Chapter 7: Natural Capital Accounting on Forested Lands in the United States: An Application to the Colorado River Basin

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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. 327,000 acres of forest are projected to be lost to development by 2100, representing a loss of 1.3 million tons of carbon stored in forests. The direct economic impacts associated with forest loss are estimated to be over $30 million, with $28 million of that coming directly from the value of lost carbon.

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. With a focus on the Colorado River Basin, this study 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 for forest accounts in the U.S.

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 in 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 (GDP). These benefits are typically private; statistics on timber output and forest sector

[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.

employment, for example, are readily available. Other benefits from forests – usually public benefits, such as clean drinking water and carbon storage, 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, existing data allow forest account development including those related to forest extent and condition. In others, ecosystem service values cannot be calculated effectively due to data and methodological limitations.

Our goal is to create the first set of natural capital accounts for forests and demonstrate how they can interact with economic models to capture the integrated ecological processes that constitute a forest and the ecosystem services they provide. Existing research on 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 (Apriesnig et al., 2022; Crocker & Tschirhart, 1992). We address these limitations by integrating a general equilibrium economic model with a set of ecological production functions estimated from data to examine jointly produced ecosystem services from forests in the United States. Computable general equilibrium (CGE) models require specific representations of economies, and in this case, interactions with the natural world. CGE models can offer forward-looking analyses of changes in natural capital by accounting for changes in local and national markets due to changes in the natural system. Specifically, we model market-based environmental services (timber) and non-market ecosystem services (NMES) (water purification and carbon storage).

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 be underprovided, ignoring complementarities between production technologies and economy-wide benefits leads to the under-provision of NMES.

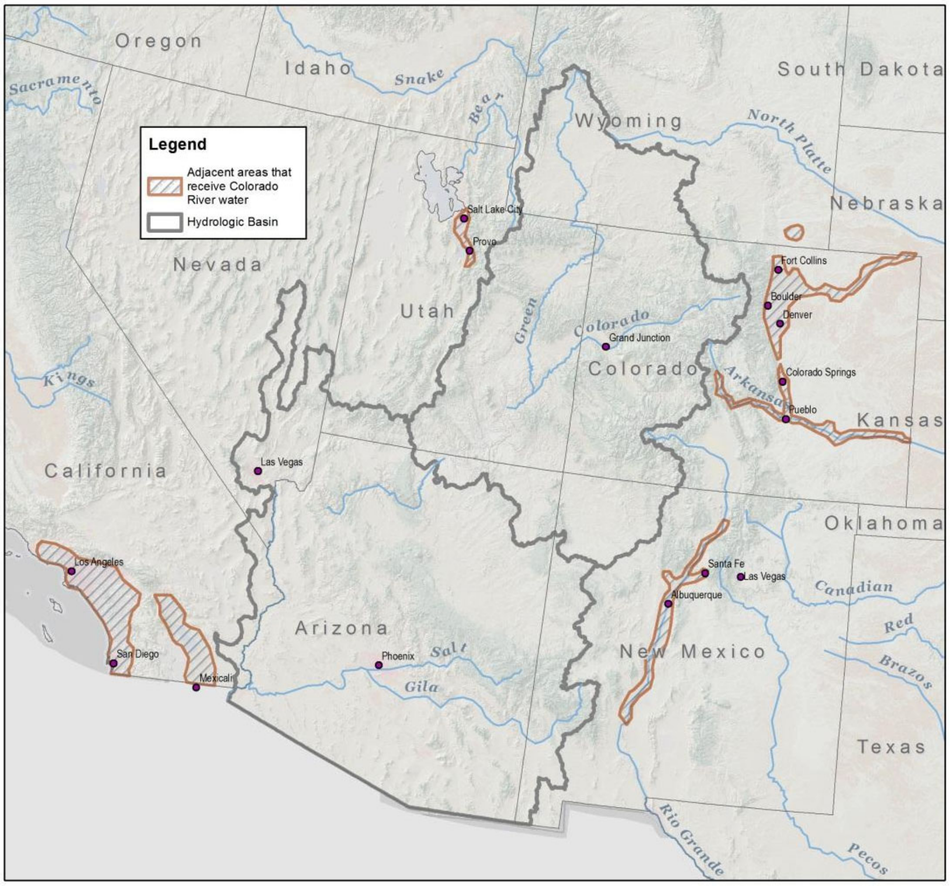
This work also builds on the work incorporating ecosystem services in general equilibrium models. Das et al. (2005) used a multiregional CGE model to show how reducing timber production in the U.S. Pacific Northwest can impact other timber production regions of the country, particularly the southern United States. The Forest and Agricultural Sector Optimization Model (FASOM) is a national model of the U.S. timber industry used to measure the potential impacts of carbon policies (Adams 1996; Alig et al. 2002). More recent work has integrated ecological production relationships to allow for an analysis of a broader range of ecosystem services (Allan et al. 2019; Banerjee et al. 2020; Jendrzejewski 2020; Ochuodho and Alavalapati 2016; Warziniack et al. 2011; 2014; 2017). These models show 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 the ecosystem service (Warziniack et al. 2011).

Study area

We develop methods that are applicable to forests throughout the U.S. and operationalize them with a case study of the Upper Colorado River Basin (UCRB). The Colorado River and its tributaries provide water to a semi-arid region that includes seven southwestern U.S. states and portions of northern 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 Gulf of California (**Figure 1**). 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 at Lee's Ferry in northern Arizona. The UCRB encompasses parts of Colorado, Utah, Wyoming, and areas of northern Arizona and New Mexico. The Lower Colorado River Basin includes the remainder of Arizona and parts of southern 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 annual river capacity 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 the 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. Just recently, basin states agreed on a 13 percent reduction in water use through 2026 in an attempt to avert serious disaster (Buschatze et al., 2023).

Figure 1. Map of the Colorado River Basin



Our model measures the impact of land use change on timber production, drinking water provision, and carbon storage – ecosystem services that one might assume *a priori* to drive much of the story for the region – across a broad set of tree species. The biggest driver of decreased forestland is expansion of developed land, and land use change in the UCRB is projected to be low compared to other U.S. regions due to the limited number of urban centers in the area and the ownership distribution. Our results show that loss of carbon stored in forests is the greatest impact from projected land use change, but damage is mitigated by extensive public management in the case study region. Furthermore, most forest reductions occur outside of municipal source watersheds resulting in limited impacts to drinking water provision – highlighting the spatial link between water intakes and forests. Lastly, timber market activity impacts are low in the UCRB which may be attributed to the low merchantable quality of timber that limits market activity in the UCRB. Although the magnitude our estimated impacts are low in this region, our approach demonstrates the value of environmental-economic accounting by elucidating the trade-offs relevant to a regional context, revealing the pivotal role of land ownership and market activity on natural capital accounting.

A key takeaway of our results is that the value of forest natural capital is likely to vary substantially across the country, and for some types of ecosystem services, those values, or the threats to them, may be relatively small. Our study area contains large amounts of federal land that is both protected from development pressure and the dominant source of drinking water (Liu et al., 2021). While our estimated timber market impacts are closely tied to the size of the regional timber industry, our drinking water results point to the value of the region's public lands in protecting drinking water sources from the threat of development.

This paper proceeds as follows: Section 2 describes the data and gives 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 timber harvest, water purification, and carbon storage. 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 create forest extent accounts using U.S. Forest Service Forest Inventory Analysis (FIA) Program data (USFS, 2021). We then examine the impacts of land use change 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.

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 2** provides a conceptual overview of our approach where the dark blue boxes represent marketed goods and services, and the light blue boxes indicate non-market ecosystem services. Forest resources (timber and non-timber forests) produce non-market products like carbon storage and water quality and are combined with factors of production (e.g., capital and labor) to produce marketed products like timber. Water quality affects downstream economic activity such as the cost of water treatment and its suitability for industrial water use. Increased costs for water treatment and similar indirect uses of forest benefits can be viewed as ecosystem externalities – forest loss impacts water usage via hydrologic processes internal to the ecosystem but external to the economy. In other words, the ecosystem externality implies that forest accounts are incomplete (they are missing service accounts) and are therefore undervalued.

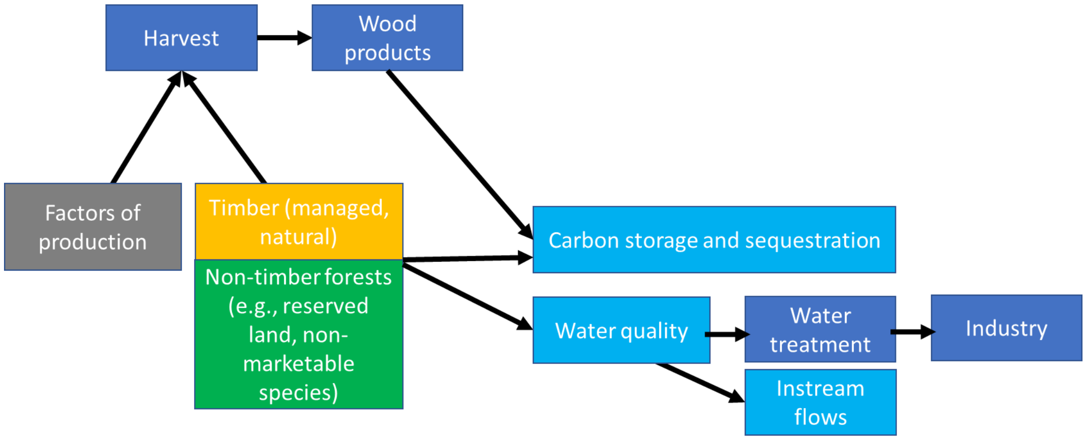


Figure 2. Conceptual model of ecosystem services in general equilibrium. Changes in the area of forests managed for timber reduce the supply of forested land available for harvest. This loss impacts downstream industries, such as the wood products industry. The model also includes changes to water quality, water treatment costs, and carbon storage. Linkages are included between economic and ecological systems in the computable general equilibrium model used to measure economic impacts.

2.1 Asset accounts for forest extent

Data for forest extent and condition are available from the US Forest Service's Forest Inventory and Analysis (FIA) program. FIA maintains the largest continuous body of forest inventory data in the world, including data on forest type, ownership, forest health, and forest condition. These data are the basis for land management, policy decision-making, 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 (yellow box in figure 2) 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, including California, which is heavily dependent on Colorado

River Basin water, did not begin publishing annual inventories until 2017, hence the choice of 2017 as the first year in **Table 1**.

Table 1. Extent 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%

2.2 *Service accounts for carbon storage and water purification*

The FIA's Big Data, Mapping, and Analytics Platform (BIGMAP) raster layers were utilized for carbon storage estimates and forest extent for the year 2018 by forest-type group (USFS, 2021). International reporting through the U.S. National Greenhouse Gas Inventory also relies on FIA's carbon estimates and these data will play a vital role in future development of forest-related natural capital accounts in the United States. BIGMAP includes carbon pools for live biomass, dead biomass, and organic biomass in soils at 30 m spatial resolution. Here, we focus on impacts on the live biomass pool, though impacts occur in other pools as well. Therefore, our estimates should be viewed as conservative.

Water provision estimates are based on drinking water intake data from the U.S. Environmental Protection Agency's Safe Drinking Water Information System (SDWIS) (U.S. EPA, 2017) and spatially joined 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. Of the 5,375 intakes within the study area boundaries, 22.8 percent (1,303 intakes) are in forests.[3]

2.3 *Changes in accounts due to land use change*

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

[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)

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 climate model.

ICLUS baseline data are layered with the 2018 Forest Inventory Analysis BIGMAP data to form the reference which is summarized by forest extent and total carbon stored in each UCRB state for the year 2018 by forest type group (https://fia-usfs.hub.arcgis.com/). ICLUS projection rasters are then applied to each BIGMAP layer to calculate the change in forest area and carbon storage due to new land development on land that was forested in 2018.

2.4 Integrating natural capital accounts with the economic model

Natural capital accounts are integrated into the economic analysis through a CGE model 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 changes in forest cover from ICLUS projections and impacts on carbon storage and drinking water costs from forest loss in those projections. 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 et al., 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 a 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_{k0} and f_k are the initial and final forest covers in watershed k, 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 projected by ICLUS and the carbon stored in that forest. Land transitioning out of forests goes into a developed use, 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 CO_2e 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).

Economic data in the SAM is based on a benchmark 2012 dataset from 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 in the model were kept distinct while city, county, and state governments were aggregated into a single state and local government agent. 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 least squares differences between regional supplies and demands.

Elasticities of substitution in CGE models have a strong effect on measuring economic impacts. Armington elasticities that determine the ability to substitute locally produced goods with imports are especially interesting in the context of natural resources for two reasons. First, benefits from ecosystem services tend to be very local, with little substitution from other regions. Drinking water provision, at least on the scale of large basins, has limited substitution possibilities with other domestic sources and virtually no substitute possibilities with international sources. Similarly, forest products, due to their bulk and importance in local supply chains, are also mostly processed within the region of harvest. Second, it is likely that impacts on natural resources affecting one region are affecting other regions that might serve as substitutes. Here, the driving force behind the economic analysis was the conversion of forested land to development. Conversion of forests is occurring throughout the United States, particularly in the southern United States where much of the U.S. timber production is located. If similar impacts are occurring among trade partners, substitution possibilities might be limited. We examine sensitivity to changes in Armington elasticities by varying their value from 3.2 (the median value found in a review of the literature by Feenstra et al. 2014), to half that value (1.6) for the forest products and water sectors.

3 RESULTS

Carbon stocks and suitability of timber depend on forest type, the distribution of which is shown in **Figure 3** across the UCRB. **Table 2** shows the 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.

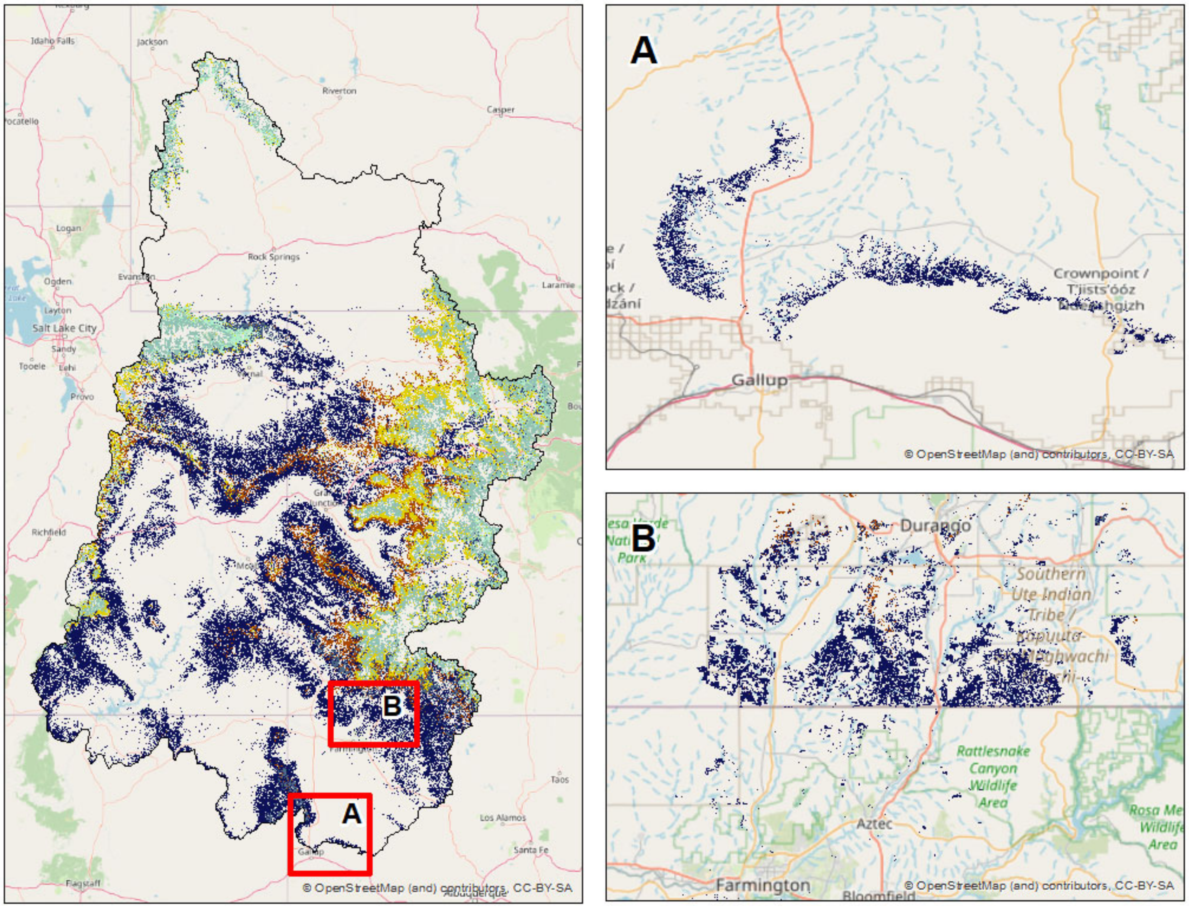


Figure 3. Forest type distribution in the Upper Colorado River Basin (UCRB). The left panel shows forestland extent by forest type group distributed across the UCRB. Panel A is the area of forestland lost to development by 2100 resulting from growth out of Gallup, NM. Panel B shows the area of forestland 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 4,000 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 for the Upper Colorado River Basin

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

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

Development-driven forest loss implies economic growth for the region, at least as growth is traditionally defined ignoring externalities, and possible short-term gains for the forest industry as those trees are cut down. Impacts measured here are the losses associated with land use change, both in direct effects to industry sectors like timber and indirect effects associated with loss of carbon storage and declines in water quality. Projections of forest loss and reductions in timberland have two direct effects in the CGE model. 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 value of general equilibrium impacts is 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 327,500 acres of forests (about 0.4 percent loss in timberland) in the UCRB, as measured by the CGE model, has a present value of $2.24 million using an Armington elasticity of 1.6, indicative of fewer substitution possibilities. This loss includes $2.15 million associated with reductions in timberland and $90,000 from impacts to water treatment costs (table 4). The wood products industry sees an annual decrease of $2 million by 2100, compared to a total sector output of $183 million. The forestry and wood products sectors together contribute only 1 percent of total output to the regional economy, so that even with some highly local impacts, capital and labor are readily employed by other sectors, resulting in minor general equilibrium impacts to the prices of factors and goods.

Table 3 shows the sensitivity of impacts to substitution elasticities. The relatively localized nature of the forest sector leads to larger economic losses than would occur if the economy was more integrated with other regions. Allowing more substitution with supplies outside of the region (increasing the Armington elasticity to 3.2) decreases economic losses by $1.03 million. There are no good estimates in the literature of what such elasticities should be for ecosystem services, though these results show their importance and a need for future work.

Table 3. Present value of economic impacts of forest loss in the Upper Colorado River Basin

Type of impact	Armington elasticity 3.2	Armington elasticity 1.6
Reductions in timberland	$1.13 million	$2.15 million
Impacts to water treatment costs	$80,000	$90,000
Carbon from forest loss	$28 million	$28 million
Total impact	**$29.21 million**	**$30.24 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 CO_2 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 $28 million. Secondary impacts from lost carbon stored in wood products are negligible by comparison. Model estimates show a $94,000 decrease in the wood products

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

industry. At 6 kg per dollar, that amounts to a reduction in carbon stored in wood products of 564 kg of carbon.[6]

The timing of damages and role of discounting has considerable effects on the above damage estimates. If the 327,500 acres of forest loss were to occur within a single year, the undiscounted economic damages would be roughly $127,000 owing to the relatively small size of the forest and wood products sectors in the regional economy. Carbon impacts would be much larger, where a decrease of 1.3 million tons of carbon stored in forests results in an undiscounted value of $76.5 million.

4 DISCUSSION

Our results demonstrate how a set of natural capital accounts can interact with economic models. However, they rely on several assumptions about substitution possibilities between goods, among factors of production, and between the natural and built environments. Many of these factors are well-studied in the literature. Values for land have been an active area of research for a long time (North & Thomas, 1973). Other ecosystem service values, ranging from the ability of forests to provide recreation and purify the air, to more complex interactions between forest health, fire risk, and air pollution impacts from wildfire, are noticeably missing from this analysis - more complicated models could certainly be built. The advantage of CGE models is that they prompt discussion about what has been left out of the model as much as what has been included.

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) and Warnell et al. (2020). Aggregated models, such as CGE models, are designed to examine large impacts on large

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

economic systems. Defining features of CGE models include substitution possibilities and changes in prices. When changes in the natural system cause significant changes in local and national markets, CGE models can offer a forward-looking analysis of changes in natural capital and the impacts of actions that preserve natural capital. Spatial and sectoral economic data, however, are often limited, necessitating the use of county-level economic data for aggregated economic sectors. These might not be appropriate assumptions for many natural resources. The impact of forest loss to water treatment, for example, is a highly localized 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, the use of local partial equilibrium studies might be more appropriate.

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 in our case study, we find the largest to be from lost carbon, overwhelming all other impacts. Given the relatively small size of the forestry sector in the region and the large amount of public land in the region, small economic impacts associated with timber production and drinking water provision are perhaps not surprising. Over a third of Colorado is in federally preserved lands, and those lands are the source of 80 percent of Colorado residents' drinking water, for example.[7] The largest amount of development in the study area is projected to happen on grazing land, not on forests. The small size of the impacts on the timber industry speaks to the small size of the regional forestry sector, but the small size of the impacts on drinking water speaks to the large value of the region's public lands on decreasing threats of deforestation in source watersheds.

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 parts of the Rocky Mountain region[8] are publicly owned. At the lower end, roughly 20 percent of forests in the southern United States[9] are publicly owned (Congressional Research Service, 2021; Oswalt et al., 2019). The mix of private

[7] According to the Colorado Department of Public Health and Environment, https://www.cohealthmaps.dphe.state.co.us/cdphe_swap_protection_planning/ (accessed 12/12/2023)

[8] Includes AZ, CO, ID, KS, MT, NE, NV, NM, ND, SD, UT, and WY.

[9] AL, AR, FL, GA, KY, LA, MS, MT, NC, OK, SC, TN, TX, and VA.

and public interests and private and public ownership of U.S. forests highlights the need for a better accounting of the benefits and costs of forest management.

Disclaimer: The findings and conclusions in this report are those of the author(s) and should not be construed to represent any official U.S. Government determination or policy. This research was supported in part by the U.S. Department of Agriculture and U.S. Geological Survey. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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7 APPENDIX

A 1. Computable general equilibrium model

Most parameters of the model are found through calibration as in Ballard et al. (1985) and de 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, utility maximization, and 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] $$VA_j = ava_j DY_j$$

The Leontief assumption implies costs, CV_j, can be written

[13] $$CV_j = \sum_t atax_t CV_j + \sum_{jj} aint_{jj,j} PX_{jj} + ava_j CVA_j$$

The value-added composite includes capital and labor, combined using a constant elasticity of substitution CES production function $VA_j = \psi_j \left(\delta_j K_j^{-\rho_j} + (1-\delta_j) L_j^{-\rho_j} \right)^{-1/\rho_j}$, 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] $$CVA_j(PF_K, PF_L) = min_{K_j, L_j} \left\{ PF_K * K_j + PF_L * L_j : VA_j(K_j, L_j) = VA_j \right\}.$$

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 $\underline{C}$. The mathematical expression of this optimization is

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

The first order conditions require

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

A 2. Timberland extent by state based on Forest Inventory Analysis data

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