addition to standard economic impact indicators such as gross domestic product, income and employment, IEEM generates indicators that describe policy impacts on the use of environmental resources, wealth and environmental quality which together determine prospects for future economic growth and well-being. To illustrate the analytical capacity of IEEM, the model is calibrated with Guatemala's environmental-economic accounts and applied to analysis of its forest and fuelwood sector where negative health and environmental impacts arise from inefficient household fuelwood use.

JEL Codes: D58 Computable and Other Applied General Equilibrium Models; Q56 Environment and Development • Environment and Trade • Sustainability • Environmental Accounts and Accounting • Environmental Equity • Population Growth.

Keywords: ex-ante economic impact evaluation; system of environmental-economic accounting; computable general equilibrium model; system of national accounting; economic and environmental indicators; wealth; natural capital; ecosystem services.

Contents

1.0 Introduction	4
2.0. The SEEA and the IEEM Database	5
3.0 The IEEM Platform.....	8
4.0. An Illustrative Application of IEEM to Guatemala’s Fuelwood and Forestry Sector.....	12
4.1. Scenario Design	14
4.2. Results and Analysis	16
5.0. Concluding Remarks and the Way Forward.....	29
Acknowledgements.....	32
References.....	33
Appendix A. Construction of an Environmentally Extended Supply and Use Table.....	39
Appendix B. Building a MacroSAM and a Disaggregated SAM.....	43
Appendix C. From an EE SUT to Environmentally Extended SAM	48
Appendix D. The IEEM Platform Modules	51
D.1. Forest Resources Module.....	51
D.2. Land Market Module	53
D.3. Water Module	56
D.4. Energy and Emissions Module.....	59
D.5. Mineral Resources Module	60
D.6. Aquatic Resources Module	62
D.7. Waste and Residuals Module.....	65
D.8. Household Consumption Module	66

1.0 Introduction

Computable General Equilibrium (CGE) Models are powerful tools that provide insights on policy impacts on economic indicators. With the recent publication of the first international standard for environmental-economic accounting, the System of Environmental-Economic Accounting Central Framework (SEEA CF; UN et al., 2014), the analytical strength of this approach are significantly enhanced. This paper builds on and operationalizes Banerjee et al's (2016) conceptual framework for integrating data organized under the SEEA into CGE models to construct an Integrated Economic-Environmental Modelling (IEEM) platform. IEEM enables the analysis of public policy and investment impacts on the economy and the environment in a quantitative, comprehensive and consistent framework (Banerjee, Cicowiez, Horridge, & Vargas, 2016).

IEEM reduces the need for making strong assumptions in reconciling environmental and economic data; it reduces analytical start-up costs and increases the timeliness of evidence-based policy advice. IEEM considers quantitatively how economic activities critically depend on the environment both as a source of inputs in the form of environmental resources, and as a sink for outputs in the form of emissions and effluents. For the first time in an ex-ante economic analytical framework, IEEM captures how depletion and degradation of the natural resource base and emissions affects national wealth and prospects for future economic growth, which is reflected in the indicators generated by IEEM.

Wealth may be understood as the aggregate value of manufactured capital, natural capital, and human and social capital. Nobel Laureate Joseph Stiglitz argued that a firm's health and potential are assessed based on its income and balance sheets. Before the SEEA, countries mostly reported income flows, while information on environmental resources, and thus a key dimension of

national assets and the national balance sheet, was seldom reported on. The SEEA provides a framework for accounting for environmental resources in the national balance sheet, which integrated into IEEM, enables the ex-ante assessment of the impacts of public policies, investments and exogenous shocks on wealth.

This paper describes the development of IEEM. To illustrate the analytical capacity of IEEM, Guatemala's Environmental-Economic Accounts (EEA) are used to calibrate an IEEM for Guatemala (IEEM-GUA) which is applied to analysis of the country's fuelwood and forestry sector where negative health and environmental impacts arise from inefficient household fuelwood use. This paper is structured as follows. Following this introduction, a brief overview of the SEEA and IEEM's database is provided. Section 3 offers a snapshot of IEEM's modular approach to modelling environmental resources. Detail on the development of the IEEM database and IEEM's mathematical underpinnings are included in the appendices. Section 4 applies IEEM-GUA to the fuelwood and forestry sector, describes the scenario design, and presents results analysis. Section 5 concludes the paper with an overview of the key outcomes of this body of work and our view on the frontier of integrated economic-environmental modelling.

2.0. The SEEA and the IEEM Database

Over the last 20 years, efforts to measure the interactions between the economy and the environment have increased with progress demonstrated with the 2012 United Nations Statistical Commission adoption of the SEEA Central Framework as the first international standard for environmental-economic accounting (Obst & Eigengaam, 2016). To understand SEEA's contribution to advancing environmental statistics, the concept of the production boundary is fundamental. The System of National Accounts (SNA) states that:

“Economic production may be defined as an activity carried out under the control and responsibility of an institutional unit that uses inputs of labour, capital, and goods and services to produce outputs of goods or services. There must be an institutional unit that assumes responsibility for the process of production and owns any resulting goods or knowledge-capturing products or is entitled to be paid, or otherwise compensated, for the change-effecting or margin services provided.” With regard to environmental resources, it is added that: “A purely natural process without any human involvement or direction is not production in an economic sense” (EC, IMF, OECD, UN, & WB, 2009).

Thus, in order to account for environmental resources, the production boundary must be expanded to account for environmental processes that do not have a defined owner or receive compensation. In monetary terms, the asset boundaries of the SEEA Central Framework and the SNA are the same. In physical terms, however, the boundary of the SEEA is broader and includes all natural resources and areas of land of an economic territory, not limited to only those resources with a market value. In the ecosystem services terminology, the SEEA captures data on provisioning ecosystem services ([MA], 2005; TEEB, 2010). Furthermore, the SEEA encourages the recording of the production and use of all goods and services in physical and where possible, monetary units, on own account within enterprises, whereas the SNA favors recording the transactions which are relevant to capital formation or ancillary activities¹. This last step enables the clear accounting of the supply and use of environmental resources by economic units; for example, the production of energy from the burning of bagasse in the sugar milling industry, or the abstraction of water for livestock rearing.

¹ An ancillary activity is a supporting activity within a business that creates the conditions necessary for the undertaking of the primary/secondary business activity (for example, cleaning and maintenance of a building in which automobile manufacturing occurs).

The SEEA makes it possible to track natural capital inputs to the economy, the output of residuals in the form of emissions and effluents from the economy back to the environment, and changes to natural capital stocks. One of the most useful features of the SEEA is the ability to combine in single framework physical and monetary quantities. Banerjee et al. (2016) describe in detail the main elements of the SEEA which are relevant for integrated economic-environmental modelling.

The first step toward developing the database that underpins IEEM is the production of an Environmentally Extended Supply and Use Table (hereafter EE SUT) based on the SEEA. From Guatemala's EEA, a single consistent framework was constructed that extends the monetary SUTs of the SNA with extensions to incorporate a column for the environment, and rows for natural inputs and residuals as proposed by the SEEA. The procedures for constructing the EE SUT and the EE SUT's basic structure are presented in Appendix A.

Once an EE SUT has been developed, the next step in constructing the IEEM database is to construct a SAM for the country in question. A SAM is a matrix representation of the interrelationships existent in an economy at the level of individual economic sectors, factors, and institutions. As stated in Round (2003), "it is a comprehensive, flexible, and disaggregated framework which elaborates and articulates the generation of income by activities of production and the distribution and redistribution of income between social and institutional groups".

A SAM is the core database for a CGE model and is constructed based on SNA SUTs, integrated economic accounts, balance of payments accounts, government accounts data and other ancillary data sources. The literature offers descriptions of what a SAM is and its key features; see for example: Breisinger, Thomas, & Thurlow (2009); King (1985), and; Round (2003). Appendix B

provides detail on the construction of a SAM, starting with an aggregate MacroSAM and then a disaggregated SAM. Appendix C discusses the structure of the Environmentally Extended SAM (ESAM) and the satellite matrices which are used to track stocks and flows of environmental resources in physical units.

3.0 The IEEM Platform

IEEM takes a standard recursive dynamic CGE modelling framework as its starting point and integrates environmental resource-specific modules whose design follows the IEEM conceptual framework developed in Banerjee et al. (2016). The SEEA was formulated to enable flexible and modular implementation according to implementing country priorities. Similarly, the IEEM platform was developed with a modular structure such that the environmental modules, namely the forest and deforestation, land, water, energy and emissions, mineral resources, aquatic/fisheries resources, waste and residuals modules may be switched on or off depending on whether or not SEEA data are available for the country in question. In the case of IEEM-GUA, all environmental modules are included.

In the forestry and deforestation module, IEEM tracks forest commodity flows in physical units, at commodity-specific, observed unit values. In terms of modeling, the production function of the forestry sector singles out the logged land area as a factor of production. Specifically, a Constant Elasticity of Substitution (CES) function is used to combine labor and capital factors, while a fixed coefficient, Leontief assumption is used for the logged land area. In turn, also under the Leontief assumption, intermediate inputs are calculated as exogenous quantities per unit of the activity.

The forestry and deforestation module accounts for the natural growth rate of the forest resource. Logically, deforestation occurs when the rate of timber extraction is higher than the natural growth rate of the forest resources. For the purposes of policy simulations, the module enables that an upper bound for deforestation be set to simulate the imposition of a mechanism to regulate land conversion.

In the land module, the treatment of agricultural land is similar to that of other factors.² Land demand is derived from the first order conditions of the cost minimization optimization problem solved by the representative firm in each activity that uses land, namely agriculture. In terms of land supply, total land supply may be fixed or the supply curve may be upward sloping. The module enables the option of modeling land use incentive policies through imposing a lower bound on land use for a given economic activity.

The water module models non-registered water used in agricultural activities; non-registered water is water not supplied by the water utility company.³ In the case of Guatemala, given the available information in Guatemala's EEA, it is assumed that water supply is initially larger than water demand and the price of non-registered water is zero. Then, if water demand increases in a non-baseline or policy simulation, the price of non-registered water becomes positive, generating a cost for producers and an income for water owners. In the model calibration, it is assumed that water income is allocated across institutions in proportion to an institution's ownership share of land.

² In other contexts, this treatment can also be applied to land used in managed forests.

³ In its full version, IEEM can include various water categories. In the case of Guatemala, registered and non-registered water is distinguished, while non-registered water could be further split between agriculture and non-agriculture uses.

The energy and emissions module is structured so as to include any number of emissions generated through production processes and by final users of goods and services, such as households. In the Guatemalan EEA, carbon dioxide (in CO₂ tons), nitrous oxide (in CO₂ tons equivalent), and methane (CO₂ tons equivalent) are accounted for. For potential policy simulations, the module enables the imposition of exogenous changes in the emissions coefficients that could be brought about by autonomous improvements in the level of emissions per unit of use. IEEM also enables limits to be imposed on the level of emissions. To that end, an endogenous tax on emissions may be introduced, for example, a carbon tax, at the same time that emissions are capped at a user-specified level.

In the case of the mining resource module, it is relevant to consider that mineral extraction over time is limited by the size of recoverable reserves. Minerals are nonrenewable resources and extraction costs are a function of the stock of recoverable reserves. The smaller the remaining stock, the higher is the marginal cost of extraction (Ghadimi, 2007). This dynamic is captured by expanding the definition of total factor productivity (TFP) as it relates to the productivity of mineral resource extraction. The stock of mineral resources is updated each period, based on the stock remaining from the previous period, extraction, and new recoverable discoveries. In this formulation, where new discoveries do not make up for extraction, the TFP in mining activities decreases over time as the stock of minerals is depleted. This declining TFP increases the marginal cost of extraction and lowers the productivity of the mining sector.

A CGE approach has not been widely applied to exploring fisheries, though it has been shown that there is significant potential for extending a standard CGE framework to take into account fish population and management dynamics (Banerjee et al., 2016). The approach developed in this module follows guidance from the literature related to the integrated ecosystem-based

management of fisheries, which considers the entire ecosystem, including humans (Pikitch et al., 2004). An extension to this approach involves incorporating a biological systems module to represent the processes that affect fisheries productivity.

In the IEEM fisheries module, the resource stock is a function of the quantity of fish harvested, the intrinsic growth rate of the resource and the carrying capacity of the environment. The module includes a catch-per-unit-effort production function which assumes that catch per-unit of effort is proportional to the existing stock (Conrad, 2010). Typically, partial equilibrium models of fisheries use "effort" as the single human factor of production. IEEM, as a general equilibrium framework, expands on this specification and considers both capital and labor at the same time that the fishing sector interacts with other sectors and competes for factors of production. In contrast to conventional partial equilibrium formulations, IEEM captures the economy-wide effects of stock variation. For policy simulation purposes, the fisheries module enables simulation of maximum sustainable yield assumptions as well as experimentation around upper bounds for fishing in a given year to simulate a fishing quota.

In the waste and residuals module, the Guatemalan EEA provides information in physical units (tons) of the supply and use of residuals such as hospital waste, paper waste, glass waste and rubber waste, among others. Users and suppliers of this waste and residuals are economic activities, households, and the rest of the world. The module is able to track the supply and use of these residuals.

Appendix D provides considerable detail on each of the modules described above including their mathematical formulation. IEEM is currently programmed in the General Algebraic Modelling System (GAMS, 2013) and is being programmed in GEMPACK (Harrison and Pearson, 1996; Harrison et al. 2016). The generic IEEM platform, IEEM-GUA, and an instructive manual for

their use will be available by request from the corresponding author in 2017. To demonstrate the analytical capabilities of IEEM, the sections that follow apply IEEM-GUA to Guatemala's fuelwood sector.

4.0. An Illustrative Application of IEEM to Guatemala's Fuelwood and Forestry Sector

Sixty-seven percent, approximately 2.1 million, of Guatemalan households use fuelwood as a primary source of energy with fuelwood constituting 57% of the country's overall energy use. Fuelwood is primarily used in cookstoves for cooking food and heating homes, as well as serving cultural purposes (Banco de Guatemala & IARNA-URL, 2009; Bielecki & Wingenbach, 2014; INAB, 2015). Increasing demand for fuelwood is generating a number of problems for Guatemala.

Population growth and the expansion of the agricultural frontier is resulting in fuelwood scarcity, requiring more time for fuelwood collection. Fuelwood collection is often the responsibility of women and children which takes an increasing share of their time away from other important activities such as education. The use of open cookstoves is well known to have detrimental health effects, increasing the probability of household members' contraction of respiratory illness by 31% (SEGEPLAN, 2010), the premature death of over 5,000 people per year, and productivity losses of around 1% of GDP (Global Alliance for Clean Cookstoves, 2014). Finally, with a national fuelwood deficit of over 10 million m³, there is increasing pressure on forests, leading to more rapid deforestation and forest degradation (INAB, IARNA-URL, & FAO, 2012).

To address this critical issue, more efficient use of fuelwood is one of 5 specific objectives of Guatemala's National Energy Policy 2013-2027 and is the overall goal of The National Strategy for Sustainable Production and Efficient Use of Fuelwood 2013-2024 (INAB, 2015; MEM,

2013). The National Strategy sets out to: (i) establish 48,000 ha of forest plantations to produce 1.2 million m³ of fuelwood/per year, and; (ii) promote efficient fuelwood use by providing technical and financial support for the use of efficient fuelwood cookstoves. The strategy aims to reduce the fuelwood deficit by 25% and benefit over 200,000 or 13% of the households that currently use open cookstoves.

The IEEM-GUA framework is applied to explore the economic, environmental and social impacts of implementation of Guatemala's fuelwood strategy. Another important parallel policy that is explored in this study is the implementation of PROBOSQUE. This program provides incentives for reforestation and sustainable forest management and is one of the largest forest incentive programs in the Latin American and Caribbean region. In addition to these being critical policy issues for the Guatemalan government, these issues were chosen for exploration in this study for their multidimensional nature with regard to economic-environmental interactions in order to illustrate the analytical power of the IEEM framework.

IEEM's ability to track land use and forest resources will capture how the fuelwood strategy affects forest stocks. The creation of forestry and agroforestry plantations, and the adoption of more efficient cookstoves may lower costs of fuelwood and have employment generating implications. Less pressure on standing natural forests for fuelwood will ensure these forests are retained as important carbon sinks. Reduction of effort expended to collect fuelwood and more efficient fuelwood use in the home will have both productivity and health impacts, freeing up labor for more productive activities. Finally, more efficient fuelwood use will have implications for the country's energy-emissions profile. All of these interactions are captured in the IEEM framework.

4.1. Scenario Design

Three scenarios were developed to explore the impacts of Guatemala's fuelwood strategy and PROBOSQUE. All three scenarios are compared to the baseline forecast. Most results are described as the percent difference with respect to the baseline forecast. In the baseline and scenarios, IEEM updates the underlying data to 2016. The period of analysis with which this study is concerned with is from 2016 to 2025. Following the description of the baseline, the three scenarios are described:

- **Baseline.** The baseline forecast is the “business-as-usual” scenario. This first simulation is designed to replicate observed trends during 2010-2015 at the macro and sectoral levels. From 2016 on, this first simulation assumes that past trends will continue into the period from 2016 to 2025. In the scenarios that follow, all shocks are introduced during the period 2016-2025.
- **Efficiency:** The efficiency scenario imposes a 25% increase in household fuelwood consumption efficiency. This scenario simulates the introduction of more efficient fuelwood household cooking technology, such as the Patsari cookstove.⁴ The efficiency gains are simulated to follow a logistic implementation pathway from 2016 and 2020.
- **Efficiency + health:** The efficiency + health simulation links increased household fuelwood efficiency with improvements in the health of household members which in turn have implications for the productivity of working household members. Various studies in Guatemala and elsewhere have measured improvements in household air quality arising from the more efficient use of fuelwood (Ahmed, Awe, Barnes, Cropper, & Kojima, 2005; Duflo, Greenstone, & Hanna, 2008; Jagger & Shively, 2014; Lambe & Ochieng, 2015; McCracken

⁴ See for example: http://www.appropedia.org/Patsari_Cookstove

& Smith, 1998; Smith et al., 2011; Smith et al., 2013; Smith-Sivertsen et al., 2009). There are a handful of studies that have used this information to estimate the economic benefits that improved fuelwood use efficiency can generate. For example, García-Frapolli et al (2010), using data from Habermehl (2007), account for the number of work hours lost that were attributable to sickness (acute respiratory diseases, eye disease and burns) arising from open cookstoves.

In this scenario, figures from Garcia-Frapolli et al (2010) are used to estimate the number of hours saved due to improved efficiency of household fuelwood use. The hours saved translate into the equivalent of 0.5% of labor value added in the baseline. Given that a large proportion of fuelwood use occurs in rural areas (51% of the population), a conservative approach is taken in this scenario and a 0.125% productivity shock is implemented on rural household labor productivity.

- **Efficiency + zero deforestation:** This simulation imposes the same shock as the efficiency shock together with a constraint on deforestation; for illustrative purposes, a policy of zero deforestation is imposed. This constraint is enforced through an endogenous incentive. This scenario represents the joint implementation of the fuel wood strategy, and Guatemala's PROBOSQUE program. Forest incentives in IEEM are implemented as a tax on the forest management sector which is then transferred to the owners of capital used by the forest management sector. The rate applied to the sector is 15.3% in 2016, 3.7% in 2020, and 1.2% in 2021. This declining rate is due to the fact that increased fuelwood efficiency over time reduces the extent to which an incentive is required to deter deforestation.

At the macro level, IEEM as with any other CGE model, requires the specification of the equilibrating mechanism for three macroeconomic balances. For the non-baseline scenarios: (i)

changes in income tax rates on households clear the government budget which implies that there is no domestic and/or foreign financing beyond baseline values ensuring the budget neutrality of simulations; (ii) the model is savings-driven where private investment is the clearing variable in the savings-investment balance, adjusting to make use of available financing, and; (iii) the real exchange rate equilibrates inflows and outflows of foreign exchange, by influencing export and import quantities. This equilibrating mechanism implies that the simulations are neutral in terms of changes in net foreign assets. The non-trade related payments of the balance of payments, specifically, transfers and foreign investment, follow exogenously imposed paths.

In the simulations undertaken, the household expenditure elasticity on components of the energy bundle is an important driver of simulation results. To obtain the best estimate possible, expenditure elasticities for both rural and urban households were estimated with a Tobit model, based on data from the National Living Conditions Survey (INE, 2011). For rural households, expenditure elasticities for electricity, fuelwood and petroleum products were estimated as 0.688, 0.530 and 1.191, respectively while for urban households, these were estimated as 0.813, 0.431 and 1.159, respectively.

4.2. Results and Analysis

First, to provide a picture of baseline household fuelwood consumption, table 1 shows: households disaggregated by income quintile; each household income quintile's share of fuelwood in their consumption bundle, and; the share of total income that each household income quintile spends on fuelwood. For rural households, the lower quintiles have the greatest fuelwood expenditure share while for urban households, the highest income quintile, with over 27% of total household income, spends the least on fuelwood.

Table 1. Household fuelwood consumption.

	Household quintile	Fuelwood expenditure share	Share of total income
Rural	HH q1	13.1	3.3
	HH q2	15.2	4.6
	HH q3	14.1	5.5
	HH q4	13.9	6.8
	HH q5	11.3	10.0
Urban	HH q1	12.4	6.3
	HH q2	9.0	8.8
	HH q3	5.4	11.9
	HH q4	4.0	15.2
	HH q5	1.6	27.7
Total		100.0	100.0

The increase in fuelwood efficiency is introduced as shown in figure 1. The efficiency shock begins in 2016 and increases in intensity following a logistic functional form up until 2020 after which it remains constant at 25%.

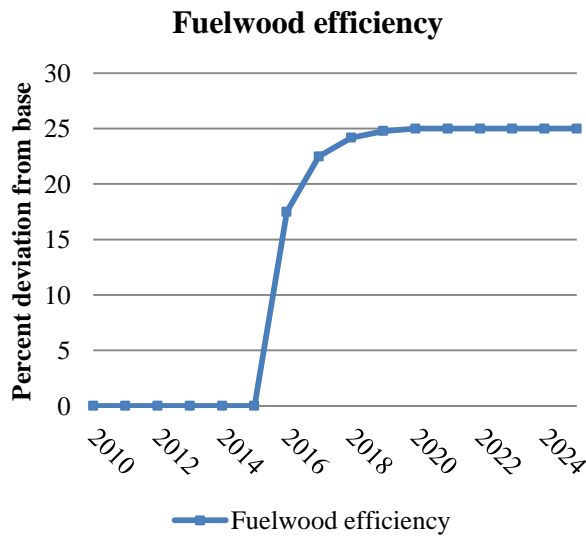


Figure 1. Implementation of fuelwood efficiency shock. Source: Authors' own elaboration.

Figure 2, Panel A, shows private consumption as a proxy for household welfare. The improvement in fuelwood efficiency has a positive impact on well-being on the order of around

0.20% with respect to the baseline by 2025. The efficiency + zero deforestation scenario also has a positive impact though to a slightly lesser degree than in the efficiency scenario alone. This less pronounced impact in the efficiency + zero deforestation scenario is driven by a decrease in wages that the constraint on deforestation brings about, given the decrease in the output of agriculture which is a labor-intensive sector. The efficiency + health scenario which accounts for the improved productivity arising from health benefits has the greatest positive impact on private consumption of the three scenarios equivalent to 0.30% with respect to the baseline in 2025.

In terms of unemployment impacts, there are small differences across scenarios with unemployment slightly lower by 2025 in the efficiency + health scenario compared with the efficiency and efficiency + zero deforestation scenarios. Impacts on GDP are positive for the efficiency (0.18% as a percent deviation from the baseline by 2025), efficiency + zero deforestation (0.16%) and the efficiency + health scenario (0.31%).

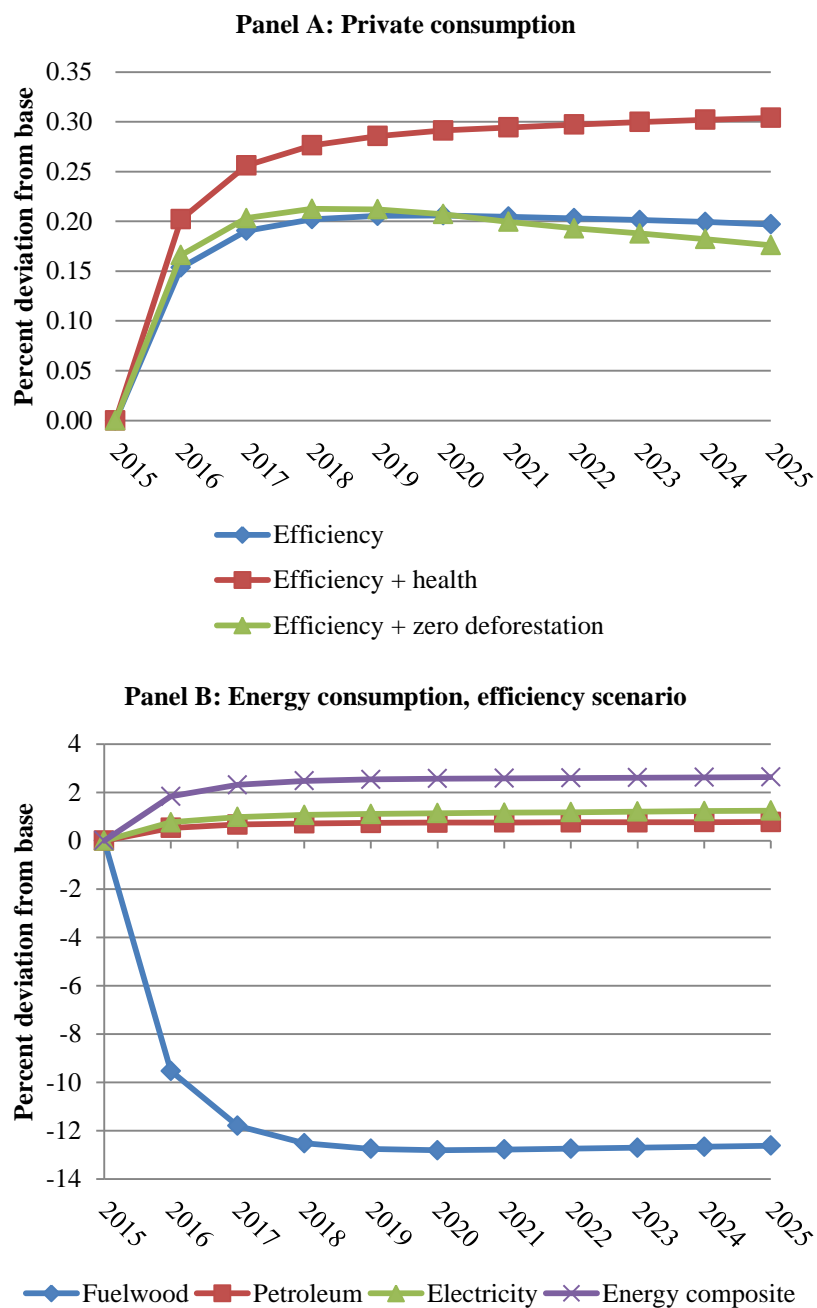


Figure 2. Panel A: Household private consumption. Panel B: Household energy consumption.
Source: Authors' own elaboration.

Figure 2, Panel B, depicts household energy consumption. There is a 12% decline in the value of fuelwood consumption which remains relatively steady after the full implementation of the

shock. This 12% decline is less than the 25% increase in fuelwood use efficiency since in terms of Tera joules of energy of fuelwood used, the increase in efficiency also induces an increase in the number of Tera joules consumed. In a practical sense, this implies that households are changing their behavior in response to increased fuelwood efficiency by one or a combination of the following: consuming more food that is cooked; cooking food longer; allowing food to reach a higher temperature; heating homes to a higher temperature, and/or; heating homes for a longer period of time. There are small increases in the consumption of other forms of energy and a larger positive impact on the overall energy consumption bundle. This effect is driven by the decrease in the cost of the energy bundle as well as an income effect due to the savings on fuelwood consumption arising from the fuelwood efficiency shock.

While not shown in Panel B, household fuelwood consumption in the efficiency + zero deforestation scenario is slightly lower than in the efficiency scenario, though the difference is small. Output from the fuelwood sector is still lower in the efficiency + zero deforestation scenario, given the constraint imposed on deforestation. This decrease in fuelwood output is also related to a decrease in the use of non-land factors of production. Impacts on energy consumption in the efficiency + health scenario are very similar in trend and magnitude to those presented in Panel B.

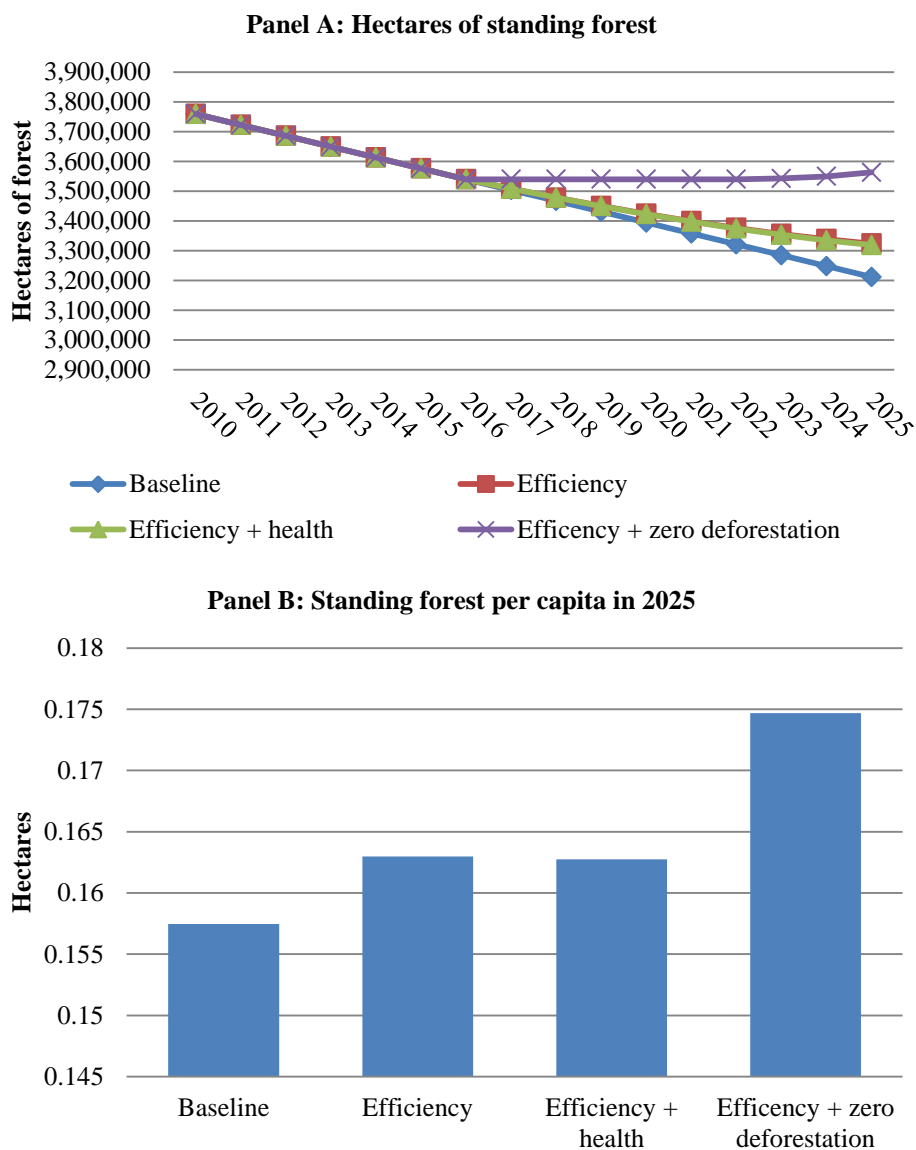


Figure 3. Panel A: Hectares of standing forest. Panel B: Hectares of forest per capita in 2025.

Panel A of figure 3 shows the policy impacts on stocks of forest resources. The baseline represents declining forest stock due to deforestation and logging. In the baseline, by 2025 Guatemala loses half a million hectares of forest. The efficiency and efficiency + health scenarios reduce the loss by 100,000 hectares. The efficiency + zero deforestation scenario maintains forest cover at its 2016 level. In terms of standing forest per capita, in 2025 there are 0.157 ha/capita in the baseline and 0.163 ha/capita in both the efficiency and efficiency + health

scenarios. In the efficiency + zero deforestation scenario, forest stock per capita increases to 0.175 ha/capita.

Table 2. Impacts on sectoral output, percent deviation from baseline in 2025. Source: Authors' own elaboration.

Commodity	Base value added (M of quetzals)	Efficiency	Efficiency + health	Efficiency + zero deforestation
Coffee	5,554	-0.43	-0.17	-1.57
Banana	3,506	-0.66	-0.55	-2.21
Cereals	4,048	0.18	0.28	0.25
Other agriculture	19,728	0.04	0.16	-0.18
Livestock	11,930	0.09	0.19	0.02
Other forestry	2,612	0.81	1.05	-1.47
Fuelwood	1,424	-12.52	-12.48	-12.40
Fishing	882	0.07	0.12	0.15
Mining	7,879	0.05	0.11	0.14
Food prod	66,421	0.15	0.26	0.19
Beverages and tobacco prod	8,160	0.13	0.22	0.20
Textiles and wearing apparel	23,433	0.35	0.54	0.80
Wood and wood prod	2,393	0.13	0.30	0.03
Paper and paper prod	4,613	0.15	0.30	0.32
Refined petroleum prod	178	0.05	0.14	0.17
Chemicals	12,467	0.15	0.30	0.37
Rubber and plastics	6,161	0.10	0.24	0.22
Non-metallic mineral prod	7,228	0.09	0.28	0.15
Basic metals and metal prod	8,050	0.05	0.23	0.19
Machinery and equipment	1,582	0.32	0.56	0.87
Other manufactures	6,425	0.14	0.29	0.15
Recycling	146	0.39	0.66	1.17
Electricity	10,985	0.33	0.45	0.35
Water	2,252	0.09	0.20	0.15
Construction	35,013	0.05	0.26	0.07
Trade	73,909	-0.13	-0.01	-0.20
Hotels and restaurants	20,398	0.20	0.40	0.43
Transport	18,586	-0.09	0.05	-0.08
Other services	169,064	0.06	0.18	0.10

Impacts on sectoral output are shown in Table 2. In the efficiency scenario, other forestry, textiles and electricity sectors experience the greatest positive impact while the fuelwood, export-oriented agriculture such as the coffee and banana, and trade and transport sectors are most negatively impacted. The efficiency + zero deforestation scenario has overall more positive impacts on sectoral output, with the exception of the fuelwood sector. The impact on the agricultural sector is considerably more negative than in the efficiency scenario, however. Magnitudes of positive impacts are amplified across sectors in the efficiency + health scenario.

Figure 4, Panel A shows the greenhouse gas emissions captured in the Guatemalan EEA, namely carbon dioxide, nitrous oxide and methane, and their decline in the efficiency scenario; the efficiency + zero deforestation scenario and efficiency + health scenarios, with similar levels of fuelwood consumption, generate similar results in terms of emissions. Figure 4, Panel B demonstrates that those households consuming a greater share of fuelwood, particularly the poorer rural households, experience the greatest shift in their emissions profile and therefore benefit the most from the fuelwood strategy in terms of income savings and the potential health benefits.

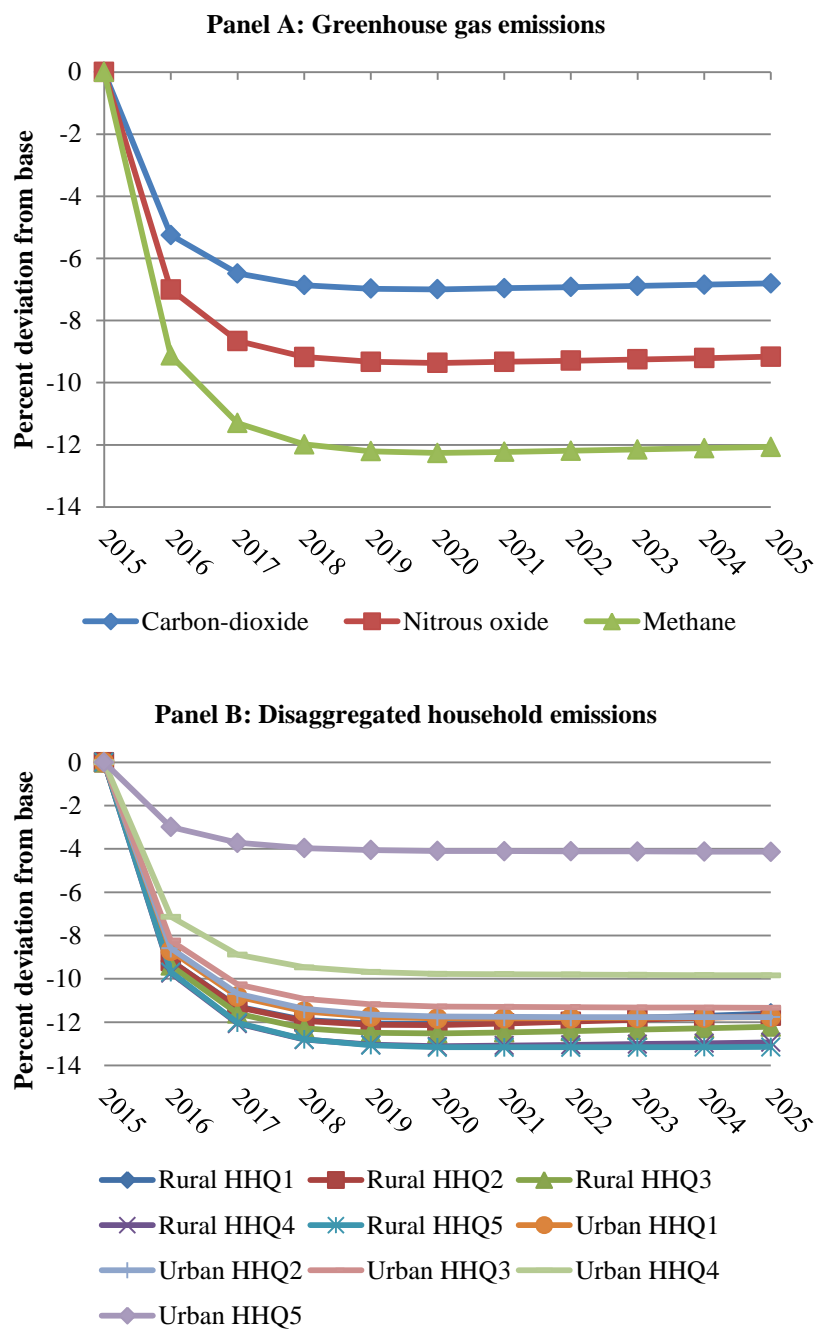


Figure 4. Panel A: Greenhouse gas emissions. Panel B: Disaggregated household emissions.
Source: Authors' own elaboration.

Figure 5 presents baseline emissions levels and shows that the electricity sector and food processing sectors are the greatest emitters of greenhouse gases, followed by non-metallic mineral production and transportation services.

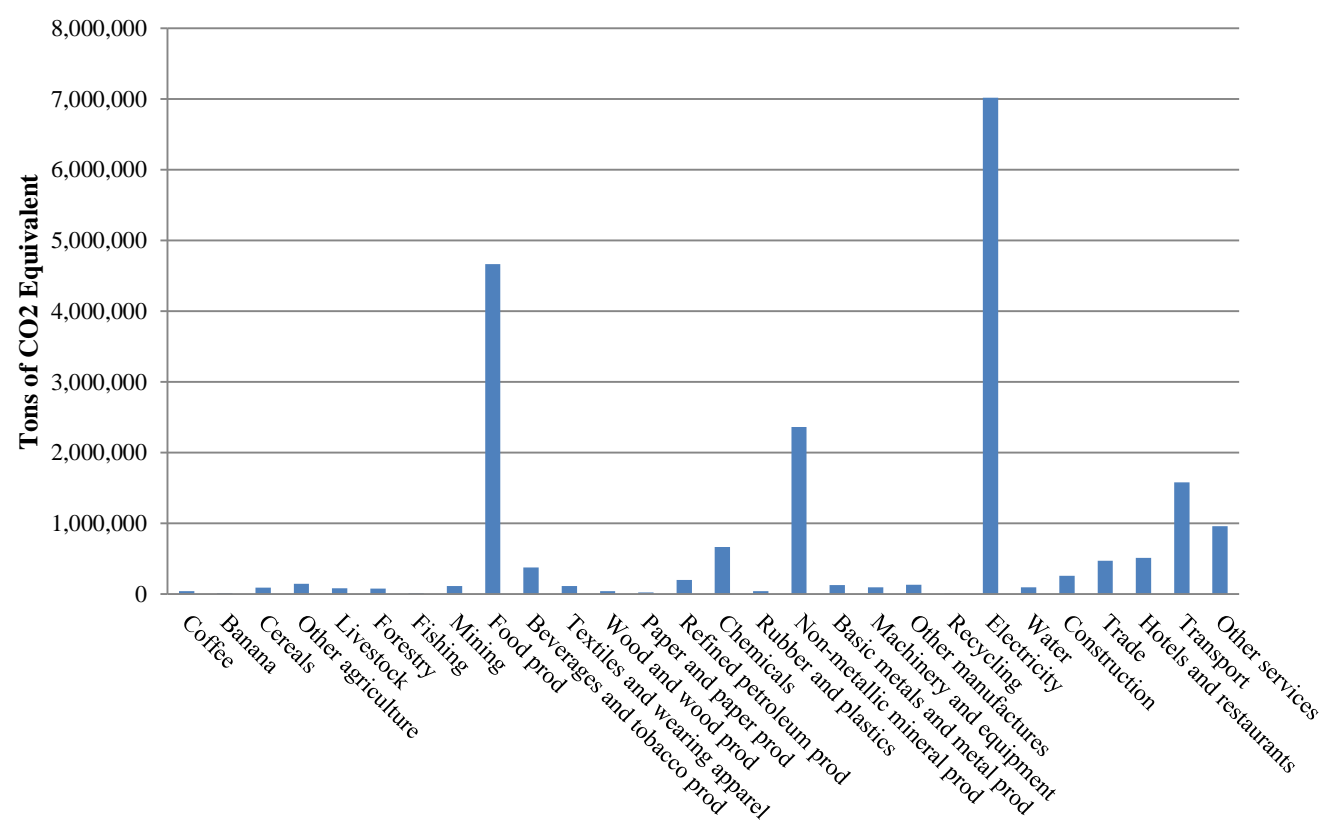


Figure 5. Baseline emissions. Source: Authors’ own elaboration.

Figure 6 illustrates some of the multidimensional impacts of the efficiency scenario. The figure shows a decline in agricultural land use with a concomitant increase in the stock of forestland as deforestation is slowed as a result of the fuelwood strategy. Forestry output declines as would be expected, with fuelwood prices falling. Water use remains similar to baseline consumption despite the small decline in agricultural output. Total greenhouse gas emissions fall as a result of the improvements in efficiency.

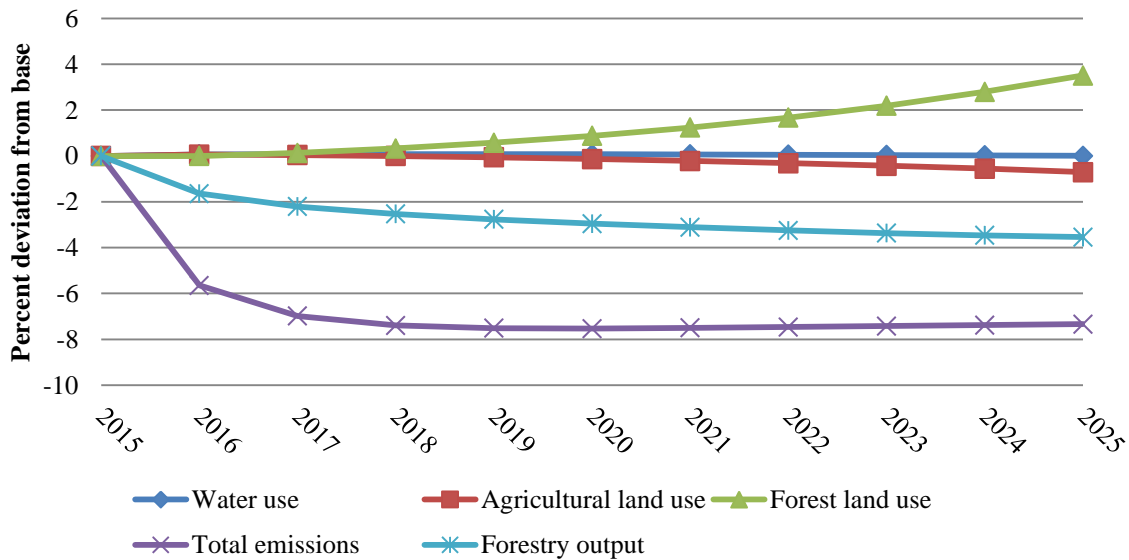


Figure 6. Multiple impacts of household fuelwood efficiency shock. Source: Authors' own elaboration.

Genuine savings is a key indicator generated by IEEM which reflects policy impacts on national wealth and the national balance sheet. Genuine savings is calculated as national savings adjusted for depletion of the underlying environmental resource base and pollution damages, with the addition of expenditure on education as a proxy for investment in human capital (UN et al., 2005). What follows is the estimation of a variation of genuine savings which emphasizes IEEM's environmental dimension, without the estimation of investment in education.

Adjusted genuine savings in IEEM is calculated as follows. Depreciation is the reduction in the value of an asset through time due to wear and tear; depreciation of the forest stock is calculated using IEEM results as the product of the annual volume of deforestation and the output price of timber in that year. Similarly, depreciation of mining stocks is calculated using IEEM results as the product of the annual volume of mineral extraction and the output price. Emissions damages are calculated based on IEEM results as the product of annual greenhouse gas emission and the

value used by the World Bank in its estimation of adjusted net savings estimations which is equal to US\$20/ton of carbon dioxide equivalent (World Bank, 2011). Adjusted genuine savings is therefore calculated as Gross National Savings less forest depreciation, mineral depreciation and the cost of emissions.

Figure 7, Panel A shows the scenario impacts on genuine savings until 2025. In the efficiency and efficiency + health scenario, there is a steady increase in genuine savings following implementation of the fuelwood strategy, with health impacts resulting in greater savings than the efficiency scenario alone. The efficiency + zero deforestation scenario has the most wealth enhancing impact.

Once both fuelwood and zero deforestation strategies are implemented, there is a sudden increase in adjusted genuine savings which is greater than the efficiency + health scenario. This is the result of the full detention of deforestation. While always above baseline levels, the increased savings slowly falls to USD76 million in 2022 from its peak of USD130 million following implementation of the strategies. After 2022, savings begins to rise again. This trend is explained by the sudden increase in forest stock following implementation of PROBOSQUE. The small decline between 2016 and 2022 and the stabilization that follows are explained by movement toward equilibrium between the natural rate of forest growth and the legal forest harvest.

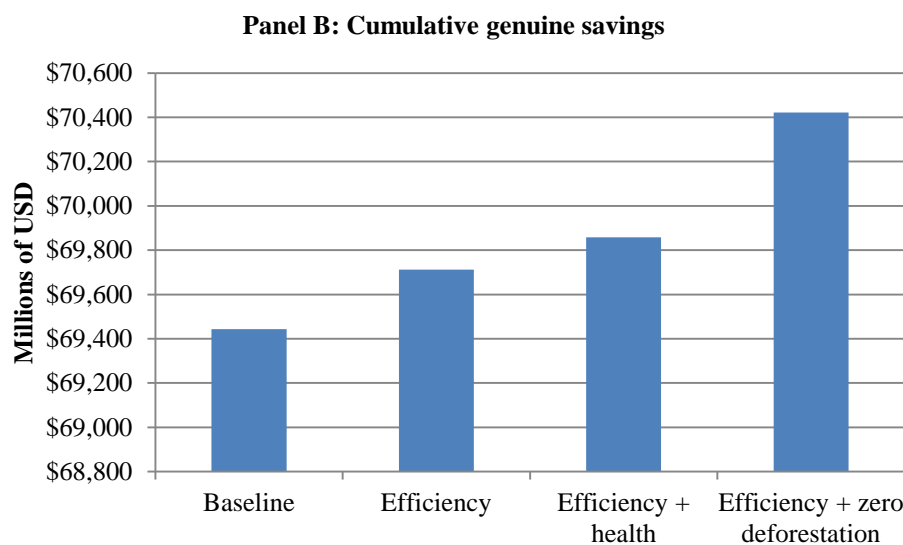
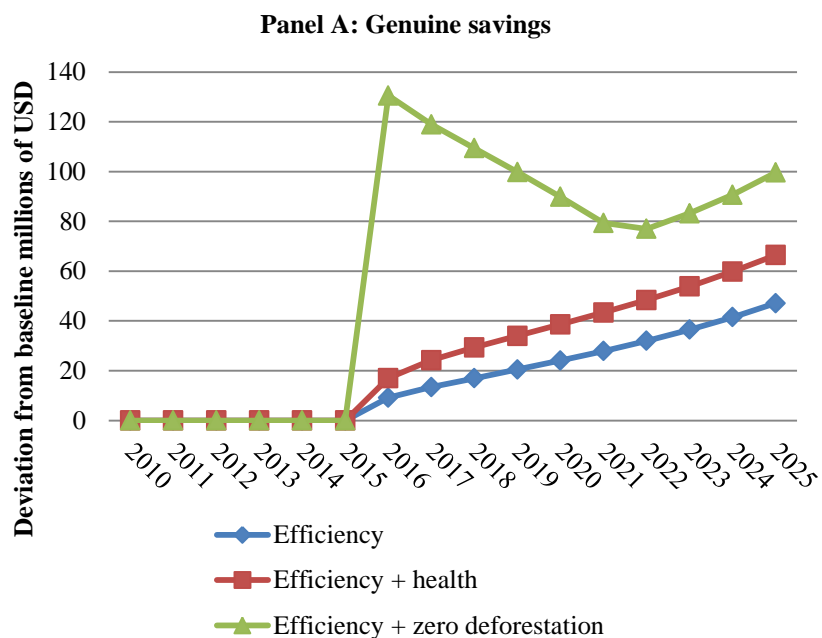


Figure 7. Panel A: Scenario impacts on genuine savings until 2025. Panel B: Cumulative impact on genuine savings in 2025, real 2010 USD. Source: Authors' own elaboration.

Panel B of figure 7 shows cumulative genuine savings in 2025 with the efficiency + zero deforestation scenario generating an additional USD978 million in savings above baseline business as usual levels.

5.0. Concluding Remarks and the Way Forward

This paper develops the IEEM platform which enables the analysis of policy impacts on the economy and the environment in a quantitative, comprehensive and consistent framework. With the SEEA database as the foundation for the IEEM platform, IEEM explicitly considers how economic activities critically depend on the environment both as a source of inputs and as a sink. While most previous economy-wide analyses of environmental issues have tended toward the study of one environmental issue in isolation, the SEEA underpinnings of the platform provides a more robust representation of the environment, facilitating the detection of unexpected impacts. The ability to track impacts on stocks of some environmental resources and land use, as well as environmental inputs and outputs in physical units are all new features that comprise IEEM. IEEM complements the comprehensive data of the SEEA with environmental resource-specific modeling approaches or modules, such as resource-specific production functions, that are not found in standard CGE frameworks.

To illustrate the analytical capabilities of IEEM, an IEEM-GUA is developed by calibrating IEEM with Guatemala's EEA. IEEM-GUA is used to examine the country's fuelwood strategy coupled with PROBOSQUE, Guatemala's forest incentive program. Implementation of the fuelwood strategy results in a reduction in fuelwood consumption and emissions, though a small increase overall in household consumption of the energy bundle. With a reduction in fuelwood production and consumption, there is a decrease in deforestation. This shift, while resulting in decreased export-oriented agricultural production, also tends to increase water consumption and emissions from the expanding sectors. Overall, the effect is positive with increased household income and consumption contributing to enhanced well-being.

Coupling of the fuelwood strategy with the forest incentive program, the combined effect is generally in the same direction, though of a lesser magnitude. When the impact of reduced household emissions on household labor productivity is taken into account, the positive impacts on household well-being are amplified. The primary channel of impact is the increase in household income which generally results in greater consumption of most goods and services. This greater consumption of course has implications for rates of consumption of environmental resources as well as levels of emissions and effluents returning to the environment.

Prior to development and implementation of the SEEA, national accounting focused on national income flows. The SEEA now makes it possible for a country to report on the status of the environmental dimension of its national balance sheet. In the illustration with Guatemala's fuelwood and forest incentive strategies, analysis with IEEM-GUA shows generally positive environmental impacts in terms of reductions in fuelwood use, deforestation and harmful greenhouse gas emissions. The reduction in greenhouse gas emissions in turn has positive health impacts, particularly on rural poor households which induces improvements in labor productivity and higher incomes. For the first time in an ex-ante economic analytical framework, IEEM estimates the impact of these policies in terms of national wealth in the form of genuine savings. From this perspective both the fuelwood strategy and fuelwood incentive policy enhance Guatemala's underlying wealth and thus prospects for future economic growth.

In ecosystem services terminology, the SEEA extends the production boundary of the SNA to include provisioning ecosystem services for which there may be no owner and there is no market transaction. In the Guatemalan EEA, for example, water used for irrigation is not subject to a market transaction, though it is accounted for in Guatemala's EEA. We view the next step in advancing IEEM is in the accounting for regulating, and cultural and aesthetic ecosystem

services, such as sediment control and recreational values, respectively⁵. Fortunately, guidance on how to organize ecosystem service supply and use data in a way that is consistent with the SNA and SEEA is under development (European Commission et al., 2013). Though there is no international standard of yet, experimentation with these emerging frameworks is underway⁶.

While part of the challenge lies in how non-provisioning services may be valued and structured for use in IEEM, another significant challenge is in how to accurately represent and model the biophysical processes that underpin the supply of these ecosystem services, as well ecosystem service supply capacity. IEEM is truly a transdisciplinary challenge. Working alongside our colleagues in the natural sciences, these are all ripe areas for future research that we will address in our advancement of the IEEM framework and in our ambition to account for how ecosystems are critical in underpinning national wealth and well-being, and future prospects for economic growth and development.

⁵ For an overview of some of the terminology used in ecosystem service science and classification systems, see: <http://cices.eu/>

⁶ See for example: <http://snappartnership.net/groups/natural-capital-accounting/>

Acknowledgements

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References

- Ahmed, K., Awe, Y., Barnes, D. F., Cropper, M. L., & Kojima, M., 2005. Environmental Health and Traditional Fuel Use in Guatemala. Washington DC: World Bank.
- Almeida dos Reis, J.G. & Paes de Barros, R., 1991. Wage Inequality and the Distribution of Education: A Study of the Evolution of Regional Differences in Inequality in Metropolitan Brazil. *Journal of Development Economics* 36 (1): 117-143.
- Armington, Paul A., 1969. A Theory of Demand for Products Distinguished by Place of Production, IMF Staff Papers 16 (1): 159-78.
- Banco de Guatemala & IARNA-URL., 2009. *Cuenta Integrada del Bosque: Bases Teóricas, Conceptuales y Metodológicas*. Ciudad de Guatemala: Banco de Guatemala & IARNA-URL.
- Banerjee, O., Cicowiez, M., Horridge, J. M., & Vargas, R., 2016. A Conceptual Framework for Integrated Economic-Environmental Modelling. *Journal of Environment & Development*, 25(3), 276-305.
- Bielecki, C., & Wingenbach, G., 2014. Rethinking Improved Cookstove Diffusion Programs: A Case Study of Social Perceptions and Cooking Choices in Rural Guatemala. *Energy Policy*, 66, 350-358. doi: <http://dx.doi.org/10.1016/j.enpol.2013.10.082>
- Blanchflower, David G. & Oswald, A.J., 1994. The Wage Curve. MIT Press.
- Blanchflower, David G. & Oswald, A.J., 2005. The Wage Curve Reloaded, National Bureau of Economic Research, NBER Working Paper 11338.

- Bourguignon, François; Bussolo, Maurizio and Pereira da Silva, Luiz Awazu (eds.), 2008. The Impact of Macroeconomic Policies on Poverty and Income Distribution: Macro-Micro Evaluation Techniques and Tools, World Bank and Palgrave Macmillan.
- Breisinger, C., Thomas, M., & Thurlow, J., 2009. *Social Accounting Matrices and Multiplier Analysis: An Introduction with Exercises*. Washington D.C.: IFPRI. Retrieved from: <http://www.ifpri.org/publication/social-accounting-matrices-and-multiplier-analysis>
- Devarajan, S., Ghanem, H. & Thierfelder, K., 1999. Labor Market Regulations, Trade Liberalization and the Distribution of Income in Bangladesh, Policy Reform 3: 1-28.
- Duflo, E., Greenstone, M., & Hanna, R., 2008. Indoor Air Pollution, Health and Economic Well-Being. *Surveys and Perspectives Integrating Environment and Society*, 1, 1-9.
- EC, IMF, OECD, UN, & WB, 2009. *System of National Accounts 2008*. New York: United Nations.
- EC, OECD, UN & WB, 2013. System of Environmental-Economic Accounting 2012: Experimental Ecosystem Accounting. White Cover Publication. New York: United Nations.
- GAMS, 2013. General Algebraic Modeling System (GAMS) Release 24.2.1. Washington, DC: GAMS Development Corporation.
- García-Frapolli, E., Schilman, A., Berrueta, V.M., Riojas-Rodríguez, H., Edwards, R.D., Johnson, M., . . . Masera, O., 2010. Beyond Fuelwood Savings: Valuing the Economic Benefits of Introducing Improved Biomass Cookstoves in the Purépecha Region of Mexico. *Ecological Economics*, 69(12), 2598-2605.

- Giesecke, J.A. and Madden, J.R., 2013. Regional Computable General Equilibrium Modeling, in Peter B. Dixon and Dale W. Jorgenson, eds., *Handbook of Computable General Equilibrium Modeling*, Chapter 7, Pages 379-475, North-Holland: Amsterdam.
- Global Alliance for Clean Cookstoves, 2014. *Plan de Acción Nacional de Guatemala para Estufas y Combustibles Limpios*. Guatemala City: Global Alliance for Clean Cookstoves.
- Habermehl, H., 2007. Economic Evaluation of the Improved Household Cooking Stove Dissemination Programme in Uganda. Eschborn: GTZ.
- Harrison, W.J. & Pearson, K.R., 1996. Computing Solutions for Large General Equilibrium Models Using GEMPACK. *Computational Economics*, 9, 83-127.
- Hertel, T.W., Tyner, W.E. & Birur, D.K., 2010. The Global Impacts of Biofuel Mandates. *The Energy Journal*, 31 (1): 75-100.
- INAB, 2015. *Estrategia Nacional de Producción Sostenible y Uso Eficiente de Leña 2013-2014*. Ciudad de Guatemala: INAB.
- INAB, IARNA-URL, & FAO., 2012. *Oferta y Demanda de Leña en la República de Guatemala*. Ciudad de Guatemala: INAB, IARNA-URL and FAO.
- INE, 2011. Encuesta Nacional de Condiciones de Vida, ENCOVI 2011. Guatemala City: Instituto Nacional de Estadística. Retrieved from:
<https://www.ine.gob.gt/index.php/encuestas-de-hogares-y-personas/condiciones-de-vida>
- Jagger, P., & Shively, G., 2014. Land Use Change, Fuel Use and Respiratory Health in Uganda. *Energy Policy*, 67, 713-726. doi:http://dx.doi.org/10.1016/j.enpol.2013.11.068

- King, B., 1985. What is SAM? In Pyatt & Round (Eds.), *Social Accounting Matrices: A Basis for Planning*. Washington, D.C.: World Bank.
- Lambe, F., & Ochieng, C., 2015. Improved Cookstoves in Central America: Health Impacts and Uptake. Stockholm: Stockholm Environment Institute.
- Lofgren, Hans, Rebecca Lee Harris & Sherman Robinson, 2002. A Standard Computable General Equilibrium (CGE) Model in GAMS, *Microcomputers in Policy Research* 5. Washington, D.C.: IFPRI.
- McCracken, J.P., & Smith, K.R., 1998. Emissions and Efficiency of Improved Woodburning Cookstoves in Highland Guatemala. *Environment International*, 24(7), 739-747.
- Millenium Ecosystem Assessment [MA]., 2005. *Ecosystems and Human Well-being: Synthesis*. Washington, D.C.: Island Press.
- MEM, 2013. *Política Energética 2013-2027: Energía para el Desarrollo*. Guatemala City: MEM.
- Mercado, R. & Cicowiez, M., 2016. Crecimiento Argentino en el Largo Plazo: Un Modelo Intertemporal y una Agenda Empírica, *Desarrollo Económico* Enero-Abril.
- Narayanan, B., Aguiar, A., & McDougall, R., 2015. Global Trade, Assistance and Production: The GTAP 9 Data Base. West Lafayette: GTAP. Retrieved from https://www.gtap.agecon.purdue.edu/databases/v9/v9_doco.asp
- Obst, C., & Eigengraam, M., 2016. Using the SEEA Experimental Ecosystem Accounting Framework to Advance I-O and CGE Integrated Environmental-Economic Modelling. Paper presented at the GTAP Annual Conference, Washington DC.

- Pikitch, E.K., Santora, C., Babcock, E.A., Bakun, A., Bonfil, R., Conover, D.O., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., Houde, E.D., Link, J., Livingston, P.A., Mangel, M., McAllister, M.K., Pope, J., & Sainsbury, K.J., 2004. Ecosystem-based Fishery Management. *Science*, 305: 346–347
- Robinson, S., 1989. Multisector models, in Hollis Chenery and T. N Srinivasan (eds.), *Handbook of Development Economics*, Vol. 2, North Holland.
- Round, J., 2003. Constructing SAMs for Development Policy Analysis: Lessons Learned and Challenges Ahead. *Economic Systems Research*, 15(2), 161-183. doi:10.1080/0953531032000091153
- Sánchez, M.V. and Cicowiez, M. 2014. Trade-offs and Payoffs of Investing in Human Development, *World Development*, 62: 14-29.
- SEGEPLAN, 2010. *Tercer Informe de Avances en el Cumplimiento de los Objetivos d Desarrollo del Milenio*. Guatemala City: SEGEPLAN.
- Singh, R.J. and Barton-Dock, M., 2015. Haiti: Toward a New Narrative, Washington, DC: World Bank.
- Smith-Sivertsen, T., Díaz, E., Pope, D., Lie, R. T., Díaz, A., McCracken, J., . . . Bruce, N., 2009. Effect of Reducing Indoor Air Pollution on Women's Respiratory Symptoms and Lung Function: The RESPIRE Randomized Trial, Guatemala. *American Journal of Epidemiology*, 170(2), 211-220.
- Smith, K. R., Frumkin, H., Balakrishnan, K., Butler, C. D., Chafe, Z. A., Fairlie, I., . . . Schneider, M., 2013. Energy and Human Health. *Annual Review of Public Health*, 34(1), 159-188. doi:10.1146/annurev-publhealth-031912-114404

- Smith, K. R., McCracken, J. P., Weber, M. W., Hubbard, A., Jenny, A., Thompson, L. M., . . . Bruce, N., 2011. Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. *The Lancet*, 378(9804), 1717-1726. doi:10.1016/S0140-6736(11)60921-5
- TEEB (Ed.), 2010. *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*. London: Earthscan.
- United Nations, European Commission, Food and Agriculture Organization, International Monetary Fund, Organisation for Economic Cooperation and Development, & The World Bank, 2014. *System of Environmental Economic Accounting 2012- Central Framework*. New York: UN, EC, FAO, IMF, OECD and the World Bank.
- United Nations, European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development, World Bank, 2005. *Handbook of National Accounting: Integrated Environmental and Economic Accounting 2003*, Studies in Methods, Series F, No.61, Rev.1, Glossary, United Nations, New York, para. 10.159.
- Vos, R. and Sánchez, M.V., 2010. A Non-Parametric Microsimulation Approach to Assess Changes in Inequality and Poverty, *International Journal of Microsimulation* 3 (1): 8-23.
- World Bank, 2011. The Changing Wealth of Nations. Measuring Sustainable Development in the New Millennium. Washington DC: World Bank. Retrieved from <https://siteresources.worldbank.org/ENVIRONMENT/Resources/ChangingWealthNations.pdf>

Appendix A. Construction of an Environmentally Extended Supply and Use Table

The first step toward developing the database that underpins IEEM is the production of an Environmentally Extended Supply and Use Table (hereafter EE SUT) based on the SEEA. Guatemala's EEA are used to produce the EE SUT for Guatemala. Based on Guatemala's EEA, a single consistent framework was constructed that combines natural economic and physical information. This framework extends the monetary SUTs of the SNA with extensions to incorporate a column for the environment, and rows for natural inputs and residuals as proposed by the SEEA.

Although the aggregated Guatemalan EEA tables published by the statistical authorities were consistent with relevant SEEA and other international classifications, in the case of Guatemala, it was found that some preliminary steps would be required to map different levels of data disaggregation used in the international standard classification system for commodities and industries⁷, and local aggregation decisions and adaptations made by Guatemala's Central Bank, and other government institutions working on development of Guatemala's EEA. In some cases, the locally adapted classifications mixed levels of disaggregation, making it impossible to find unique correspondence between a particular commodity group in the Guatemalan EEA, for example, with a standardized classification used in the Central Product Classification (CPC) System.

In order to address this challenge, an ad-hoc unique identifier classification approach was used to account for every data item from various sources, whether it clearly belonged to one of the standard international classifications or if there were ambiguities that made this distinction

⁷ For industries, see: <http://unstats.un.org/unsd/cr/registry/regcst.asp?Cl=27>
and for commodities, see: <http://unstats.un.org/unsd/cr/registry/cpc-21.asp>

difficult. Data processing steps like these are not uncommon when bringing together information from various sources and workflows.

The resulting EE SUT starts with the basic structure of a SUT as outlined in the SNA (EC et al., 2009) and adapted locally to the Guatemalan economy. Information on environmental interactions of economic agents (economic activities, households and the government) in the basic SUT is then added. This extends the SUT to account for environmental inputs to the economy, and emissions and waste returned back from the economy to the environment.

Although conceptually, the EE SUT follows the structure of tables in the SEEA Central Framework, some rearrangement along thematic lines is beneficial to facilitate analysis and interpretation. For example, rows explaining water used for irrigation were rearranged such that they sit adjacent to rows that describe water returns from that same form of irrigation. In the tables proposed by the SEEA Central Framework, one environmental input (e.g. water) would be found above all transactions within the economy, with water returned to the environment below all economic transactions and in a residual outputs section.

The EE SUT is a double entry framework that shows socioeconomic and environmental interactions on the rows and 21 different types of transactions on the columns. Table A1 depicts an EE SUT, with data cells that are typically populated, blackened.

Table A1. Basic structure of the Environmentally Extended Supply and Use Table; Authors' own elaboration.

	T01	T02	T03	T04	T05	T06	T07	T08	T09	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21
01. Supply (Monetary)																					
02. Use (Monetary)																					
03. Value Added (Monetary)																					
04. Employment																					
05. Water supply (Registered/Unregistered)																					
06. Water use (Registered/Unregistered)																					
07. Cultivated Area (Ha)																					
08. Rainfed irrigation use (m3)																					
09. Sprinkler irrigation use (m3)																					
10. Drip irrigation use (m3)																					
11. Gravity use (m3)																					
12. Other use (m3)																					
13. All irrigation (m3)																					
14. Sprinkler irrigation return (m3)																					
15. Drip irrigation return (m3)																					
16. Gravity return (m3)																					
17. Other return (m3)																					
18. Energy supply (terajoule)																					
19. Energy use (terajoule)																					
20. Carbon Dioxide supply (CO2 tonnes)																					
21. Nitrous Oxide supply (CO2 tonnes equivalent)																					
22. Methane supply (CO2 tonnes equivalent)																					
23. Forest products supply (m3)																					
24. Forest products use (m3)																					
25. Animal species supply (number of individuals)																					
26. Animal species use (number of individuals)																					
27. Residuals supply (tonnes)																					
28. Residuals use (tonnes)																					
29. Subsoil resource supply (tonnes)																					
30. Subsoil resource use (tonnes)																					
31. Fishery supply (tonnes)																					
32. Fishery use (tonnes)																					

Note: Column names correspond to: T01 Output/Intermediate consumption, T02 Environment, T03 Imports of goods, T04 Imports of services, T05 CIF/FOB adjustment on imports, T06 Value added tax (VAT), T07 Tariffs exc. VAT on imports, T08 Taxes on products, excluding VAT and Tariffs, T09 Subsidies on products, T10 Trade margins, T11 Transportation margins, T12 Electricity, gas, water margins, T13 Exports of goods, T14 Exports of services, T15 Household final consumption, T16 NFPI final consumption, T17 Individual government final consumption, T18 Collective government final consumption, T19 Gross capital formation, T20 Stock variation, T21 Valuable objects.

The majority of columns correspond to transactions that are mostly relevant for the monetary and socioeconomic data domain represented by row sections 01 Supply (Monetary) and 02 Use (Monetary). Blackened cells in the table are not single values, rather, they are either commodity by industry matrices (T01) or commodity by transaction column vectors (T02-T021).

Commodities and industries are disaggregated according to the CPC system and the International Standard Industry Classification (ISIC), respectively.

As shown in table A1, the EE SUT is divided in 32 different sections of either supply, use, or complementary socioeconomic information for: (i) National Accounts monetary and socioeconomic information (sections 01 through 04); (ii) water accounting information (sections 05 through 17); (iii) energy accounting and greenhouse gas emissions information (sections 18 through 22); (iv) forest accounts information (sections 23 through 26); (v) residuals accounting information (sections 27 and 28); (vi) subsoil resources information (sections 29 and 30); and (vii) fisheries information (sections 31 and 32).

Appendix B. Building a MacroSAM and a Disaggregated SAM

The first step of building a SAM is to construct a schematic representation of the economy based on macroeconomic aggregates from the National Accounts. Specifically, data from the integrated economics accounts and the SUT are combined to build a MacroSAM as shown in Table B2. This step helps ensure consistency in the data at all levels of SAM disaggregation. SEEA data is not required for the construction of the MacroSAM. For Guatemala, the complete set of National Accounts was available (which is not always the case) thus, no additional information was required to build the MacroSAM. When this is not the case, additional data on the balance of payments and government accounts/fiscal data needs to be obtained from other sources to construct the MacroSAM.

Table B2. MacroSAM for Guatemala 2010 (GDP share, percent); source: Authors' own elaboration.

	act	com	f-lab	f-cap	cssoc	tax-act	tax-imp	tax-com	tax-dir	hhd	gov	row	sav	invng	invg	dstk	total
act		160.6															160.6
com	66.9									86.1	10.5	25.1		11.9	2.9	-0.9	202.5
f-lab	50.0											0.2					50.2
f-cap	40.6																40.6
cssoc	2.5																2.5
tax-act	0.6																0.6
tax-imp		0.7															0.7
tax-com		5.6															5.6
tax-dir										3.3		0.3					3.5
hhd			50.2	40.6	2.5						3.2	12.0					108.5
gov				0.0		0.6	0.7	5.6	3.5	4.1		0.2					14.6
row		35.6	0.0							3.0	0.7						39.3
sav										12.1	0.3	1.5					13.9
invng													11.9				11.9
invg													2.9				2.9
dstk													-0.9				-0.9
total	160.6	202.5	50.2	40.6	2.5	0.6	0.7	5.6	3.5	108.5	14.6	39.3	13.9	11.9	2.9	-0.9	657.1

Notes: the following abbreviations are used: act = activities; com = commodities; f-lab = labor; f-cap = gross operating surplus + mixed income; tax-act = activity taxes; tax-com = commodity taxes; sub-com = commodity subsidies; tax-imp = import tariffs; tax-dir = direct taxes; hhd = households; gov = government; row = rest of the world; sav = savings; invng = non-government investment; invg = government investment; dstk = stock change.

Additionally, our MacroSAM further disaggregates labor payments into gross operating surplus and mixed income. In other words, the MacroSAM provides information on the labor income of salaried and non-salaried (i.e., self-employed income and income from unincorporated enterprises owned by households) workers. Also, the activity and commodity taxes accounts are further split in order to single out activity and commodity subsidies which follows the structure of the SUTs. Finally, the MacroSAM further disaggregates the household account into: more narrowly defined households, non-profit institutions serving households (NPISH), and enterprises (non-financial and financial corporations).

Once a MacroSAM has been constructed, the next step is to disaggregate economic sectors and then institutions according to the data available as well as the intended application of the SAM.

Specifically, sectoral information from the SUTs is used as the main input to disaggregating activities and commodities. In the case of Guatemala, a highly disaggregated MicroSAM was produced with 122 activities and 219 commodities for the base year of 2010. Due to space limitations, an aggregate version of the accounts in the MicroSAM is reproduced in Table B3 (Panel A). Panel B of Table B3 lists the environmental accounts in the extended SAM.

Some additional adjustments were required in constructing the SAM. These adjustments include the following:

1. Treatment of export sectors with no domestic production (i.e. re-exports);
2. The splitting of gross operating surplus among payments to capital and land used in the agriculture and forestry sectors, and; the splitting of gross operating surplus among payments to capital, land and other natural resources used in the fishing and mining and mining sectors. These splits were undertaken based on Guatemala's EEA and data from the Global Trade Analysis Project (GTAP) database (Narayanan, Aguiar, & McDougall, 2015).
3. The splitting of trade and transport margins between domestic products, imports, and exports. These splits were undertaken assuming that the distribution of margins are proportional to the corresponding size of each transaction, and;
4. Adjustments to the 'stocks' account. In the SAM, stock variation as a component of total gross investment is expressed as a payment from the savings-investment account ("sav", in table B.2) to the stock variation account ("dstk", in table B.2).

Table B3: Accounts in the aggregated Guatemala 2010 ESAM; Source: Authors' elaboration.

Panel A: Economic Accounts				
Category - #		Item	Category - #	Item
Sectors- activities and commodities (29)	Primary (9)	Coffee	Factors (8)	Labor, salaried unskilled
		Banana		Labor, salaried skilled
				Labor, non-salaried unskilled
		Cereals		Labor, non-salaried skilled
		Other agriculture		Capital
		Livestock		Land
		Other forestry		Nat res, fishing
		Fuelwood		Nat res, mining
		Fishing		
		Mining		
	Manufacturing (13)	Food prod	Trade and transport margins (3)	Dist marg, domestic
		Beverages and tobacco prod		Dist marg, imports
		Textiles and wearing apparel		Dist marg, exports
		Wood and wood prod	Taxes and subsidies (8)	Social contributions, unskilled
		Paper and paper prod		Social contributions, skilled
		Refined petroleum prod		Tax, activities
		Chemicals		Subsidy, activities
		Rubber and plastics		Tax, value added (VAT)
		Non-metallic mineral prod		Tax, imports (tariffs)
		Basic metals and metal prod		Tax, commodities
		Machinery and equipment		Subsidy, commodities
				Tax, income
		Other manufactures	Institutions (13)	Households, rural, quintiles 1-5
		Recycling		Households, urban, quintiles 1-5
	Services (7)	Electricity		Enterprises
		Water		Government
		Construction		Rest of world
		Trade	Savings-Investment (4)	Savings
		Hotels and restaurants		Investment, private
		Transport		Investment, government
		Other services		Stock change

Panel B: Environmental accounts

Category - #	Item	Category - #	Item
Water (11)	Registered, supply	Energy (10) (*)	Supply, Fuelwood
	Registered, use		Supply, Mining
	Non-registered, rainfed		Supply, Refined petroleum prod
	Non-registered, sprinkler irrigation		Supply, Recycling
	Non-registered, drip irrigation		Supply, Electricity
	Non-registered, gravity use		Use, Fuelwood
	Non-registered, other use		Use, Mining
	Return, sprinkler irrigation		Use, Refined petroleum prod
	Return, drip irrigation		Use, Recycling
	Return, gravity use		Use, Electricity
	Return, other use	Emissions (12)	Carbon-Diox (CO2), by comm, 4
Forestry Res (14)	Supply by commodity, 7		Nitrous Oxide (N2O), by comm, 4
	Use by commodity, 7		Methane (CH4), by comm, 4
Fishing Res (4) (*)	Supply, Fishing	Waste (2) (*)	Total supply
	Supply, Food prod		Total use
	Use, Fishing	Land use (8)	Agriculture, 4
	Use, Food prod		Bushes
Mining Res (4) (*)	Total supply		Pastures
	Total use		Forest
	Initial stock		Other
	Final stock		

(*) more disaggregated information is available in Guatemala SEEA

Appendix C. From an EE SUT to Environmentally Extended SAM

What follows are some of the basic steps required to build an Environmentally Extended SAM (ESAM) as well as the satellite matrices used to track stocks and flows of environmental resources in physical units. The basic structure of the ESAM is presented in stylized form in Table C4 where the first eight accounts are those found in a standard SAM.

Table C4. A stylized environmentally-extended social accounting matrix; source: Authors' own elaboration.

receipts\spending														
	act	com	factors	hhd	gov	RoW	sav-inv	total mon	enviro	water-reg	water-unreg	other resources	waste	emissions
act		dom-prod						inc firms		supply		supply	by-prod	by-prod
com	IO			C	G	E	I	demand						
factors	VA							inc fac						
hhd			VA					inc hhd						by-prod
gov	T	T						inc gov						
RoW		M	INC-F	TR				out forex				M	imp	
sav-inv				SH	SG	SF		sav						
total mon	cost firms	supply	spnd fac	spnd hhd	spnd gov	in forex	inv							
enviro	enviro invest									source	source			
water-reg	int-dem			fin-dem										
water-unreg	int-dem													
other resources	int-dem			fin-dem		E	fin-dem							
waste	int-dem						fin-dem		sink					
emissions									sink					

Where: act = activities, com = commodities, dom-prod = domestic production, gov = government, RoW = rest of the world, sav-inv = savings-investment, total-mon = total monetary, enviro = environment, water-reg = water registered, water-unreg = water unregistered, IO = intermediate consumption, VA = value added, T = taxes, M = imports, INC-F = factor income to/from abroad, TR = transfers, C = private consumption, G = government consumption, E = exports, I = investment, SH = households savings, SG = government savings, SF = foreign savings, int-dem = intermediate demand, and fin-dem = final demand. Source: Author's own elaboration.

In an ESAM, the basic SAM framework is extended by incorporating environmental accounts. Specifically, accounts are added which represent the environment as the source of natural capital and as a sink for by-products generated through economic activity (UN et al., 2014). For illustrative purposes, in the ESAM of table C4, three natural inputs are singled out: registered water, un-registered water, and other resources. As shown in cell [act,water-reg], registered water is supplied by the industries, using unregistered water (i.e. from the environment) as an input; specifically, the water utility company. On the other hand, unregistered water is obtained directly from the environment, and used for irrigation in the agricultural sector, among other things.

In the case of other environmental resources, such as mining products, these can also be exported and/or imported; see cells [other-resources,row] and [row,other-resources], respectively. In addition, industries and households generate waste and emissions (i.e. cells [act,waste], [act,emissions], [hhd,emissions]) which can in turn be used as intermediate inputs (i.e. cell [waste,act]) and/or absorbed by the environment (i.e. cells [waste,environment] and [emissions,environment]). It should be noted that cells in the basic SAM are measured in local currency units, while the extra cells needed for the ESAM are measured in physical units.

Not all environmental data is amenable or practical to integrate in an ESAM. These data are housed in satellite matrices linked to the ESAM through model equations. Specifically, data on stocks are stored in satellite matrices. These satellite matrices include opening stocks, change in stocks, and closing stocks, expressed in physical and/or monetary units depending on the particular environmental resource. In the case of Guatemala, satellite accounts were developed for: (i) stocks of extractive resources, expressed in physical units; (ii) stocks of forest resources, expressed both in physical and monetary units, and; (iii) land use by activity/commodity. In the

case of extractive resources, data on stocks for 11 extractive resources and data on flows of 52 extractive resources are available in the Guatemala EEA. In the case of fisheries, Guatemala's EEA does not provide data on stocks, though this data is available from the United Nation's Food and Agriculture Organization⁸ and could be used to develop a satellite account for fisheries. With regard to land use, the satellite account records the number of hectares used to produce output of each agricultural sector, and the forestry and fuelwood sectors.

⁸ See for example: <http://www.fao.org/fishery/information/en>

Appendix D. The IEEM Platform Modules

D.1. Forest Resources Module

For the forest sector, IEEM uses monetary unit values for model calibration, specifically, quetzales per m³ of forest products. For the forest sector, both the forest account and the SUT use the same product classification. As will be shown in a later section, this is not the case for the mineral resources. IEEM tracks the commodity flows in physical units, at commodity-specific, observed unit values.

In terms of the modeling approach, the production function of the forestry sector singles out the logged land area as a factor of production. Specifically, a Constant Elasticity of Substitution (CES) function is used to combined labor and capital factors (equation F1), while a fixed coefficient assumption (i.e., Leontief) is used for the logged land area (equation F2) -- (see also land market module below. In turn, also under the assumption of fixed coefficients, intermediate inputs are exogenous quantities per unit of the activity (not shown here). Equation F3 tracks the evolution of the forestry stock which is the number of hectares used by the forest sector.

Given a small mismatch between the forest asset and forest flow accounts in the case of the Guatemalan EEA, the adjustment parameter $forstkadj_t$ is used to reconcile this incongruence and assumes that the relative size of the mismatch is constant⁹. In equation F4, the deforested area is computed, as the (negative of the) difference between forest land area in period t and forest land area in period $t-1$. Thus, equation F3 and F4 together show that deforestation occurs

⁹ This mismatch is due to an accounting decision made in the development of the Guatemalan EEA. Essentially, reductions in stock of forests due to removals from the asset accounts differ from their counterpart in the supply of products coming from the forest in the flow account. The latter are called “forest products” and “felling residues”. The explanation given by the Guatemalan EEA compilation team is that the production of fuelwood that is generated as a by-product of the sawmill, furniture, and other manufacturing activities was added to the extractions of the forest. The consequence of this mismatch is that primary extraction is mixed with reuse of residuals in the EEA.

when logging, $QFOR_t$, is greater than the natural growth rate of the forest resources,

$$QFORSTK_t (1 + forgrw_t).$$

$$(F1) \quad QVA_{a,t} = \phi_a^{va} TFP_{a,t} \left(\sum_{a \in A} \delta_a^{va} QF_{a,t}^{-\rho_a^{va}} \right)^{\frac{-1}{\rho_a^{va}}} \quad f \in F$$

$$(F2) \quad QFOR_t = ifora_a QA_{a,t} \quad a \in A$$

$$(F3) \quad QFORSTK_t = QFORSTK_{t-1} (1 + forgrw_{t-1}) - forstkadj_t QFOR_{t-1}$$

$$(F4) \quad QDEFOR_t = -(QFORSTK_t - QFORSTK_{t-1})$$

where

$QA_{a,t}$ = level of activity a

$QF_{f,a,t}$ = quantity demanded of factor f from activity a

$QDEFOR_{a,t}$ = land deforestation

$QFOR_{a,t}$ = forest area logged in a given period

$QFORSTK_t$ = stock of forestry resources

$QVA_{a,t}$ = quantity of aggregate value added

$TFP_{a,t}$ = sectoral TFP index

$forgrw_t$ = growth rate of forest resources

$forstkadj_t$ = adjustment factor for FORSTK

$ifora_{a,t}$ = area logged per unit of forestry output

Upper bound on deforestation

IEEM allows imposing an exogenous (e.g., regulated) upper bound on deforestation (equation

F5). To that end, an endogenous indirect tax at the user specified $GAMMADEFOR_t$ tax rate is

levied on the forestry activity (equation F6). When imposing an upper bound on deforestation,

one of the following two equilibrium situations will be observed: (i) deforestation is less than the specified upper bound and the tax rate is zero, or; (ii) deforestation is equal to the upper bound and the tax rate is positive. In turn, in order to mimic a regulatory mechanism, tax collection is transferred in full to the owners of the capital inputs used in the forestry sector.

$$(F5) \quad QDEFOR_t \leq qmaxdefor_t$$

$$(F6) \quad GAMMADEFOR_t \geq 0$$

$$(F7) \quad (QDEFOR_t - qmaxdefor_t) GAMMADEFOR_t = 0$$

where

$qmaxdefor_t$ = maximum level for deforestation

$GAMMADEFOR_t$ = rate of tax on forestry activity used to impose an upper bound on deforestation.

D.2. Land Market Module

Sectoral demand for agricultural land

On the demand side, the treatment of agricultural land is similar to that of other factors. Land demand in equations L1 to L2 is derived from the first order conditions of the cost minimization optimization problem solved by the representative firm in each economic activity that uses land, namely agriculture. Equation L2 defines the user price of land as the supplier price of land plus the tax on land use minus the endogenous subsidy on land use.

$$(L1) \quad QF_{f,a,t} = \left(\frac{PVA_{a,t}}{WFA_{f,a,t}} \right)^{\sigma_a^{va}} \left(\delta_{f,a}^{va} \right)^{\sigma_a^{va}} \left(\phi_a^{va} TFP_{a,t} \right)^{\sigma_a^{va}-1} QVA_{a,t} \quad f \in F \wedge a \in A$$

$$(L2) \quad WFA_{f,a,t} = \overline{WF}_{f,t} WFDIST_{f,a,t} (1 + tfact_{f,a,t} - GAMMAFA_{f,a,t}) \quad f \in F \wedge a \in A$$

where

$QF_{f,a,t}$ = quantity demanded of factor f from activity a

$PVA_{a,t}$ = value-added price for activity a

$WF_{f,a,t}$ = average price of factor f

$WFA_{f,a,t}$ = wage for factor f in activity a

$TFP_{a,t}$ = sectoral TFP index

$QVA_{a,t}$ = level of activity a

$WFDIST_{f,a,t}$ = wage distortion factor for factor f in activity a

$tfact_{f,a,t}$ = rate of factor use tax

$GAMMAFA_{f,a,t}$ = rate of factor return subsidy to f from private capital

Lower bound on sectoral land use

To enable the option of modelling land use incentive policies, IEEM allows the imposition of a lower bound of the land used by a given sector. To that end, an endogenous subsidy is introduced in equation L2 above. In turn, equations L3 to L5 are used to endogenously compute the subsidy rate on the corresponding land rent. Specifically, one of the following two equilibrium situations will be observed: (i) land use in the selected sector (e.g., managed forestry) is larger than the specified lower bound and the subsidy rate is zero, or; (ii) land use selected sector (e.g., managed forestry) is greater than or equal to the lower bound and the subsidy rate is positive. This same mechanism can be used to impose minimum factor use in other sectors should an application warrant this treatment.

$$(L3) \quad QF_{land,a,t} \geq qmin_{land,a,t}$$

$$(L4) \quad GAMMAFA_{land,a,t} \geq 0$$

$$(L5) \quad (QF_{land,a,t} - qmin_{land,a,t}) GAMMAFA_{land,a,t} = 0$$

where

$qfmin_{f,a,t}$ = minimum level of employment of factor f in activity a .

Sectoral land supply

On the supply side, IEEM allows two alternatives: (i) an upward-slopping land supply curve as formulated in equations L6a and L7, or; (ii) a vertical supply curve with total land fixed as formulated in equations L6b and L7.¹⁰ In equations L6a and L6b, deforested land (see equation F4) is added to the supply of agricultural land (see last term on the right-hand side). Equation L7 defines the total national land endowment. Next, total land supply is allocated to each sector under the assumption of perfect or imperfect mobility. In the case of perfect mobility, the return to land is uniform across sectors. In the case of imperfect mobility, the return to land in each sector is related to some extent to sectoral conditions and thus becomes sector-specific. Equation L9 computes total land supply. Equation L8 is derived from the first order condition of a Constant Elasticity of Transformation (CET) function that preserves physical additivity; this equation determines sectoral land supply.¹¹ Equation L9 defines the national return to land. Equation L10 is the equilibrium condition where supply is equal to demand for the sectoral land markets.

$$(L6a) \quad \begin{aligned} ENDOW_{i,f,t} = & \overline{endow_{i,f,t}} \overline{ENDOWADJ}_{f,t} \left(\frac{WFS_{f,t}}{CPI} \right)^{\eta_f} \\ & + \sum_{\substack{t' \leq t \in T \\ f \in FLAND}} SHIF_{i,f,t'-1} QDEFOR_{t'-1} \end{aligned} \quad f \in F$$

¹⁰ For related modeling of land use, see among others, Hertel et al. (2010).

¹¹ In the modified CET, the sum of the volume components is equal to the total volume; this specification has been used for land supply allocations in Giesecke et al. (2013).

$$(L6b) \quad \overline{ENDOW}_{i,f,t} = \overline{endow}_{i,f,t} \overline{ENDOWADJ}_{f,t} + \sum_{\substack{t' \leq t \in T \\ f \in FLAND}} SHIF_{i,f,t'-1} QDEFOR_{t'-1} \quad f \in F$$

$$(L7) \quad QFS_{f,t} = \sum_{i \in INS} \overline{ENDOW}_{i,f,t} \quad f \in F$$

$$(L8) \quad QFSA_{f,a,t} = QFS_{f,t} (\delta_{f,a}^f)^{\sigma_f^f + 1} \left(\frac{\overline{WF}_{f,t} WFDIST_{f,t}}{WFS_{f,t}} \right)^{\sigma_f^f} \quad f \in F \wedge a \in A$$

$$(L9) \quad WFS_{f,t} = \left[\sum_a (\delta_{f,a}^f)^{\sigma_f^f + 1} (\overline{WF}_{f,t} WFDIST_{f,t})^{\sigma_f^f} \right]^{\frac{1}{\sigma_f^f}} \quad f \in F$$

$$(L10) \quad QFSA_{f,a,t} = QF_{f,a,t} \quad f \in F \wedge a \in A$$

where

$\overline{ENDOW}_{i,f,t}$ = real endowment of factor f for institution i

$QFS_{f,t}$ = total supply of factor f

$QFSA_{f,a,t}$ = supply of factor f to activity a

$SHIF_{i,f,t}$ = share for institution i in the income of factor f

$WFS_{f,t}$ = supply price of factor f

η_f^s = land supply elasticity.

D.3. Water Module

This section describes how non-registered water, in other words, water not supplied by the water utility company used in agricultural activities is modeled. In Guatemala, water not supplied by the water utility company is not subject to an economic transaction and therefore, initially, has a price of zero. Then, depending on supply and demand condition, the price of water can become

greater than zero. Mathematically, equations W1 to W6 summarize the agricultural water use module of the IEEM platform.¹²

Equation W1 states that, within a given period, water demand in agricultural sectors is proportional to the corresponding commodity output in agricultural sectors. Equation W2 allows for adjustments in water demand per unit of agricultural output. Specifically, we assume a negative relation between water use per hectare of a given crop and the price of water. In turn, water demand by households is proportional to the respective population sizes (equation W3). Equations W4 to W6 represent the equilibrium conditions in the market for agricultural water. In modelling agricultural water, one of the following two situations can be observed: (i) water supply is larger than water demand and the price of water is zero, or; (ii) water demand is equal to water supply and the price of water is positive.

In the case of Guatemala, given the available information in the EEA, we assume that water supply is initially larger than water demand and the price of non-registered water is zero. Then, as water demand increases in a non-base simulation, restriction (W4) becomes binding and the price of non-registered water becomes positive, generating a cost for producers (equation W5) and an income for water owners (equation W7). In the model calibration, it is assumed that water income is allocated across institutions in proportion to their ownership of land ($SHIWAT_{i,t}$ in equation W7).

$$(W1) \quad WATD_{a,t} = IWAT_{a,t} QA_{a,t} \quad a \in A$$

¹² In its full version, IEEM can handle various water categories. In the case of Guatemala, registered and non-registered water is distinguished, while non-registered water could be further split between agriculture and non-agriculture uses.

$$(W2) \quad IWAT_{a,t} = \overline{iwat}_{a,t} \left(\frac{PWAT_t}{PWAT_t^0} \right)^{\eta_a^{wat}} \quad a \in A$$

$$(W3) \quad WATD_{h,t} = \overline{iwat}_{h,t} pop_{h,t} \quad h \in H$$

$$(W4) \quad \sum_{a \in AAGR} WATD_{a,t} \leq \overline{WATS}_t$$

$$(W5) \quad PWAT_t \geq 0$$

$$(W6) \quad \left(\sum_{a \in AAGR} WATD_{a,t} - \overline{WATS}_t \right) PWAT_t = 0$$

$$(W7) \quad YIWAT_{i,t} = SHIWAT_{i,t} PWAT_t \sum_{a \in AAGR} WATD_{a,t} \quad i \in INS$$

where

A = set of activities

$AAGR$ = set of agricultural activities

$WATD_{a,t}$ = water demand

$WATS_t$ = water supply

$PWAT_t$ = water price

$YIWAT_{i,t}$ = institutional income from water

$SHIWAT_{i,t}$ = share of institution ins in total water income

η_a^{wat} = price elasticity of water demand.

In addition, we also consider water categories that record monetary and physical information in the SUT and the SEEA, respectively. Specifically, this is registered water supplied by the water utility company. In those cases, water is treated as a “standard” commodity but model calibration is conducting using value (quetzales) and volume (m³) data. In so doing, we found that unit values for registered water demand differ among water demanders. Thus, we introduce an

implicit water tax rate or distortion factor that allows modeling water prices that (exogenously) differ across demanders, relative to an economy-wide average water price.

D.4. Energy and Emissions Module

Following the SEEA, IEEM is structured so as to include any number of emissions (indexed by *emi*) generated through production processes and by final users of goods and services. In the Guatemalan EEA, emissions from the following pollutants are accounted for: carbon dioxide (in CO₂ tons), nitrous oxide (in CO₂ tons equivalent), and methane (CO₂ tons equivalent). In IEEM, equations EM1 and EM2 determine the level of emissions from intermediate and final demand, respectively. In equation EM3, the basic coefficient is *iemibar*, which represents the initial level of emissions per unit of consumption, for example, tons of CO₂ emitted per m³ of fuelwood consumed. In turn, changes in IEMIADJ would reflect exogenous changes in the emissions coefficients that could be brought about by autonomous improvements in the level of emissions per unit of use.

Equation EM4 determines the level of emissions generated by emitter, which in the Guatemalan EEA are industries and households. This information can be used, for example, to track the level of emissions from certain sectors. Equation EM5 determines the total level of emissions, for emission *emi*. Finally, equation EM6 calculates the total of greenhouse gas emissions where the individual gases are weighted by their global warming potential (GWP)¹³. In the Guatemalan EEA all emissions are greenhouse gases.

IEEM enables limits to be imposed on the level of emissions. To that end, an endogenous tax on emissions may be introduced, for example, a carbon tax, at the same time that emissions are capped at EMITOT(*emi*,*t*).

¹³ For more information, see: http://unfccc.int/ghg_data/items/3825.php

$$(EM1) \quad EMIS_{emi,c,a,t} = IEMI_{emi,c,a,t} QINT_{c,a,t} \quad emi \in EMI \wedge c \in C \wedge a \in A$$

$$(EM2) \quad EMIS_{emi,c,h,t} = IEMI_{emi,c,h,t} QH_{c,h,t} \quad emi \in EMI \wedge c \in C \wedge h \in H$$

$$(EM3) \quad IEMI_{emi,c,ac,t} = \overline{iem_i}_{emi,c,ac,t} IEMIADJ_{emi,c,ac,t} \quad emi \in EMI \wedge c \in C \wedge ac \in (A \cup H)$$

$$(EM4) \quad EMISAC_{ac,t} = \sum_{emi \in EMI, c \in C} EMI_{emi,c,ac,t}$$

$$(EM5) \quad EMISTOT_{emi,t} = \sum_{c \in C, ac \in A \cup H} EMIS_{emi,c,ac,t}$$

$$(EM6) \quad EMISGHG_t = \sum_{emi} gwpwts_{emi} EMISTOT_{emi,t}$$

where

EMI = set of emission categories

A = set of activities

C = set of commodities

H = set of households

$EMIS_{emi,c,ac,t}$ = emissions of emi from commodity c by emitter ac

$QINT_{c,a,t}$ = quantity of commodity c as intermediate input to activity a

$QH_{c,h,t}$ = quantity consumed of commodity c by household h

$IEMI_{emi,c,ac,t}$ = emissions of emi per unit demanded of commodity c by emitter ac

$EMISAC_{ac,t}$ = total emissions by emitter ac

$EMITOT_{emi,t}$ = total emission by pollutant emi

$EMISGHG_t$ = total of GHG emissions

$gwpwts_{emi}$ = global warming potential weights.

D.5. Mineral Resources Module

In the case of the mining sector, mineral extraction over time is limited by the size of recoverable reserves. Minerals are nonrenewable resources and extraction costs are a function of the stock of

recoverable reserves; the smaller the remaining stock, the higher is the marginal cost of extraction (Ghadimi, 2007). Mathematically, we relate mining sector productivity to the mineral resource stock, expanding the total factor productivity (TFP) definition to that shown in equation MN1. Equation MN2, due to different classification of commodities and extractive resources, determines the extraction of resource type ext through a fixed coefficient of the level of output of the corresponding mining sector. For example, the extractive resources are classified as oil, natural gas, silica sand, attapulgite, chromite, quartz, and others. On the other hand, the SUT follows the Central Product Classification with less sectoral detail. Of course, the information in the extractive resources account can be aggregated to match the commodities in the SUT, particularly at the aggregate level such as “non-metallic minerals”.

In equation MN3, the stock of mineral resources is updated, based on the stock remaining from the previous period, extraction, and new recoverable discoveries. In this formulation, where new discoveries do not make up for extraction, TFP in mining activities decreases over time as the stock of minerals is depleted, reflecting the increase in the marginal cost of extraction. Considering that the baseline scenario is generated under the assumption of a balanced growth path, to avoid changes in sectoral TFP in the baseline, it is assumed that new discoveries are equal to current extraction as indicated in equation MN4. Thus, sectoral TFP, which is a function of the remaining stock, does not change in the baseline. This assumption in IEEM can be calibrated according to the particular resource and country context that is the subject of analysis.

$$(MN1) \quad TFP_{a,t} = tfpexog_{a,t} \prod_{inv \in INVGINF} \left(\frac{KG_{inv,t}}{KG_{inv}^{00}} \right)^{tfpelas_{a,inv}} \prod_{ext \in EXT} \left(\frac{EXTSTK_{ext,t}}{EXTSTK_{ext}^{00}} \right)^{fpelas_{a,ext}} \quad a \in AMIN$$

$$(MN2) \quad EXTS_{ext,a,t} = iext_{ext,a,t} QA_{a,t} \quad ext \in EXT \wedge a \in AMIN$$

$$(MN3) \text{ EXTSTK}_{ext,t} = \text{EXTSTK}_{ext,t-1} - \sum_{a \in A} \text{EXTS}_{ext,a,t-1} + \text{EXTDISC}_{ext,t-1} \quad ext \in EXT$$

$$(MN4) \text{ EXTDISC}_{ext,t} = \sum_{a \in A} \text{EXTS}_{ext,a,t}^0 \quad ext \in EXT$$

where

EXT = set of extractive resources

$AMIN$ = set of mining activities

$INGINF$ = set of government investment in public infrastructure

$QA_{a,t}$ = level of activity a

$TFP_{a,t}$ = sectoral TFP index

$KG_{inv,g,t}$ = government capital stock

$EXTS_{ext,ac,t}$ = supply of extractive resource ext by supplier ac

$EXTSTK_{ext,t}$ = stock of extractive resource ext

$EXTDISC_{ext,t}$ = discovery of extractive resource ext

$tfpexog_{a,t}$ = exogenous component of sectoral TFP

$iext_{ext,a}$ = supply of extractive resource ext per unit of output from act a

$tfpelas_{a,ext}$ = elasticity of the resource output with respect to the available resource stock.

D.6. Aquatic Resources Module

A CGE approach has not been widely applied to exploring fisheries issues, though there is significant unexplored potential for extending a standard CGE framework to take into account fish population dynamics (Banerjee et al., 2016). The approach developed in this module follows guidance from the literature related to ecosystem-based management of fisheries. This is an integrated approach to management that considers the entire ecosystem, including humans (Pikitch et al., 2004). An extension to this approach involves incorporating a biology module representing the biological processes that affect fisheries productivity. Mathematically, a biological logistic production function for fisheries may be written in two steps as:

$$(FS1) \quad B_t = B_{t-1} + \left[rB_{t-1} \left(1 - \frac{B_{t-1}}{k} \right) \right] - QA_t$$

where

B_t = resource stock (biomass; marine population) in time t

QA_t = quantity of fish harvested; level of activity a

r = intrinsic growth rate of the resource stock

k = carrying capacity of the environment.

Then, equation (FS2) is the classical harvest function often used in bio-economic analysis.

Equation (FS2) is frequently referred to as the catch-per-unit-effort production function (Conrad,

2010), because it assumes that catch per-unit of effort QA_t/E_t is proportional to the stock B_t

with $q > 0$ being the constant of proportionality.

$$(FS2) \quad QA_t = qB_tE_t$$

where

E_t = fishing effort as function of labor and capital

q = catchability coefficient.

The effect of changing stock size B_t may then be modeled by modifying the production function

for the fishing sector in IEEM. Specifically, equation FS2 is replaced with

$$(FS3) \quad QA_a = A_a \phi_a^{va} TFP_a \left(\sum_f \delta_{f,a}^{va} QF_{f,a}^{-\rho_a^{va}} \right)^{\frac{-1}{\rho_a^{va}}}$$

where alternative ecosystem states and associated stock levels B_t are incorporated into the shift

parameter A_t ($=qB_t$). Thus, when B_t increases, $A_t > 1$, this in turn leads to an adjustment in

fishing effort, which is a function of capital and labor inputs in the CGE model. Typically, partial

equilibrium models of fisheries use "effort" as the single factor of production. On the other hand, IEEM considers both capital and labor at the same time that the fishing sector interacts with other sectors and competing factor demand. Consequently and in contrast to conventional partial equilibrium formulations, IEEM captures the economy-wide effects of stock variation.

In the dynamic implementation of IEEM, when the capital stock grows at the same rate as the effective labor force, the economy is on a balanced growth path. However, balanced growth cannot be a feature of the aquatic resource module, because species populations cannot grow continually. In fact, unlike the growth of the effective labor force and capital stock, ecosystem populations are limited by photosynthesis and tend to converge to steady states, with zero net growth. Thus, the sectors reliant on ecosystem inputs will not be expected to grow at the rate of the (effective) labor and capital stocks.

Usually, a common objective of renewable resource management such as fisheries is to maintain a standing (per capita) stock $B_t \equiv B$, so as to attain a maximum sustainable yield (MSY). Note that steady-state equilibrium means that corresponding to each biomass level B is a certain rate of harvest Q that just balances the natural rate of growth and thus maintains an intertemporal equilibrium situation. This rate of harvest, at which $Q_t = [rB_{t-1}(1 - B_{t-1}/k)]$, is the sustainable yield, and MSY is simply the maximum sustainable yield. Of course, there is a level of fishing effort (E_{MSY}) and quantity of fish harvested (Q_{MSY}) that corresponds to the MSY. In turn, the modeling of an upper bound to the amount of fishing permitted in a given year (i.e., a quota) can be introduced as follows, using the following formulation:

$$(Q_t - \bar{Q}_{MSY})' = 0$$

$$Q_t \leq \bar{Q}_{MSY}$$

$$Q_t \geq 0$$

$$\gamma \geq 0$$

where gamma the (endogenously determined) rent per unit of fish harvested. Thus, one of the following two situations can occur:

$$(i) \quad Q_t < \bar{Q}_{MSY} \text{ and } \gamma = 0$$

$$(ii) \quad Q_t = \bar{Q}_{MSY} \text{ and } \gamma > 0$$

In case (ii), when the fishing quota is binding, the owner of the fishing rights would collect the rents.

D.7. Waste and Residuals Module

For waste and residuals, the Guatemalan EEA provides information on physical units (tons) of the supply and use of waste and residuals (e.g. hospital waste, paper waste, glass waste and rubber waste, among others) by activities, households, and the rest of the world through imports (supply) and exports (use). In the Guatemalan EEA, waste and residuals accounts follow a specific classification, however these are currently not linked to the commodities classification of the ESAM. In the SEEA, the supply of waste and residuals is greater than that which is used or demanded. The supply of waste and residuals is therefore equal to the sum of the amount demanded and the amount returned to the environment. The fact that the number of residuals supplied (23) is larger than the number of residuals used (8) is illustrative of this feature of the Guatemalan EEA.

In terms of modeling, we assume that the supply (see equations W1 to W3) and use (see equations W4 and W5) of waste and residuals is a fixed proportion of the corresponding volume

variable in the model. In other words, IEEM is able to track the supply and use of waste residuals. For example, the supply of paper waste by the households is a fixed proportion of total household consumption (equation W2). However, due to the specific classification of waste and residuals, we cannot link their supply and use to the supply and use of specific commodities in the ESAM.

$$(W1) \quad RESIDS_{resid,a,t} = iresids_{resid,a,t} QA_{a,t} \quad resid \in RESID \wedge a \in A$$

$$(W2) \quad RESIDS_{resid,h,t} = iresids_{resid,h,t} \sum_c PQD_{c,h}^{00} QH_{c,h,t} \quad resid \in RESID \wedge h \in H$$

$$(W3) \quad RESIDS_{resid,row,t} = iresids_{resid,row,t} \sum_c pwm_{c,h}^{00} EXR^{00} QM_{c,t} \quad resid \in RESID$$

$$(W4) \quad RESIDD_{resid,a,t} = iresidd_{resid,a,t} QA_{a,t} \quad resid \in RESID \wedge a \in A$$

$$(W5) \quad RESIDD_{resid,h,t} = iresidd_{resid,h,t} \sum_c PQD_{c,h}^{00} QH_{c,h,t} \quad resid \in RESID \wedge h \in H$$

where

$RESID$ = set of waste and residuals categories

$RESIDS_{resid,ac,t}$ = supply of waste of residual $resid$ by supplier ac

$RESIDD_{resid,ac,t}$ = demand of waste of residual $resid$ by demander ac

$iresids_{resid,ac,t}$ = waste and residuals per unit supplied by supplier ac

$iresidd_{resid,ac,t}$ = waste and residuals per unit demanded by demander ac .

D.8. Household Consumption Module

Firstly, household consumption expenditure is distributed across composite commodities according to a Stone-Geary utility function, from which a linear expenditure system is derived (equation H1). Secondly, household decide on the composition of the commodities bundle (equation H2) through a CES production function. Alternatively, the model allows for a different

classification of consumer and producer goods and services. In fact, a “make matrix” of three dimensions (i.e., c [produced commodities], v [consumed commodities], and h [households]) is used where each consumed good can be composed of one or more supplied goods, combined using a CES function.

For example, households can consume the good “energy” composed by the produced goods fuelwood, petroleum goods, and electricity; in other words, “energy” is not produced by one individual activity in the model. Equation (H3) defines the price of the composite commodities. Equation (H4) is the corresponding production function of the composite commodities. In Section 4, we simulate autonomous improvements in energy efficiency in the household consumption of fuelwood through an increase in the $qheff_{c,h,t}$ parameter in equation (H2).

$$(H1) \quad QH_{v,h,t} = qhmin_{v,h,t} + \frac{\delta_{v,h}^{les}}{PCV_{v,h,t}} \left(EH_{h,t} - \sum_{v' \in CH} PCV_{v',h,t} qhmin_{v',h,t} \right) \quad v \in V \wedge h \in H$$

$$(H2) \quad QCV_{c,v,h,t} = \left(\frac{PCV_{v,h,t}}{PQD_{c,h,t}} \right)^{\sigma_{v,h}^c} \left(\delta_{c,v,h}^c \right)^{\sigma_{v,h}^c} \left(qheff_{c,h,t} \phi_{v,h}^c \right)^{\sigma_{v,h}^c - 1} QH_{v,h,t} \quad c \in C \wedge v \in V$$

$$(H3) \quad PCV_{v,h,t} QH_{v,h,t} = \sum_{c \in C} PQD_{c,h,t} QCV_{c,v,h,t} \quad c \in C \wedge h \in H$$

$$(H4) \quad QH_{v,h,t} = \phi_{v,h}^c \left(\sum_{c \in C} \delta_{c,v,h}^c QCV_{c,v,h,t}^{-\rho_{v,h}^c} \right)^{\frac{-1}{\rho_{v,h}^c}} \quad v \in V \wedge h \in H$$

where

V = set of composite consumption commodities

$PCV_{v,h,t}$ = price of (household-specific) composite commodity v (e.g., energy)

$PQD_{c,h,t}$ = composite commodity demand price for c demanded by h

$QH_{v,h,t}$ = quantity consumed of composite commodity v by household h

$QCV_{c,v,h,t}$ = quantity consumed of commodity c by household h through composite commodity v

$qheff_{c,h,t}$ = commodity- and household-specific consumption efficiency parameter.