Natural Capital Accounting on Forested Lands

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Abstract

This paper creates a first set of forest natural capital accounts and demonstrates how these accounts can be integrated with general equilibrium models of the economy. Focusing on the Colorado River Basin, we show that deforestation has direct implications for the forest industry and indirect impacts on the economy through water treatment costs and carbon stock. We find that the loss of carbon stored in forests results in the net cost to the economy of $28 million in present value.

Disclaimer

1 INTRODUCTION

In January 2023, the United States government released a strategy to develop natural capital accounts for the Nation (hereafter, the National Strategy).[1] The National Strategy outlines a 15-year plan to move from experimental and pilot accounts to what are called production-grade statistics. The timeline is intentionally long, recognizing that the methods and data for doing so still need to be developed for many natural resources. This work initiates the development of natural capital accounts for forested lands in the U.S. that are suitable for forward-looking economic analysis and examines gaps in data, information, and science that might be needed to develop the U.S. accounts for forests.

To the extent feasible, the U.S. will follow standards in the United Nations System of Environmental-Economic Accounting (SEEA), which is the accepted international standard for environmental-economic accounting (United Nations et al., 2014; United Nations Statistical Commission, 2021). SEEA formalizes relationships between natural capital and human economic benefits and provides a means to map, quantify, and value them. The SEEA approach is primarily characterized by the quantification of stocks of environmental or ecosystem assets,[2] changes in assets, and flows from these assets that benefit humanity – echoing the same stocks-and-flows design of national economic accounts.

Forest accounts in the National Strategy are to be developed as Phase 2 statistics, meaning that the methodology is still being refined and validated and that the statistics are likely to rely on results from Phase 1 accounts (air emissions, land, marine, and water). Currently, only some of the benefits of forests fit into economic accounting methodologies such as Gross Domestic Product

[1] https://www.whitehouse.gov/wp-content/uploads/2023/01/Natural-Capital-Accounting-Strategy-final.pdf
[2] Following SEEA definitions, environmental assets, ecosystem assets, and ecosystem services are defined in the Data and Methods sections below.

(GDP). Typically, these benefits are private; statistics on timber output and forest sector employment, for example, are readily available. Other provisions of forests – usually public benefits, such as clean drinking water and carbon sequestration, which are shared by society – do not fit into historic accounting methods but are nonetheless important for human and ecosystem health and well-being. In some cases, the baseline data exists to develop some of the forest accounts, particularly around forest extent and condition. In others, the methods and data are missing to effectively address include ecosystem service values.

This work acknowledges integrated ecological processes that constitute a forest and the ecosystem services they provide. Existing research valuing the benefits of forests tends to focus on single ecosystem services (IPBES, 2019; Muttaqin et al., 2019; Ojea et al., 2012; Pereira et al., 2018; Wang & Fu, 2013) without considering interactions within the forest system. Failing to account for the joint production of ecosystem services in a forest and the links between ecological and economic systems overlooks the potential for ecosystem externalities and can lead to inaccurate measurements of economic value (Crocker & Tschirhart, 1992). We address these limitations by integrating a general equilibrium economic model with a set of ecological production functions to examine jointly produced ecosystem services from forests in the U.S. Specifically, we model market environmental services (timber) and nonmarket ecosystem services (NMES) (water purification and carbon sequestration). built. A key advantage of our integrated approach is that it requires explicit links between the economic and natural systems, prompting discussion about what has been left out as much as what has been included. Our goal here was to create the first set of natural capital accounts for forests and demonstrate how they can interact with economic models.

This work builds on previous efforts to model the relationships among market services, NMES, and joint production technologies, in which NMES enhance the provision of market commodities (Fisher et al., 2009; Kragt & Robertson, 2014; Nalle et al., 2004; Sims et al., 2014). Such studies use an ecological-economic production possibilities frontier, which shows tradeoffs and complementarities between market goods and NMES and between different NMES (Bekele et al., 2013; J. Cavender-Bares et al., 2015; Polasky et al., 2005; White et al., 2012). Private firms, therefore, have some incentive to provide NMES that support their supply chain even though the market assigns no direct value to them (Wossink & Swinton, 2007), either through direct provision of NMES or by supporting policies that provide NMES on public lands (Kragt & Robertson, 2014; Kroeger & Casey, 2007; Swinton et al., 2007). Because NMES outside of a firm's supply chain are likely to be ignored by that firm and thus underprovided, ignoring complementarity between production technologies and economy-wide benefits leads to the under-provision of NMES.

This paper proceeds as follows: Section 2 describes the data and an overview of the methods, (with additional detail included in the appendix). Section 3 presents the results for the forest extent accounts, estimates of forest carbon, and impacts of land use on ecosystem services from forests. Section 4 discusses the results in the context of the broader literature. Section 5 concludes.

2 DATA AND METHODS

Herein, we create pilot natural capital accounts for forests in the U.S., operationalized around a case study for the Upper Colorado River Basin (UCRB). We create two types of accounts: 1) asset accounts for timberland, and 2) service accounts for water purification and carbon sequestration. We demonstrate the usefulness of these natural capital accounts for impact and policy analysis by examining the effects of land use change on the regional economy and forest ecosystem services. We use exogenous changes in land use based on projections from the U.S.

Environmental Protection Agency's (EPA) Integrated Climate and Land-Use Scenarios (ICLUS) (U.S. EPA, 2017) to drive impacts in a computable general equilibrium model (**Figure 1**). This section describes the main data and modeling methods. Additional methods underlying the forest asset accounts and Computable General Equilibrium (CGE) model are in **Appendix 1**.

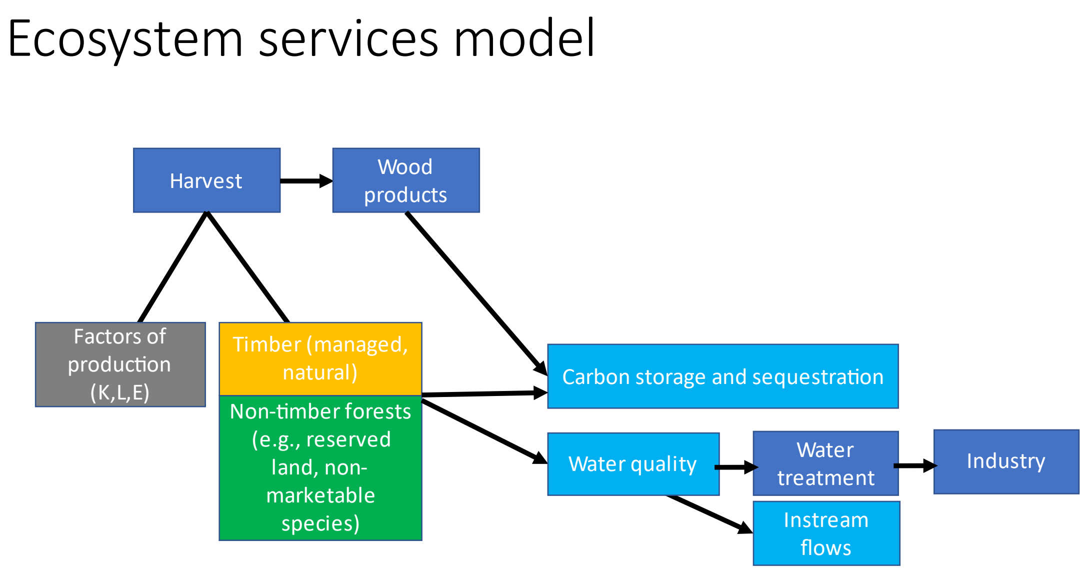


Figure 1. Conceptual model of ecosystem services. Changes in timer area reduce the supply of forested land available for harvest. This loss impacts downstream industries, such as the wood products industry. The model also includes changes to water quality, water treatment costs, and carbon storage. Linkages are included between economic and ecological systems in the CGE model used to measure economic impacts.

2.1 United Nations System of Environmental-Economic Accounting (UN SEEA)

UN SEEA takes two approaches to natural capital accounts: 1) the SEEA Central Framework (SEEA CF, FAO and UN, 2014), including the SEEA for Agricultural, Forestry, and Fisheries (SEEA-AF) manual (SEEA AFF, 2020, p. 154), and 2) SEEA Ecosystem Accounting (SEEA EA, 2021). The SEEA Central Framework focuses on environmental assets, such as water resources, energy and mineral resources, forests, and fisheries, and the use of these assets in the economy, as well as with the emissions and waste (termed "residuals" in SEEA) that return to the environment from their economic use. Asset accounts measure the quantity of resources (e.g., forests or fish) and changes in these stocks over time, in physical or monetary terms. Flow accounts record the physical flows of products between the environment and the economy (i.e., harvest), in physical or monetary terms.

SEEA EA tracks the extent, condition, and value of stocks of ecosystem assets and the flows of services generated by them. SEEA EA includes five types of ecosystem accounts: (1) ecosystem (physical) extent, (2) physical ecosystem condition, (3) monetary, (4) ecosystem service supply and use, and (5) monetary accounts for ecosystem assets (including changes in stocks). SEEA CF forest accounting depicts existing economic activities drawing specific environmental assets (i.e., timber) from the environment or returning specific waste to it, whereas a forest thematic account based on SEEA EA focuses on ecosystem service flows like recreation experiences, carbon storage, or improvements to the quality, quantity, and timing of water originating on forestland.

In SEEA EA, ecosystem assets are area-based stocks with measurable conditions, which through ecological structure and function, yield flows of ecosystem services. Ecosystem assets are classified and divided by type, with an extent and condition for each type. Extent accounts record the total area of each ecosystem type. Forest types might include broad categories like hardwoods and softwoods, or categories defined by dominant tree species, for example, ponderosa pine forests. Ecosystem extent accounts can track changes in extent over time, including the causes of change from human or natural processes that degrade or restore ecosystems (e.g., when forest land is converted to residential development, forest thinning improves forest health, or pest outbreaks lead to changes in forest composition). Ecosystem condition accounts record the condition of each ecosystem type using appropriate characteristics for that ecosystem type. Ecosystem services supply accounts record ecosystem service flows from specific ecosystem assets (and by extent, for instance, air purification services that flow from a forest ecosystem). In ecosystem services use accounts, the use of the ecosystem services supplied by ecosystem assets is recorded to specific users by type (e.g., industry or households); total supply and use must balance. Finally, monetary accounts measure changes in value associated with these changes in stock. Hence, SEEA accounts for forests may include elements of SEEA CF, SEEA EA, or both. All of these approaches are valid, and each may depict aspects of measuring forest resources and their value to people that the other approaches miss, and that past national accounting practices may have ignored or simply assigned to forest landowners.

2.2 Asset accounts for forest extent

Baseline data for forest extent and condition exist in the US Forest Service's Forest Inventory and Analysis (FIA) program. FIA maintains the largest continuous body of forest inventory data in the world. These data are the basis for land management and policy decision-making, research on forest health and conditions, and national assessments that evaluate the current and future conditions of U.S. forests and grasslands, including greenhouse gas reporting.

For this study, we begin with estimates for timberland area aggregated for each state in the conterminous U.S. from the FIA Database and grouped by forest type, then focus on the UCRB to demonstrate a method for integrating a forest extent asset account with a CGE model of the economy. Timberland is defined as accessible and non-reserved forestland with potential growth of at least 20 cubic feet/acre/year. The FIA began annual inventories in the early 2000s; however, inventory periods vary by state. Annual inventories for the Pacific states of California, Oregon, and Washington did not begin publishing annual inventories until 2017 hence the choice of 2017 as the first year in **Table 1**.

Table 1. Area of Timberland in the Conterminous U.S. by Forest Type Group (in 1000s of acres)

Forest Type Group	*2017*	*2018*	*2019*	*2020*	*2021*	*2017-2021 (% Δ)*
Alder/Maple	2,639.0	2,637.6	2,641.1	2,641.1	2,641.1	0.1%
Aspen/Birch	20,797.9	20,727.5	20,647.8	20,634.6	20,707.8	-0.4%
California Mixed Conifer	6,293.6	6,274.9	6,268.6	6,268.6	6,268.6	-0.4%
Douglas-Fir	34,723.0	34,773.9	34,730.4	34,730.4	34,730.4	0.0%
Elm/Ash/Cottonwood	24,129.2	24,004.3	23,135.3	23,198.0	23,055.2	-4.5%
Exotic Hardwoods	1,313.0	1,341.9	1,324.1	1,337.9	1,342.8	2.3%
Exotic Softwoods	603.3	579.0	602.7	599.0	605.4	0.3%
Fir/Spruce/Mtn. Hemlock	21,836.8	21,748.5	21,646.4	21,646.4	21,646.4	-0.9%
Hemlock/Sitka spruce	4,205.9	4,213.2	4,219.3	4,219.3	4,219.3	0.3%
Loblolly/Shortleaf Pine	61,345.9	61,551.1	61,814.3	62,082.9	61,052.5	-0.5%
Lodgepole pine	9,388.9	9,280.3	9,315.9	9,315.9	9,315.9	-0.8%
Longleaf/Slash Pine	12,387.8	12,307.2	12,194.4	12,229.8	12,225.9	-1.3%
Maple/Beech/Birch	43,497.6	43,321.0	43,225.9	43,231.9	43,191.8	-0.7%
Non-Stocked	9,814.8	9,909.2	10,043.7	10,005.1	9,945.5	1.3%
Oak/Gum/Cypress	23,072.1	23,051.7	22,972.7	22,922.3	22,554.9	-2.2%
Oak/Hickory	136,224.3	135,698.2	134,403.8	134,088.7	132,443.7	-2.8%
Oak/Pine	26,707.9	26,342.1	26,055.0	26,046.1	25,672.2	-3.9%
Other Eastern Softwoods	2,127.2	2,157.5	2,119.2	2,093.3	2,044.9	-3.9%
Other Hardwoods	3,205.7	3,265.9	3,309.5	3,369.0	3,367.4	5.0%
Other Softwoods	1.0	1.0	0.8	0.8	0.8	-19.6%
Other Western Softwoods	1,700.7	1,687.0	1,701.3	1,701.3	1,701.3	0.0%
Pinyon/Juniper	115.3	109.6	109.1	117.1	113.8	-1.3%
Ponderosa Pine	21,286.5	21,164.8	21,240.3	21,251.3	21,251.3	-0.2%
Redwood	679.5	678.7	689.4	689.4	689.4	1.5%
Spruce/Fir	14,290.6	14,315.4	14,374.6	14,376.3	14,313.5	0.2%
Tanoak/Laurel	1,682.6	1,678.4	1,660.1	1,660.1	1,660.1	-1.3%
Tropical Hardwoods	367.1	370.2	371.3	371.3	371.3	1.1%
Western Larch	1,597.1	1,629.9	1,636.3	1,636.3	1,636.3	2.5%
Western Oak	2,422.5	2,372.9	2,404.1	2,404.1	2,404.1	-0.8%
Western White Pine	102.7	108.1	105.3	105.3	105.3	2.5%
White/Red/Jack Pine	9,238.9	9,284.9	9,346.7	9,342.8	9,351.7	1.2%
Woodland Hardwoods	73.7	71.1	40.4	40.4	40.4	-45.1%
Total Timberland Area	497,871.9	496,656.9	494,350.0	494,357.0	490,671.3	-1.4%

2.3 Service accounts for carbon sequestration

Baseline carbon estimates use raster data from the FIA Big Data, Mapping, and Analytics Platform (BIGMAP) for forest-type group extent and total carbon in all pools for the year 2018

(USFS, 2021). BIGMAP includes carbon pools for live biomass, dead biomass, and organic biomass in soils at 30m spatial resolution. The FIA carbon estimates are used in the U.S. National Greenhouse Gas Inventory used for international reporting and are likely to play an important part in the future development of natural capital accounts for forests in the U.S.

2.4 Service account for water purification

The provision of municipal drinking water is a critical service from forested watersheds. Vegetation filters water and holds sediment in place. Benefits to water quality, therefore, generally increase with vegetation. To spatially link the supply and demand of water filtration services, we utilize location data for drinking water intakes from the U.S. Environmental Protection Agency's Safe Drinking Water Information System (SDWIS) (U.S. EPA, 2017) and spatially join them to watersheds in the conterminous U.S. (CONUS) using fourth-level hydrological unit codes (HUC) in the National Hydrography Dataset (U.S. Geological Survey, 2016). The SDWIS database includes information on intake location, type of water source, and the population served by the intake. Intakes were filtered to create a subset that serves community water systems and that uses surface water. The resulting dataset contained 5,375 public water systems. There are a total of 5,375 intakes within the study area boundaries, 22.8 percent (1,303 intakes) occur on forested lands.[3]

2.5 Land use change

Land use projections are from the US Environmental Protection Agency's Integrated Climate and Land-Use Scenarios (ICLUS) project for the period between 2020 and 2100 (U.S. EPA, 2017). ICLUS includes spatially explicit projections of land use and population throughout CONUS.

[3] Forested lands are derived from 2019 NLCD data and defined as deciduous forest (NLCD category 41), evergreen forest (NLCD category 42), and mixed forest (NLCD category 43)

ICLUS projections are based on Intergovernmental Panel on Climate Change (IPCC) scenarios and pathways, of which we use Relative Concentration Pathway (RCP) 8.5, Shared Socioeconomic Pathway (SSP) SSP5, and the HADGEM2_ES general circulation model for this implementation.

ICLUS data is projected using 2018 Forest Inventory Analysis BIGMAP data as the baseline. The BIGMAP raster data for forest extent and carbon are summarized for the year 2018 for each state in the UCRB and by forest type group. The ICLUS projection raster for new land development is applied to each BIGMAP layer to calculate the change in extent and carbon due to new land development on land that was forested in 2018.

2.6 Integrating natural capital accounts with the economic model

Natural capital accounts are integrated into economic analysis through a computable general equilibrium model (CGE) following Warziniack, (2014) and described in more detail in the appendix. We consider six production sectors: (1) Forestry and logging, (2) wood products manufacturing, (3) agriculture, (4) power generation, (5) water treatment, and (6) a catchall miscellaneous sector for all other goods. The model is extended to include the impacts of land use change on carbon storage and drinking water costs. The foundation for a CGE model is a social accounting matrix (SAM). The SAM shows the flow of expenditures from industry to industry in the production process, payments to factors of production, household expenditures, and government activities.

Ideally, the SAM would include the value of nature that goes into the production process, but SAM and CGE models with fully integrated ecosystem services are rare, as one would have to calibrate a snapshot of the economy with values of nature in the production process and returns from nature to households. In the case of forests, nascent research calculates the value of land in the production of timber, using either the allocated land value (ALV) or bare land value (BLV)

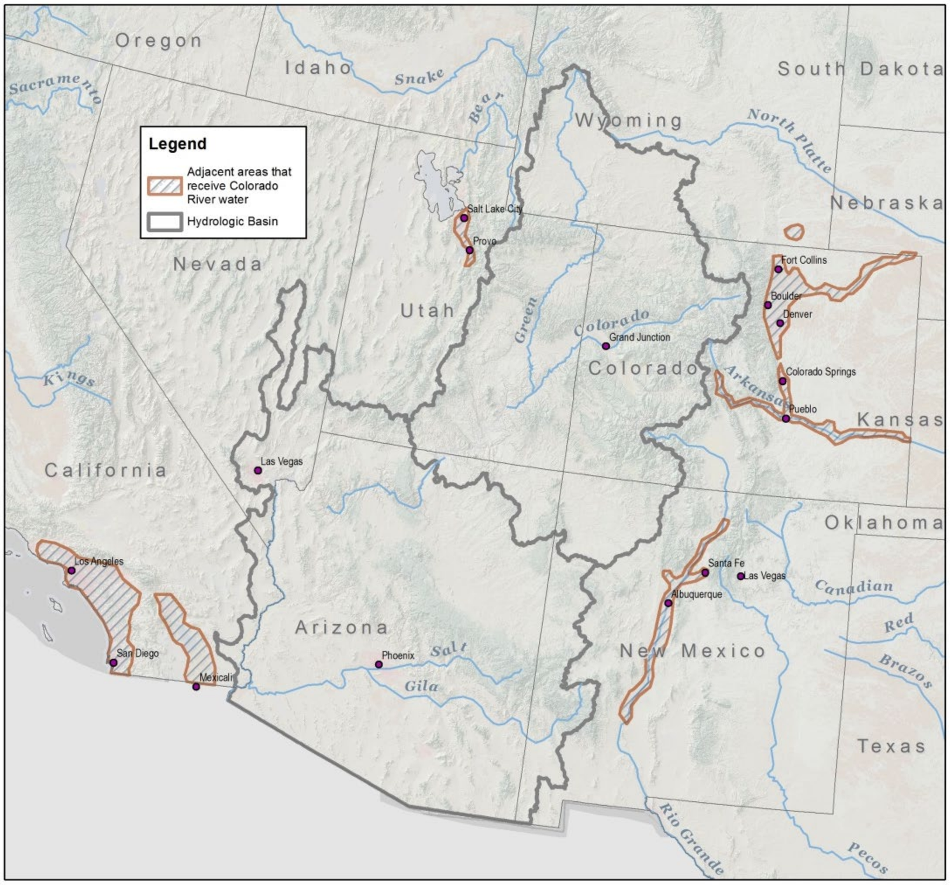
(Harris & MAI, 2018). Following this approach, we assume the ALV is included in the value of capital stock in the forestry sector and create a separate factor of production for timberland.

It may be that natural resources are not directly used by firms, but rather are complementary to the production process. As is the case for drinking water, improvements in environmental quality serve not to increase output but to decrease costs. Impacts to drinking water costs are included through impacts from land use change on sediment and turbidity in rivers, streams, and reservoirs with drinking water intakes. We assume the percentage of a watershed that is forested is inversely proportional to water treatment costs following (Warziniack et al., 2017) such that one percent decrease in the baseline forest cover increases the amount of sediment in the watershed's streams and reservoirs by 3 percent, and every 1 percent increase in turbidity increases the costs of treating drinking water by 0.19 percent. These costs are modeled through a multiplicative impact factor $\Delta_k = \left(1 - \frac{f_k}{f_{k0}}\right)\varphi$, where f_k is the percent forest cover in watershed k, f_{k0} and f_k are the initial and final forest covers, and φ is a parameter measuring the percent increase in treatment costs due to reductions in forest cover, set equal to 0.57 (3 x 0.19).

The primary impacts on carbon storage from land use change are captured directly by the loss of forests from ICLUS and the carbon stored in that forest. Land transitioning out of forests goes into development, and we assume the stock of carbon from those trees is lost forever. Secondary impacts are captured in the CGE model through the land market, in which loss of timberland raises the costs of forestry and logging, which increases costs to the wood products industry. Janowiak et al. (2017) estimate that more than 2,600 million metric tons of carbon were stored in harvested wood products in 2015, and (Christensen et al., 2021) estimate that harvested wood products from California forests alone sequestered 0.8 MMT CO2e per year, accounting for $1.4 billion in total sales. Based on the California data, we assume carbon fluxes from wood products are on average

6 kg per dollar of output. For a detailed treatment of carbon stored in wood products, see Baker et al. (2023).

Figure 2. Map of the Colorado River basin



The CGE model is calibrated for economic activities in the UCRB. The Colorado River and its tributaries provide water to a semi-arid region that includes seven southwestern states in the U.S. and the northern part of Mexico. The river basin is a complex network that covers an area of 243,000 square miles, spanning 1,450 miles from the Rocky Mountains to the Pacific Ocean (**Figure 2**). The water of the Colorado River reaches 30 million people, including the people of Denver, Las Vegas, Los Angeles, and Phoenix. The basin is divided into the Upper and Lower Colorado River Basin (LCRB) at Lee's Ferry. The UCRB encompasses Colorado, Utah, Wyoming, and the northern parts of Arizona and New Mexico. The LCRB includes the remaining area of Arizona, California, and Nevada. The Colorado River is significant for both the number of people reliant on it for drinking water and because the region faces some of the worst water shortages in the U.S. (Heidari et al., 2021). Initial studies of the river's flows put the annual capacity of the river between 15 and 17.5 million acre-feet (MAF), and early allocations of water rights required the Upper Basin states to deliver no less than 75 MAF for any period of ten consecutive years to Lower Basin states. More recent estimates put the average annual flow of the Colorado River at Lee's Ferry closer to 12.3 MAF, with recent drought years being much lower.

Economic data in the SAM is based on a benchmark 2012 dataset from an IMPLAN (MIG, 2012) for all counties in the UCRB. The industry sectors were aggregated from IMPLAN's 440 sectors to 6: i) forestry and logging, ii) wood products manufacturing, iii) agriculture, iv) power generation, v) water treatment, and vi) miscellaneous. We collapse IMPLAN households into one representative household. The Federal Government's interactions with the state were kept distinct while city, county, and state governments were aggregated into a single state and local government. Given the importance of trade flows into and out of the region, foreign trade and domestic trade were modeled separately. IMPLAN's employee compensation account was used to construct the labor account. Capital was found as the summation of proprietary income and other property income. Final balancing was done by minimizing the least square differences between regional supplies and demands.

3 PRELIMINARY RESULTS

Figure 2 shows the distribution of forest types across the UCRB and **Table 3** shows beginning stocks in forests and forest carbon in 2018 and projected changes by 2100. A more detailed summary of U.S. timberland area for 2017-2021 is presented in **Appendix 2**. The dominant forest types in the UCRB region are pinyon juniper and fir-spruce. The largest projected losses are in New Mexico, with almost 216,000 acres of forest and 763,000 tons of carbon lost between 2018 and 2100.

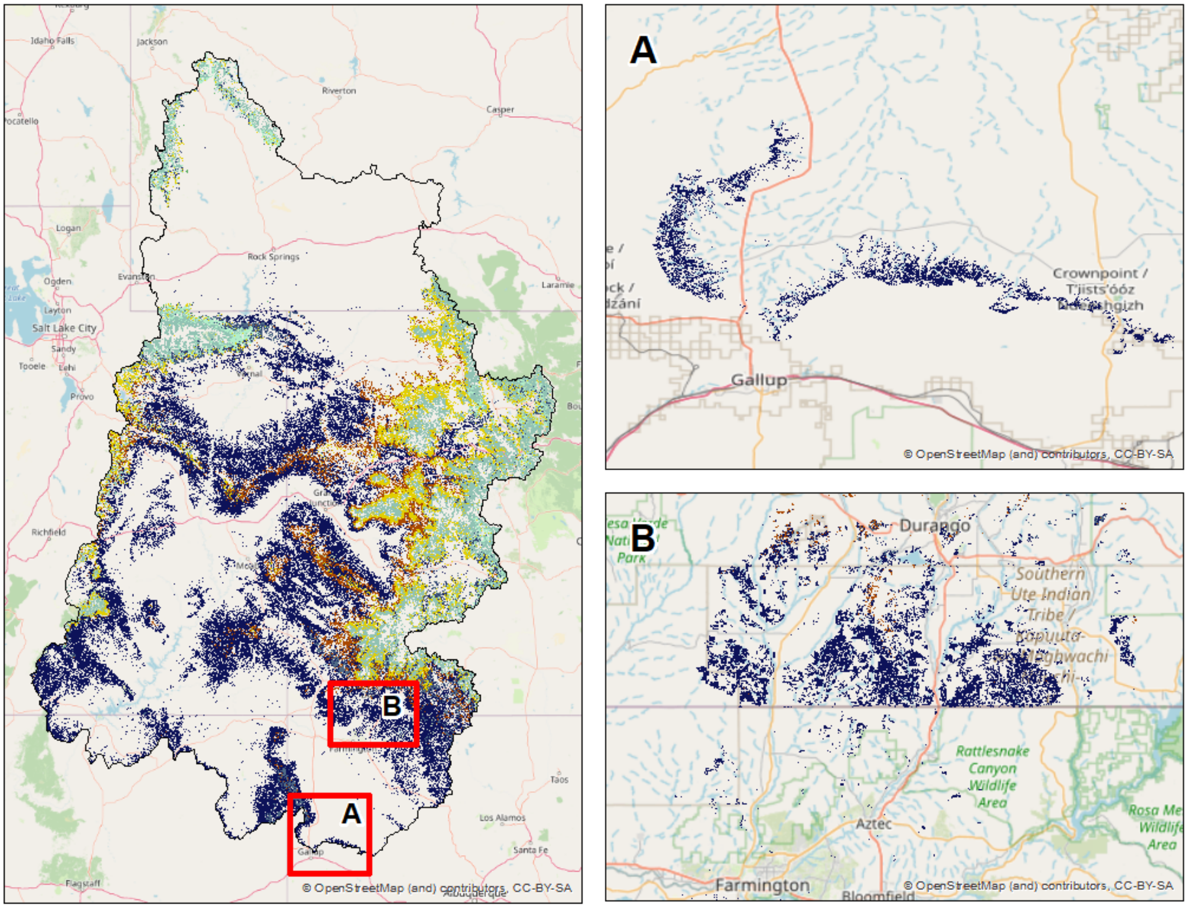


Figure 3. Forest type distribution in the UCRB. The left panel shows forestland extent by forest type group distributed across the UCRB. Panel A is the area of forestland lost to development by 2100 resulting from growth out of Gallup, NM. Panel B shows the area of forestland loss projected to occur south of Durango, CO and north of Farmington, NM.

Across the region, there is an expected loss of over 327,500 acres of forests to development, leading to a loss of 1.3 million tons of carbon stored in forests. We allocated forest and carbon loss evenly across the analysis period, such that about 4000 acres of forest and 15,700 tons of carbon storage are lost each year. To put the annual loss in perspective, the lost carbon is equivalent to the average emissions of 3,400 passenger cars per year (based on an average of 4.6 metric tons per car).[4]

Table 2. Forest extent, carbon stocks, and projected changes

State	Forests		Forest carbon	
	Extent 2018 (acres)	Change 2100 (acres)	Carbon 2018 (tons)	Change 2100 (tons)
Colorado	34,007,386	-46,789	254,026,421	-240,632
New Mexico	17,913,072	-215,788	146,344,068	-762,794
Utah	24,988,973	-48,377	117,383,671	-184,003
Wyoming	15,941,418	-16,556	122,788,823	-100,928
Total	**92,850,849**	**-327,510**	**640,542,983**	**-1,288,357**

3.1 Economic impacts

Projections of forest loss are added into the CGE model as a reduction in timberland with two direct effects. First, the loss of timberland reduces the amount of forest available for production in the forestry and logging sector. Second, loss of forests changes the condition of the region's watersheds, increasing sediment in the waterways and increasing the cost of treating drinking water. Both losses have downstream impacts, most obviously in the wood products manufacturing sector by reducing logs available for inputs, but also through broadscale impacts on all users who face increased water prices. The present values of general equilibrium impacts are calculated using a 2.25 percent discount rate, the U.S. government rate for discounting water and land projects (Federal Register, 2022).

The total economic impact from lost forests by 2100 (about 0.4 percent loss in timberland) in the UCRB, as measured by the CGE model, has a present value of $1.23 million. This loss includes $1.15 million associated with reductions in timberland and $80,000 from impacts to water treatment costs (table 4). The forestry sector loses $62,000 in annual output, and the wood products

[4] https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle

industry sees an annual decrease of $94,000 by 2100, compared to a total sector output of $183 million. The forestry and wood products sectors together only make up 1 percent of total output in the regional economy, so while there might be some highly local impacts, capital and labor are readily employed by other sectors, and general equilibrium impacts across factors and goods prices are quite small.

Table 3. Present value of economic impacts of forest loss

Type of impact	Economic impacts
Reductions in timberland	$1.15 million
Impacts to water treatment costs	$80,000
Carbon from forest loss	$28 million
Total impact	**$29.23 million**

Economic impacts on carbon occur outside the CGE model based on the ICLUS projections and are thus additive to the damages discussed above. We use the interim value of $51 per metric ton of CO2 from the Interagency Working Group on Social Cost of Greenhouse Gases.[5] If forest loss occurs at roughly equal rates between years, the present value of the lost carbon between 2020 and 2100 equals to $28 million. Comparatively, secondary impacts from lost carbon stored in wood products is negligible. The model shows a $94,000 decrease in the wood products industry. At 6kg per dollar, that amounts to a reduction in carbon stored in wood products of 564 kg of carbon.[6]

4 DISCUSSION

General equilibrium models are highly specific representations of economies, and in this case, interactions with the natural world. Our results rely on several assumptions about substitution

[5] https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

[6] $\$94{,}000 * (6kg/1\$) = 564$ kg carbon

possibilities between goods, among factors of production, and between the natural and built environment. Many of these factors are well-studied in the literature. Values for land have been an active area of research since the early days of economic sciences (North & Thomas, 1973). Other ecosystem service values, such as the ability of forests to provide recreation and purify the air, are noticeably missing from this (and many other) analysis, and more complicated models could certainly be built.

The advantage of CGE models is that they prompt discussion about what has been left out as much as what has been included. Our goal here was to create the first set of natural capital accounts and demonstrate how they can interact with economic models. It builds on previous work to incorporate ecosystem services in general equilibrium models (Allan et al., 2019; Jendrzejewski, 2020; Warziniack et al., 2011). These models showed that the value of the ecosystem service depends on the availability of other factors of production and whether those factors are substitutes or complements to ecosystem services (Warziniack et al., 2011).

Questions arise about the generalizability of such models and how they work together with bottom-up models like those proposed by (Fenichel et al., 2016; Warnell et al., 2020). Aggregated models, such as CGE models, are designed to examine large impacts to large economic systems. Defining features are substitution possibilities and changes in prices. Spatial and sectoral data of the economic data are often limitations (county-level economic data for aggregated economic sectors). These might not be appropriate assumptions for many natural resources. The impact on forest loss to water treatment, for example, is a highly local problem, affecting a particular water system serving a limited population in a market with regulated prices. New York City's Catskill water collection system, perhaps the most popular example linking forests to drinking water, spent about $1.4 billion in land acquisitions and pollution reductions in the upstream watershed that ultimately saved the city from needing a $6 billion treatment facility (Grolleau & McCann, 2012).

With a customer base of roughly 9 million people, that amounts to a $500 savings per customer over the life of the project - real savings, but not likely to have a significant impact on regional wages. In such cases, local partial equilibrium studies might be more appropriate. In other cases, however, changes in the natural system can lead to significant changes in local and national markets, and CGE models can offer forward-looking analysis of changes in natural capital and the impact of actions that preserve natural capital. For instance, Das et al. (2005) use a multiregional CGE model to show that reducing timber production in the Pacific Northwest leads to increased production in the southern U.S. The Forest and Agricultural Sector Optimization Model (FASOM) offers a highly detailed description of the forestry sector and the potential impacts of carbon policies (Alig et al., 2002).

Our results, while primarily for demonstration purposes, are in line with the rest of the literature examining ecosystem services from forests. Cavender-Bares et al. (2022) examine non-market values from trees throughout the U.S. They find the value associated with air pollution removal and carbon storage far exceeds the value derived from wood products. The reality of these values is already playing out in land markets throughout the country. In November 2022, Oak Hill Advisors and partners paid $1.8 billion for 1.7 million acres of forest as an investment in future carbon offset markets from forests (Dezember, 2022). Such direct investments by firms and through Real Estate Investment Trusts (REITs) are becoming more common.

5 Conclusion

The effects of deforestation are widespread, ranging from direct changes on the forest industry to indirect impacts on water treatment to costs associated with decreased carbon stocks. Among the impacts, we find the largest to be from lost carbon, overwhelming all other impacts. The forestry sector is relatively small in the region, and development on forestland is relatively low in the upper Colorado River region, likely due to the status of most forestland in these states being reserved (e.g., National Parks, National Forests, etc.). The most development is projected to happen on grazing land.

Forests in the U.S. involve a complicated mix of private investments in public land and public benefits from private land. Among the 310 million hectares of U.S. forests, 41 percent are publicly owned, with the Federal Government being the largest public owner (31 percent) (Oswalt et al., 2019). The percentage of public ownership varies throughout the country. At the upper end, roughly 75 percent of forests in the Resource Protection Assessment Act's (RPA) Rocky Mountain Region[7] are publicly owned. At the lower end, roughly 20 percent of forests in the Southern RPA Region[8] are publicly owned (Congressional Research Service, 2021; Oswalt et al., 2019). The mix of private and public interests and private and public ownership of U.S. forests highlights the need for better accounting of the benefits and costs of forest management.

Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government

[7] Includes AZ, CO, ID, KS, MT, NE, NV, NM, ND, SD, UT, and WY
[8] AL, AR, FL, GA, KY, LA, MS, MT, NC, OK, SC, TN, TX, and VA,

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7 APPENDIX

A 1. CGE Model

Most parameters of the model are found through calibration as in (Ballard et al., 1985; Melo et al., 1992). The calibration routine sets benchmark input and output prices equal to one (by constant returns to scale and the units of the initial data being in value terms). Using all first-order conditions from profit maximization, cost minimization, and utility maximization; and the benchmark data and prices, most parameters apart from the elasticities of substitution are found. Estimates of elasticities of substitution are taken from the literature and given in the computer code. The household is assumed to have an elasticity of substitution between consumption goods of 0.9. All general equilibrium calculations were made with the General Algebraic Modeling System (GAMS) software package using the PATH solver.

The model includes several types of goods:

- Import and export goods: Domestically produced goods are exported out of the region, and goods from the same industries are imported. The set of traded goods is the same as the set of domestically produced goods, thus traded goods are also indexed with j. The price received for exports is PE_j; the price paid for imports is PM_j.
- Armington goods: Goods consumed by households and goods used as intermediate inputs by firms are Armington composites (Armington, 1969), which are aggregates of domestically produced and imported goods. No Armington good exists that is not either produced locally or imported, thus Armington goods are also indexed with j. The price paid for Armington composite good j is PX_j.

- Primary factors: Primary factors of production are inputs that are not produced and generally include capital and labor. The set of primary factors of production is indexed $f \in F$, and each factor is paid price PF_f.

The human-produced composite is produced following a standard structure for modeling firms in CGE models. Taxes of type t are paid as a fixed share of output at rate, $atax_{tj}$, such that

[10] $$TAX_{tj} = atax_{tj}DY_j$$

After-tax output is produced with intermediate inputs and a value-added composite of primary factors. Let $V_{jj,j}$ be the level of intermediate inputs from firm *jj* to firm *j* and VA_j be the level of value-added composite used by firm *j*. This nest is assumed to be Leontief, such that

[11] $$V_{jj,j} = aint_{jj,j}DY_j$$

[12] $$VA_j = ava_jDY_j$$

The Leontief assumption implies

[13] $$CV_j = \sum_t atax_tCV_j + \sum_{jj} aint_{jj,j}PX_{jj} + ava_jCVA_j$$

The value-added composite includes capital and labor, combined using a CES production function $VA_j = \psi_j\left(\delta_jK_j^{-\rho_j} + (1-\delta_j)L_j^{-\rho_j}\right)^{-1/\rho_j}$, where $\sigma_j = \left(\frac{1}{1+\rho_j}\right)$ is the elasticity of substitution between labor and capital and ψ_j is an efficiency parameter. The firm's optimal mix of capital and labor is found by minimizing the unit cost of producing the value-added component,

[14] $$CVA_j(PF_K, PF_L) = min_{K_j,L_j}\{PF_K * K_j + PF_L * L_j : VA_j(K_j, L_j) = VA_j\}.$$

The demand functions for capital and labor are therefore

[15] $$K_j = VA_j\left(\frac{\delta\ CVA_j}{PF_K}\right)^{\sigma_j}\psi_j^{\sigma_j-1}$$

[16] $$L_j = VA_j\left(\frac{(1-\delta)\ CVA_j}{PF_L}\right)^{\sigma_j}\psi_j^{\sigma_j-1}$$

Using the price index for CES functions, we close this nest by

[17] $$CVA_j = \frac{1}{\psi_j}\left(\delta_j^{\frac{1}{1+\rho_j}} PF_K^{\frac{\rho_j}{1+\rho_j}} + (1-\delta_j)^{\frac{1}{1+\rho_j}} PF_L^{\frac{\rho_j}{1+\rho_j}}\right)^{1+\frac{1}{\rho_j}}$$

Household behavior

The allocation of expenditures between consumptive goods follows standard CGE procedures. Households choose consumption levels HX_{jh} to minimize the cost of achieving utility level $\bar{C}$. The mathematical expression of this optimization is

[31] Min $PX_j HX_{jh}$ s.t. $\bar{C} = C(HX_{1h}, HX_{2h}, .., HX_{Jh})$

The first order conditions require

[32] $$\frac{\partial C/\partial HX_{jh}}{\partial C/\partial HX_{ih}} = \frac{PX_j}{PX_i}$$

A 2. FIA Timberland Extent by State

Colorado

Forest Type Group	Forest Code	Extent 2018 (acres)	Extent Change 2021 (acres)	Carbon 2018 (tons)	Carbon Loss 2100 (tons)
Other East Soft	170	1	-	5	-
Pinyon Juniper	180	9,858,458	26,110	43,599,681	111,035
Douglas Fir	200	2,916,915	3,068	26,743,792	27,293
Ponderosa	220	2,628,786	4,626	18,722,279	32,158
Fir Spruce Mountain Hemlock	260	8,726,629	2,018	99,914,321	20,740
Lodgepole	280	1,295,146	572	11,418,973	4,936
Other West Soft	360	507	0	2,019	1
Cali, Mixed	370	11	-	68	-
Oak Hickory	500	191	0	867	1
Elm Ash Cottonwood	700	5	-	16	-
Aspen Birch	900	5,487,125	4,960	41,803,802	27,834
Other Hardwoods	960	2	-	8	-
Woodland Hard	970	3,092,859	5,433	11,817,235	16,626
Non-Stocked	999	751	2	3,355	7
Totals		34,007,386	46,789	254,026,421	240,632

New Mexico

Forest Type Group	Forest Code	Extent 2018 (acres)	Extent Change 2021 (acres)	Carbon 2018 (tons)	Carbon Loss 2100 (tons)
Pinyon Juniper	180	17,904,731	199,187	69,416,768	619,882
Douglas Fir	200	1,598	2,369	16,724,716	25,270
Ponderosa	220	4,469	6,629	39,050,429	57,220
Fir Spruce Mountain Hemlock	260	896	2,446	11,237,231	28,869
Lodgepole	280	55	195	490,844	1,653
Other West Soft	360	0	0	38	1
Cali, Mixed	370	0	-	4	-
Oak Hickory	500	0	-	1,000	-
Elm Ash Cottonwood	700	0	-	8	-
Aspen Birch	900	625	1,907	5,723,752	14,617
Other Hardwoods	960	0	-	2	-
Woodland Hardwoods	970	689	3,050	3,646,930	15,260
Non-Stocked	999	9	4	52,346	21
Totals		17,913,072	215,788	146,344,068	762,794

Utah

Forest Type Group	Forest Code	Extent 2018 (acres)	Extent Change 2021 (acres)	Carbon 2018 (tons)	Carbon Loss 2100 (tons)
Pinyon Juniper	180	16,307,209	33,391	61,806,758	118,508
Douglas Fir	200	901,516	1,433	7,645,063	10,515
Ponderosa	220	341,742	1,706	2,111,948	7,759
Fir Spruce Mountain Hemlock	260	2,306,237	528	20,208,806	4,417
Lodgepole	280	441,652	40	3,907,685	336
Other West Soft	360	20,633	9	97,167	21
Cali, Mixed	370	14	-	101	-
Oak Pine	900	2,187,565	3,244	12,263,124	16,397
oak Hickory	970	2,481,086	8,026	9,335,220	26,046
Non-Stocked	999	1,320	1	7,799	4
Totals		24,988,973	48,377	117,383,671	184,003

Wyoming

Forest Type Group	Forest Code	Extent 2018 (acres)	Extent Change 2021 (acres)	Carbon 2018 (tons)	Carbon Loss 2100 (tons)
Spruce Fir	120	229	-	925	-
Other East Soft	170	1	-	1	-
Pinyon Juniper	180	348,969	407	970,795	827
Douglas Fir	200	1,981,580	3,573	15,872,290	26,448
Ponderosa	220	1,819,013	2,943	8,174,900	9,243
Fir Spruce Mountain Hemlock	260	6,069,434	2,961	53,383,951	24,688
Lodgepole	280	4,433,351	3,721	38,215,023	27,508
Other West Soft	360	111,959	155	569,665	1,007
Oak Hickory	500	1,730	24	3,775	26
Elm Ash Cottonwood	700	29	-	57	-
Aspen Birch	900	1,122,241	2,555	5,470,866	10,593
Other Hardwoods	960	14	-	21	-
Woodland Hardwoods	970	48,360	208	114,690	567
Non-Stocked	999	4,508	10	11,865	21
Totals		15,941,418	16,556	122,788,823	100,928