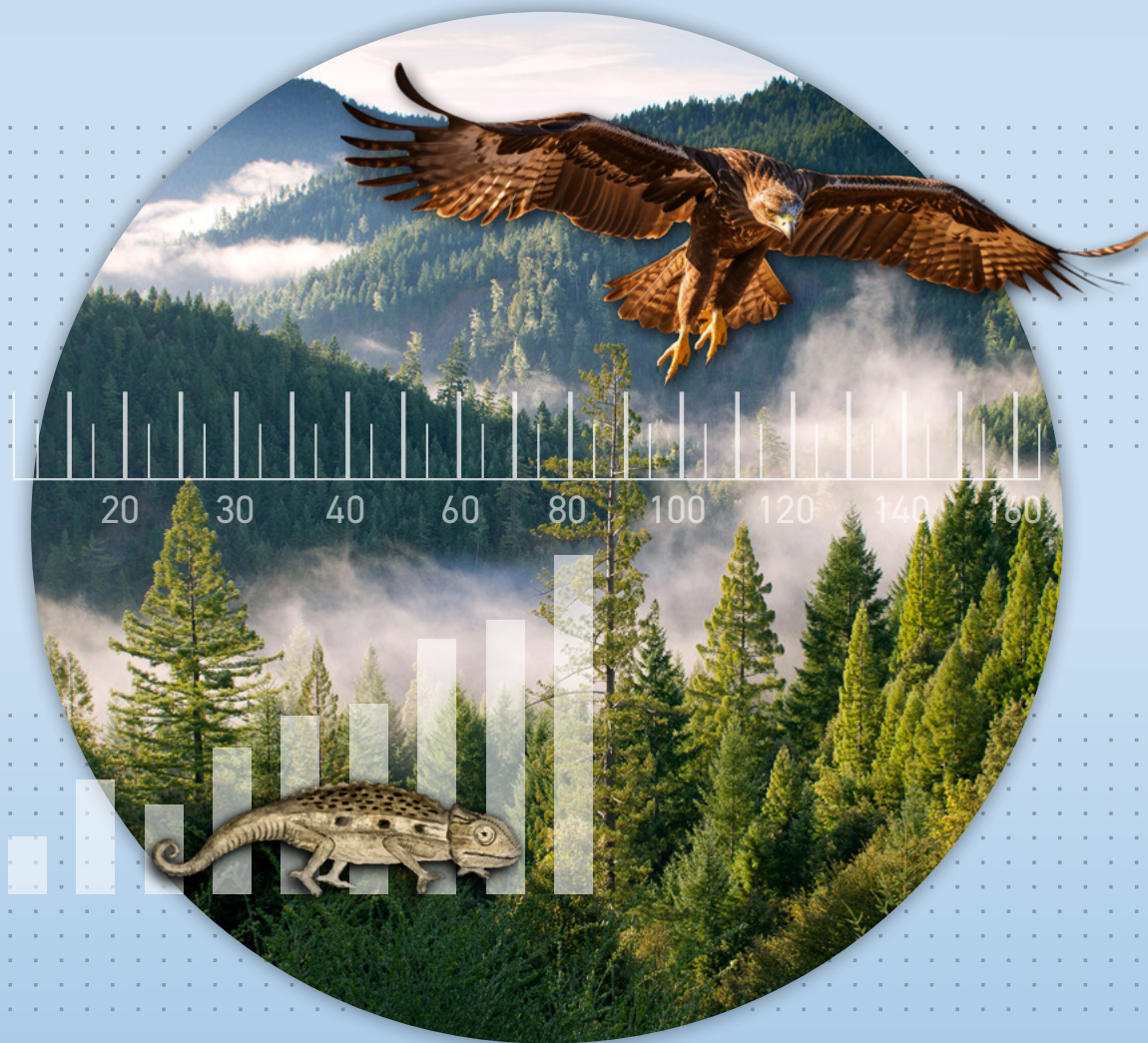


The **CHANGING WEALTH of NATIONS**

TECHNICAL REPORT

Global Assessment of the Economic Value
of Non-Wood Forest Ecosystem Services



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Design: Clarity Global Strategic Communications
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The authors would like to thank Stefanie Onder, Diego Herrera, Glenn Marie Lange, Esther Naikal, Stefano Pagiola, Grzegorz Peszko, and Robert B. Smith for their helpful input throughout this research. We also thank Helena Cárdenas, Francisco Santiago-Ávila, and Peter Vail for their assistance with this and earlier versions of this assessment.

This report received financial support from the Global Program on Sustainability (GPS) trust fund and the PROGREEN trust fund.

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ACRONYMS AND ABBREVIATIONS

AIC	Akaike Information Criteria	NCAVES	Natural Capital Accounting and Valuation of Ecosystem Services
AML	Automated machine learning	NDVI	Normalized Difference Vegetation Index
BART	Bayesian Additive Regression Trees	NOAA	National Oceanic and Atmospheric Administration
BIC	Bayesian Information Criteria	NPP	Net primary production
CART	Classification and Regression Tree	NPV	Net present value
CDR	Climate Data Record	NWFP	Non-wood forest products
CIESIN	Center for International Earth Science Information Network	PA	Protected area
CWON	Changing Wealth of Nations	PPP	Purchasing power parity
ESDV	Ecosystem Services Valuation Database	RePEc	Research Papers in Economics
EVRI	Environmental Valuation Reference Inventory	RF	Random forest
FAO	Food and Agriculture Organization of the United Nations	RMSE	Root mean square error
GDP	Gross domestic product	SEEA EA	System of Environmental-Economics Accounting Ecosystem Accounting
GIS	Geographical Information Systems	SNA	System of National Accounts
GNI	Gross national income	STAR	Species Threat Abatement and Recovery
GRIP	Global Roads Inventory Project	TEEB	The Economics of Ecosystems and Biodiversity
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services	UNEP	United Nations Environment Programme
ITOS	Information Technology Outreach Services	USD	United States dollar
IUCN	International Union for Conservation of Nature	VSURF	Variable selection using random forest
MAIA	Mapping and Assessment for Integrated ecosystem Accounting	WCMC	World Conservation Monitoring Centre
MCMC	Markov Chain Monte Carlo	WDPA	The World Database on Protected Areas
		WWF	World Wildlife Fund

1 Introduction

Forests generate considerable economic benefits through the provision of ecosystem services, including both wood and non-wood benefits. For example, according to the previous *The Changing Wealth of Nations 2021* (CWON 2021) report, more than half (54 percent) of total global natural capital wealth comes from renewable natural resources, including forests, mangroves, fisheries, protected areas, crop land, and pastureland. Out of all wealth arising from renewable natural resources, wood and non-wood ecosystem services represent approximately 29 percent (more than US\$10 trillion), with non-wood forest ecosystem services as the main contributor (73 percent) to natural capital wealth in forests.

In this report, we update and extend the methodology developed for the previous CWON 2021 report to assess the economic value of non-wood ecosystem services from forests (Siikamäki et al. 2021). Like the earlier assessment, we develop a meta-analytic predictive model using regression and machine learning techniques to spatially estimate the value of the following three ecosystem services: (1) recreation, hunting, and fishing; (2) non-wood forest products; and (3) watershed protection (hereafter, “water services”). These values are produced using 0.1° by 0.1° (approximately 10km by 10km) spatial resolution and then combined and spatially aggregated to estimate country-wealth from non-wood forest products. In addition, we develop an operational method to estimate the contribution of protected areas to the value of non-wood forest productions.

We apply the same approach to estimate the values of habitat and species protection ecosystem services. However, these values are not included in the combined value of non-wood forest ecosystem

services, to maintain alignment with the System of Environmental-Economics Accounting Ecosystem Accounting (SEEA EA) (United Nations et al. 2021). For the valuation of habitat and species protection, most of the estimates from the literature include non-use values as part of the total value estimated. The SEEA EA explains that non-use values are not within the scope of the value of ecosystem services included in the accounts, as there are no inherent transactions associated with these values. However, we include habitat and species protection as part of the overall assessment, as these estimates may still be of interest for purposes other than wealth accounting, including project appraisals.

The overall objective of the meta-analytic predictive model developed here is to help generalize current economic literature on the value of forest ecosystem services to the world’s forest more broadly. The basic problem with this generalization is that the currently available valuation literature addresses a select and limited set of forests that are probably not representative of the world’s forests. Therefore, using results derived directly from the valuation literature (for example, by using median or mean values by specific ecosystem services, forest types, and world regions) to assess the value of the forests throughout the world would likely produce biased estimates.

In this assessment, we follow and extend the approach developed by Siikamäki et al. (2015, 2021) to forecast the local value of forest non-wood ecosystem services. The approach builds on first developing a database of primary estimates of the value of non-wood forest ecosystem services, on a per hectare basis. These primary data on the value of non-wood forest ecosystem services are then combined with data on the socioeconomic, ecological, biophysical,

and climatic characteristics of the study areas. Using statistical regression and machine learning techniques, the assessment empirically identified how strongly, if at all, different socioeconomic, ecological, biophysical, and climatic characteristics of forests act as drivers of the value of non-wood forest ecosystem services. After constructing separate predictive models of the local value of four different non-wood forest ecosystem services, including recreation, hunting, and fishing; water services; non-wood forest products; and habitat and species protection, we apply the predictive models to locally estimate economic value of the four services around the world's forests.

The resulting value predictions are global in scope but local in scale. They are obtained by first dividing the world's forests into 0.1° by 0.1° (approximately 10km by 10km) grid cells, about 1.2 million cells in total; then compiling data for each grid cell on the different drivers of the value of non-wood forest ecosystem services, as identified in the meta-regressions; and finally, using the predictive models to estimate the local value of each ecosystem service in all forested grid cells across the globe. Country-level estimates are then derived by aggregating grid-cell level predictions by country. The assessment predicts substantial heterogeneity in the values by location and ecosystem service type, underlining the advantages of predicting them locally and by ecosystem service.

When conducting this assessment, we update and extend the study by Siikamäki et al. (2021) in four main ways:

- *We augment the database of primary valuation estimates* by incorporating new studies available. Siikamäki et al. (2021) included reviews of 659 studies, from which 270 primary value estimates from 164 studies met the

criteria required to be included in the final database. This report adds 79 new primary valuation estimates to the assessment, which were extracted after reviewing 677 additional papers identified mostly from the literature published since the development of the database in Siikamäki et al. (2021). The largest increases in new value estimates in percentage terms are from Asia (34 percent, 20 additional estimates), Africa (32 percent, 10 additional estimates), and Europe (19 percent, 28 additional estimates). By ecosystem service, this report adds 28 new estimates for recreation (20.1 percent of all the values for this service), 20 new estimates for habitat and species protection (20.6 percent), 17 new estimates for non-wood forest products (26.2 percent), and 14 new estimates for water services (31.1 percent).

- *We extend Siikamäki et al. (2021) by using revised and additional machine learning approaches.* These extensions include using a new approach to the selection of most important variables and using an altogether new additional machine learning algorithm, Bayesian Additive Regression Trees (BART), in addition to random forest (RF), automated machine learning (AML), and linear regression methods that were used in previous reports.
- *We add a new section to the report* to discuss the alignment of the values gathered from the literature with the SEEA.
- *We formulate an operational method for assessing* the economic value of forest non-wood ecosystem services by protected areas, as determined in the World Database on Protected Areas (UNEP-WCMC and IUCN 2022). Using the results, one can disentangle the contribution to wealth by forests that are protected versus not protected.

According to the results generated, the global average marginal value per hectare in 2020 ranges between US\$6.80 (non-wood forest products) and US\$48 (recreation) per year, depending on the service (US dollars 2020).¹ The average value of forest ecosystem services is generally highest in Europe, the United States, the Republic of Korea, Japan, and Australia. However, there is wide variation across services and geography. For example, average marginal value of protected forest can be larger or lower than non-protected forest, depending on the ecosystem service. Globally, the estimates show that in 2020, protected forest contributed 16 percent of the total value of recreation, hunting, fishing, non-wood forest products, and water services.

The rest of the report is structured as follows: Section 2 of the report explains the development of the database of non-wood forest ecosystem service valuation literature and provides summary statistics of the values obtained from the literature. Section 3

explains the construction of predictive models for four non-wood forest ecosystem services: recreation, hunting, and fishing; water services; non-wood forest products; and habitat and species protection. Section 4 describes the construction of the global database using a 0.1° by 0.1° grid, including compilation of the predictor variables to forecast local value of non-wood forest ecosystem services. Section 5 discusses the estimation results and global predictions using the world grid as well as country-level aggregations. Section 6 develops an operational method for identifying the contribution of protected areas to the value of non-wood forest products. A discussion in Section 7 concludes the report.

¹ Note that all final value predictions in this report are expressed in nominal terms (US\$ 2020) to match the currency type (nominal US\$ 2020) applied in the World Bank's The Changing Wealth of Nations report. See Section 2.1 for details.

2 Development of Database of Non-Wood Forest Ecosystem Service Valuation Studies

2.1 LITERATURE REVIEW AND DATA EXTRACTION

The first task in this assessment is to update the survey of the economic valuation literature on non-wood forest ecosystem services in Siikamäki et al. (2021). Appendix 1 describes the literature review process and summarizes the value estimates obtained. We followed the same criteria as in Siikamäki et al. (2015, 2021) in selecting the studies to be included in the review. Accordingly, they needed to:

- *Focus on the valuation* of non-wood forest ecosystem services.
- *Provide primary estimates* of the economic value of non-wood forest ecosystem services (as opposed to secondary valuation studies that estimate the value of ecosystem services based on results from other studies in the literature).
- *Estimate*, or potentially enable estimation of, values in per-unit-area units (e.g., US\$/ha).

The above criteria were purposefully general so that the first stage of the literature search was unlikely to exclude any potentially relevant studies. Because of this, we identified many studies that were not applicable to the database. We detected such studies by conducting detailed reviews of each study initially identified, as explained below.

We used a wide range of sources to help find potentially relevant literature. We started from three

general ecosystem valuation literature databases: (1) The Economics of Ecosystems and Biodiversity (TEEB); (2) the Environmental Valuation Reference Inventory (EVRI); and (3) the Ecosystem Services Valuation Database (ESDV). These databases are publicly available and comprise searchable collections of academic and non-academic literature on environmental and ecosystem valuation studies. They include information on all ecosystems, not just forests. While EVRI is continuously updated, the TEEB database was discontinued in 2014, and was integrated into ESDV. As a result, TEEB was reviewed by Siikamäki et al. (2015, 2021), while this report only reviewed ESDV for any forest-related studies (Foundation for Sustainable Development 2021).

Next, we searched for the key words “forest” AND “valuation” in Scopus. In addition, we conducted searches in specific journals where valuation studies may be published: *Environmental and Development Economics*, *Journal of Environmental Economics and Management*, *Forest Economics*, *Journal of Land Use Policy*, *Journal of Outdoor Recreation and Tourism*, *Science*, *Proceedings of the National Academy of Sciences*, and *Nature*. The search includes all journals featured on these websites, so for example, we searched all journals in the *Nature*-portfolio of journals, including *Nature Sustainability*, *Scientific Reports*, and so forth. We also conducted systematic searches of other literature databases, such as Google Scholar, EconLit, Environment Complete, and Research Papers in Economics (RePEc).

We reviewed studies identified in the most recent meta-analyses of valuation of forest ecosystem services (Nelson and Kennedy 2009; Ninan and Inoue 2013; Getzner and Islam 2020; Taye et al. 2021; Grammatikopoulou and Vačkářová 2021).² Finally, we used a “snowballing” technique by checking through the references of each study already identified and reviewed to find and add any new potentially relevant studies into our database. See Appendix 1 for further information.

Academic peer-reviewed literature, our key focus in the literature searches, offers a relatively narrow representation of geographic regions and ecosystem services. Therefore, we also searched for and included any available grey literature (reports, books, theses, other non-journal publications), so long as those studies were deemed relevant and methodologically sound.

Accounting for all studies considered in Siikamäki et al. (2015, 2021), and this assessment, a total of 1,336 studies were identified for further review (Phase 1, Figure 2.1). We were able to obtain most of the

publications identified, including the most recent publications, and especially those published in peer-reviewed academic journals. However, despite efforts to locate them online, using interlibrary loan or direct purchase, and, in some cases, directly contacting the study authors, copies of 26 studies out of the originally identified 1,336 studies were unavailable for a full review. These studies are mostly grey literature and/or published a long time ago, and they are listed in Appendix 2. This appendix also lists all of the studies included in the detailed review.

Our goal is to construct estimates of the value of forest ecosystem services on a per hectare basis. Therefore, a key task in the more detailed review (Phase 2, Figure 2.1) was to determine whether the study reports value estimates on a per unit area basis (per hectare, per acre, per km², and so forth) or includes other information to enable us to derive such estimates. If any potentially relevant value estimates were found from the study, we recorded them in the database. This review yielded 601 studies that could potentially be included in the database (Figure 2.1).

FIGURE 2.1: STUDIES FOUND IN THE DIFFERENT STAGES OF THE SEARCH AND NUMBER OF VALUES EXTRACTED DURING THE DATABASE UPDATE, INCLUDING SIIKAMÄKI ET AL. (2015, 2021) AND THIS REVISION



² These previous meta-analyses are often not directly comparable to this study, because not all of them are spatially explicit and/or are not produced by primary studies following the criteria described in our study review protocol [see Section A12 in Appendix 1].

Finally, to develop the database of primary valuation estimate, we used a study review protocol to extract all relevant information from each study (Section A1.2 in Appendix 1), including:

- *Study area ecological characteristics:* biome, forest type, inland/coastal, other landscapes.
- *Study location:* country, country income group, protection status, study site area, scale of research, region continent, and coordinates.
- *Ecosystem service(s) addressed,* as well as classification as domestic/foreign value of service and as direct use, indirect use, and non-use value.
- *Value information:* year of value, valuation method, valuation type, reported value, units, value currency.
- *Other potentially relevant study descriptors:* type of publication, publication year, and sample size, if applicable.

We used a value estimate as the unit of observation. However, we did not include in the database every possible value estimate from each study, because research publications often report many estimates addressing the same forest and service but derived under slightly different assumptions and approaches. In those situations, we determined a preferred or representative estimate, or averaged the listed estimates if no preferred estimate could be identified. If the methodologies underpinning different estimates from one study were completely different (for example, travel cost methods and contingent valuation), we recorded multiple estimates instead of choosing a preferred estimate or taking an average.

Many studies lack information that is necessary to develop value estimates on a per unit area basis.

In these situations, we searched external sources for supplemental data. Typically, these efforts included retrieving data on variables such as study area size (when not listed in the study); study area location (coordinates); number of households or population addressed by value estimate (to calculate aggregate values); and ecological characteristics of study area (type of forest, biome). We used mostly online searches to find external data, as well as Geographical Information Systems (GIS) processing and correspondence with articles authors and other relevant experts such as government officials. We implemented several steps of quality assurance/quality control to help develop robust and consistent summaries of studies included in the database (Appendix 3).

We included multiple records for studies that report separate value estimates for different ecosystem services and/or study areas. For such studies, the study area characteristics may also vary by value estimate. To address this, we recorded the location (latitude, longitude) of each value estimate.

In the end, the final database contains 346 observations derived from 225 studies (Phase 3, Figure 2.1). For the purpose of making value estimates comparable in their economic value to local populations across different countries, we converted value estimates extracted from the original studies by using purchasing power parity (PPP). We used 2017 as the base year for PPP conversions because it is the latest year for which comprehensive PPP data are available globally. Appendix 4 explains the currency conversion. However, note that the global predictions in the report are not PPP-adjusted. Rather, we express predictions in nominal terms (US dollars 2020) to match the currency type (nominal) applied in the World Bank's CWON.

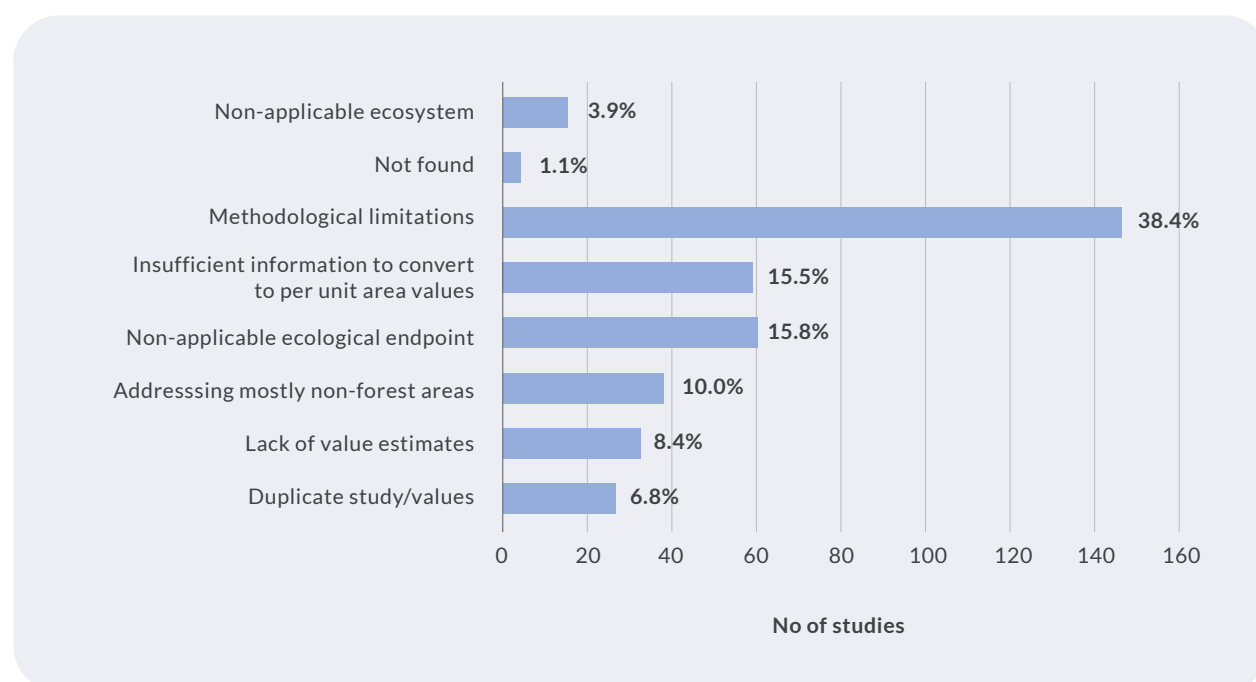
Many of the studies originally identified in the literature search did not ultimately meet the criteria required for the inclusion in this assessment. We recorded the primary reason for exclusion for each excluded study (Figure 2.2). For example, when we identified methodological approaches inconsistent with the principles of ecosystem service valuation, we excluded the study. This criterion was the leading reason for exclusion, applying to 146 studies (38.4 percent of all excluded studies). Note that in addition to general ecosystem service valuation principles, we will assess later in this report the final database of value estimates relative to requirements specific to the SEEA. The second most prevalent reason for exclusion includes studies that address values for ecological endpoints outside the scope of this assessment (non-wood benefits) (60 studies, 15.8 percent of all excluded studies); such as timber or wood fuel or carbon sequestration; and valuation studies for which there were not sufficient information to convert to per unit

area values (59 studies, 15.5 percent of all excluded studies). Non-applicable ecological endpoints also include studies, which estimate aggregate wood and non-wood benefits without sufficient information to help separate out the non-wood portion of the benefits. Similarly, if the study explicitly addressed carbon and non-carbon value without separating them from one another, we excluded the estimate. See Appendix A1.3 for more details.

2.2 VALUE ESTIMATES BY ECOSYSTEM SERVICE AND ESTIMATION METHOD

When recording the type of ecosystem service addressed in the original study, we used fine-grained classifications, including cultural/existence value; erosion control; fishing; flood protection; habitat/species protection; hunting; landscape aesthetics; non-wood forest products; recreation;

FIGURE 2.2: PRIMARY REASON FOR THE EXCLUSION OF STUDIES FROM THE DATABASE



and various types of water-related services such as water quality or water quantity. We later aggregated these classifications into fewer, but still meaningful categories, to facilitate empirical analyses that require a considerable number of observations per service statistically examined. Accordingly, we aggregated the fine-grained classifications of ecosystem services into four main categories representative of the literature:

- Recreation, hunting, and fishing
- Habitat and species protection
- Non-wood forest products
- Water services.

The above four ecosystem service categories organize value estimates so that each category represents relatively similar studies concerning the objectives, methodologies, and general setting of the original valuation studies. Figure 2.3 shows the number of values per ecosystem service category and sub-category. “Recreation, hunting, and fishing” includes 139 value estimates, almost all of them (128) addressing outdoor recreation. Note that we combine value estimates for hunting and fishing that takes place in a recreational context, typically in developed countries, with value estimates for outdoor recreation. But when hunting or fishing takes place in the context of subsistence or income generation, we combine those value estimates for non-wood forest products, as discussed below.

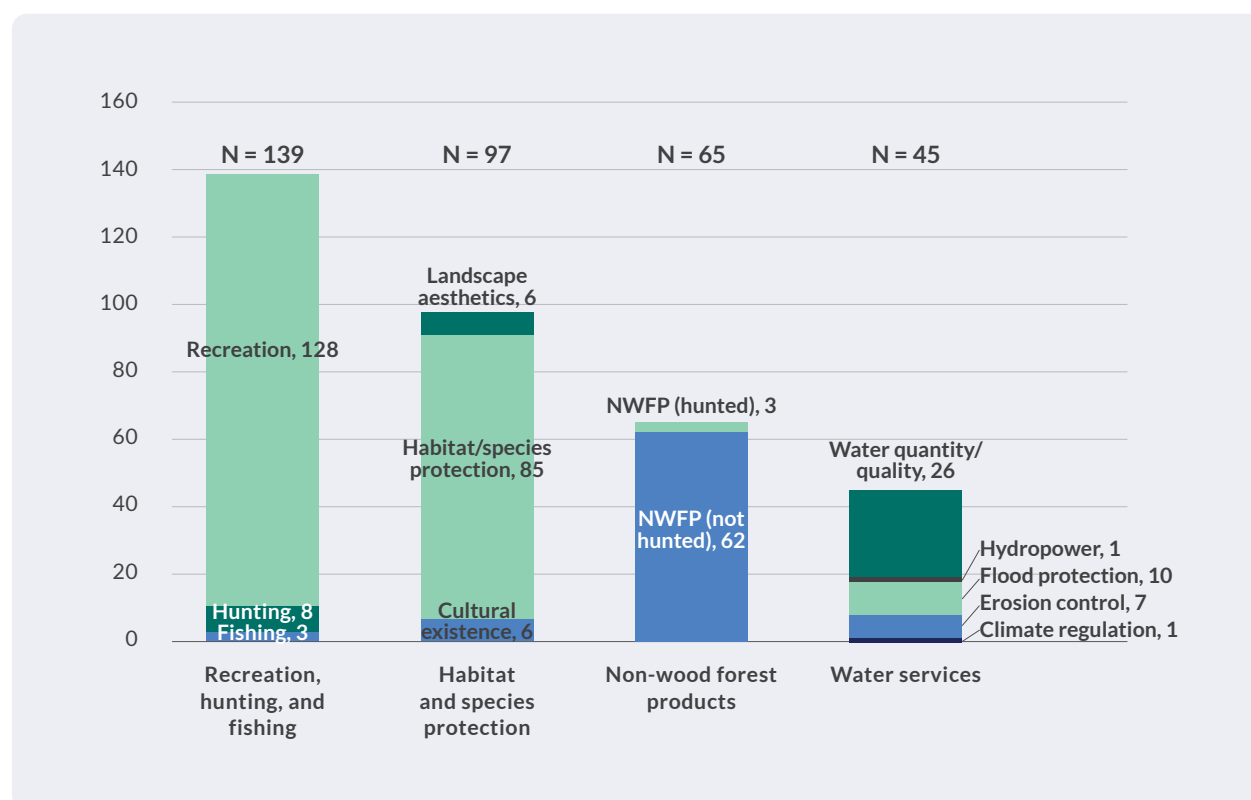
“Habitat and species protection” includes values classified as habitat and species protection, cultural/existence values, or landscape aesthetics. There are 97 value estimates in this category in the estimation dataset. Values addressing “non-

wood forest products” include 65 estimates in the estimation dataset.

Values classified as “water services” come from studies that address benefits from forests on water quality/water quantity, often in the context of controlling water flow and pollution from erosion and other sources, enabling hydropower, avoiding disasters, or the impact on crop yields by controlling weather. There are 45 value estimates for water services in the estimation dataset. Studies on water services are perhaps most varied in the estimation datasets constructed, but the limited number of studies that address any sub-category of water services prevents us from using a more disaggregated service classification.

In the original literature, value estimates come from a range of different valuation methods. Appendix 1 shows the distribution of valuation methods by ecosystem service category, including the frequency of value estimates per method between the first two waves of literature review in 2015 and 2020 and the database update conducted in this assessment (including studies published by the end of 2022).

Differences between the valuation studies, including valuation methods and concepts in the above four ecosystem service categories, are so substantial that their further aggregation is not justified. Moreover, the number of studies in each of the four categories supports conducting separate statistical assessments, including especially recreation, hunting, and fishing, and habitat and species protection, which have 139 and 97 value estimates, respectively. The number of value estimates for non-wood forest products (65) and water services (45) is more limited, but regardless enables further analyses as separate ecosystem service categories.

FIGURE 2.3: NUMBER OF VALUE ESTIMATES BY ECOSYSTEM SERVICE AND SUB-SERVICE

The source literature for each ecosystem service category includes studies from developed and developing countries, thus combining data from different settings in terms of the characteristics of activities associated with benefiting from the service. For example, while recreation in developed countries is typically associated with leisure enjoyment, individuals in developing countries may

engage in similar activities to support subsistence. We address this situation in two primary ways. First, we classify activities to collect food and/or income in developing countries as a non-wood forest product service. Second, we use statistical controls in the empirical modelling to account for differences systematically associated with conditions such as income level of the country.

2.3 GEOGRAPHICAL DISTRIBUTION OF VALUES BY ECOSYSTEM SERVICE

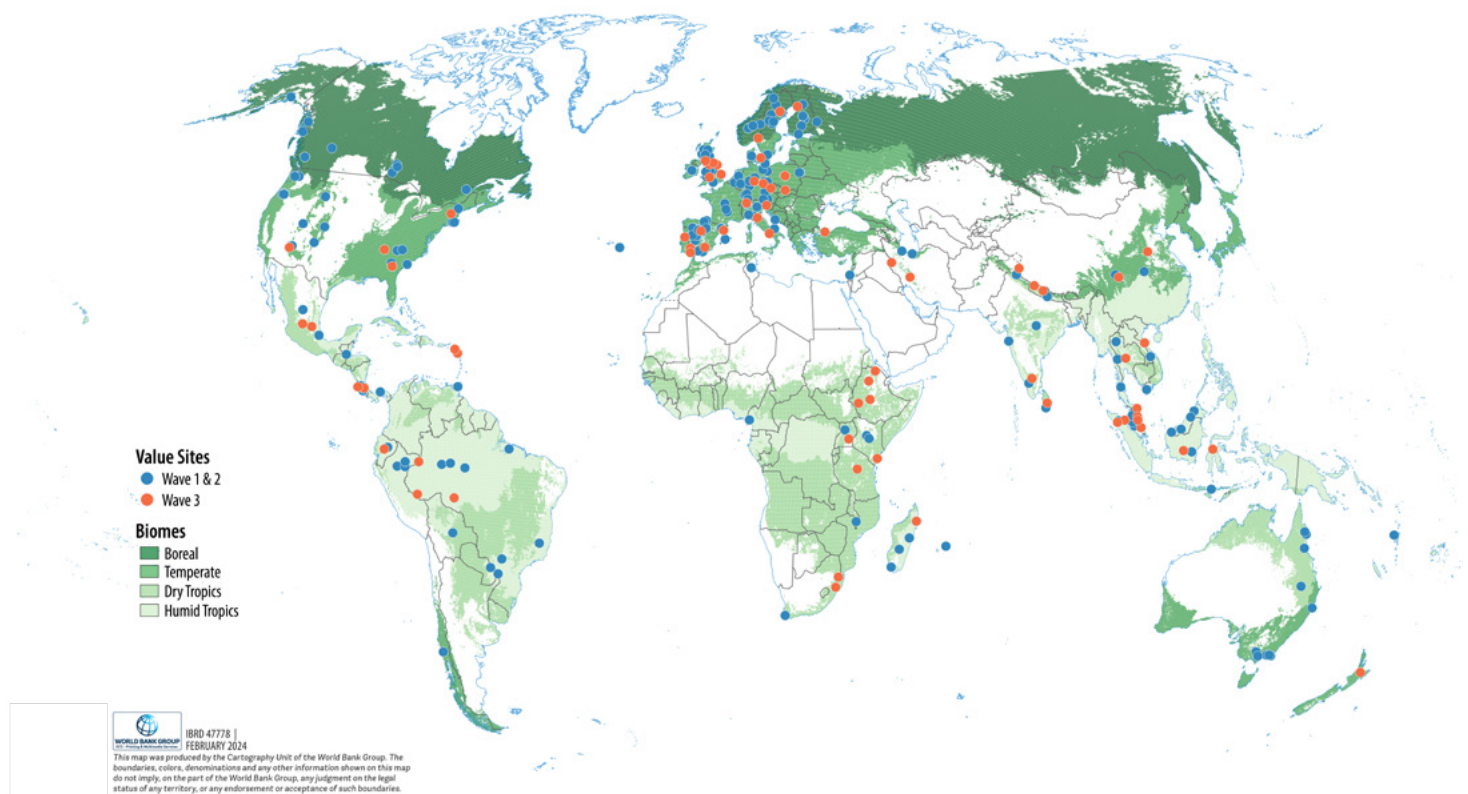
The meta-regression estimation dataset includes values from 66 different countries. Figure 2.4 maps the geographic locations of value estimates, indicating a relatively wide global distribution of estimates in the dataset but with some concentration in Europe, North and South America, and Southeast Asia.

All continents with forests and all different forest biomes—humid tropics, dry tropics, temperate, and boreal—are represented in the estimation dataset. The map also illustrates a key limitation of the forest ecosystem service valuation literature: no coverage of Russian forests exists in the literature although they cover one fifth of global forests. Based on our

literature review and consultations with experts, this is primarily due to the lack of economic valuation studies consistent with our criteria in that part of the world, not limitations of the literature review.

The greatest number of value estimates comes from Europe, which has a total of 147 estimates (42 percent of all value estimates in the dataset). The second highest number of estimates come from the Americas, including 94 estimates or 27 percent of the global total. Asia is the continent with the third highest number of value estimates. It has a total of 59 estimates (17 percent of global total). The continents with the least number of value estimates are Africa (31 estimates, 9 percent of the global dataset) and Oceania (15 estimates, 4 percent). Figure A1.6 in Appendix 1 graphs the value estimates by country and continent.

FIGURE 2.4: GEOGRAPHIC LOCATION OF VALUE ESTIMATES



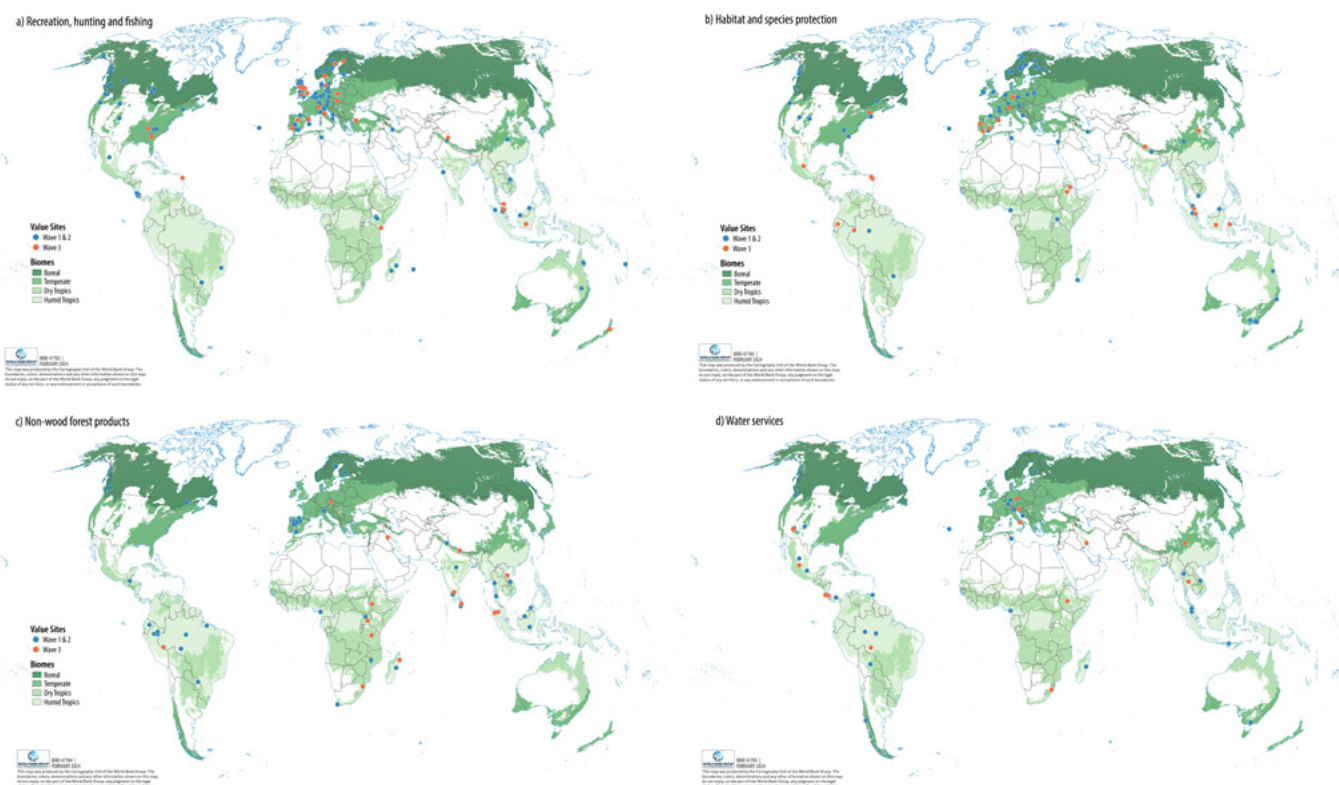
This report added 79 new value estimates to the 270 estimates already gathered by Siikamäki et al. (2015, 2021), increasing the number of value estimates in the database by 21.7 percent. The largest additions in percentage terms are in Asia (34 percent, 20 additional estimates), Africa (32 percent, 10 additional estimates), and Europe (19 percent, 28 additional estimates). As such, updating the database of value estimates helps increase geographical coverage, especially in regions where data was scarce.

Figure 2.5 maps the geographic distribution of value estimates by ecosystem service. Estimates of the value of recreation, fishing, and hunting come mainly from Europe, Southeast Asia, and North America but also represent Africa, Central and South America, and Oceania (Figure 2.5a). Value estimates for habitat/species protection are

frequently from Europe and North America but also include data from each other continent—Asia, Africa, Oceania—as well as South America as a sub-continent in America (Figure 2.5b).

The number of value estimates for non-wood forest products (2.5c) and water services (2.5d) in each category is relatively small, but the geographic distribution of the estimates is quite broad. Studies in non-wood forest products concentrate in Europe, although all continents in the dataset, except for Oceania, are represented with five or more values. Water service value estimates come mostly from the Americas, though each continent in the estimation dataset has at least one value estimate. With North America and Europe most frequently represented in the valuation literature, we re-doubled efforts to search for studies from elsewhere around the world.

FIGURE 2.5: GEOGRAPHICAL LOCATION OF VALUE ESTIMATES BY ECOSYSTEM SERVICE CATEGORY



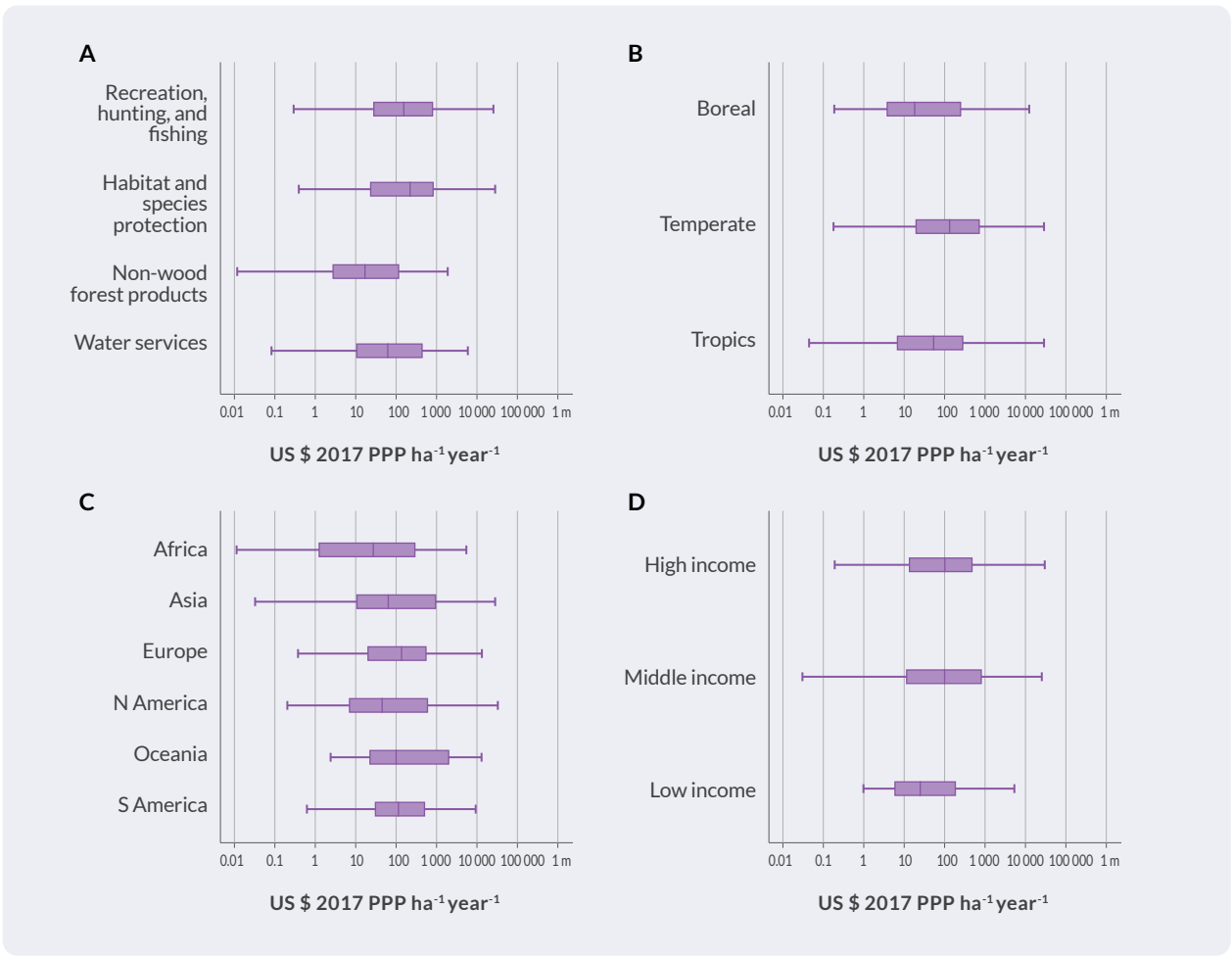
Of the 79 new values added to the estimation dataset, 28 new estimates address recreation, hunting, and fishing (20.1 percent of all the values for this service), 20 new estimates address habitat and species protections (20.6 percent), 17 new estimates address non-wood forest products (26.2 percent), and 14 new estimates address water services (31.1 percent). Therefore, in relative terms, updating the estimation database with new studies adds most information on ecosystem services for which the number of observations was lowest (non-wood forest products and water services).

2.4 VALUE ESTIMATES

Figure 2.6 uses box-whisker plots to graphically summarize the value estimates in the estimation dataset by ecosystem service; biome; continent; and country income category. In these figures, the ends of “whiskers” denote the minimum and maximum of estimates; the box in the middle ranges from the 25th to 75th percentile of the estimates, and the line within the box shows the median.

The range of values is wide both within and between different ecosystem services (Figure 2.6, top left).

FIGURE 2.6: VALUE ESTIMATES BY ECOSYSTEM SERVICE (TOP LEFT), BIOME (TOP RIGHT), CONTINENT (BOTTOM LEFT), AND INCOME GROUP (BOTTOM RIGHT)



Non-wood forest products have the lowest median (and minimum) value, followed by water services; recreation, hunting, and fishing; and habitat/species protection. Variation by biome (Figure 2.6, top right) is less distinct, with boreal values lowest in the median, followed by tropics in the middle and temperate forests as the highest. The range of value estimates is especially wide in the tropics.

When summarizing values by continent (Figure 2.6, bottom left), Africa has relatively low values, but other continents seem relatively similar. When examined by country-income group, Figure 2.6 (bottom right) shows that low-income countries tend to have relatively low values. Moreover, value estimates from low-income countries are relatively more concentrated than those from middle- and high-income countries.

2.5 LINKAGES WITH THE SYSTEM OF ENVIRONMENTAL-ECONOMIC ACCOUNTING – ECOSYSTEM ACCOUNTING

In this section, we discuss the linkages between the value estimates presented in previous sections and the SEEA EA (United Nations et al. 2021). We discuss the following three aspects:

- Correspondence of value estimates with the concept of exchange value used in the SEEA EA.
- Disentangling value-contribution by nature from contributions by manufactured and human capital.
- Consistency with the SEEA EA ecosystem services reference list.

Correspondence of value estimates with the concept of exchange value used in the SEEA EA

A key characteristic of the SEEA EA is that it uses

exchange value as the measure of the monetary value of ecosystem services, like the measurement of monetary value of goods and services in the System of National Accounts (SNA), including gross domestic product (GDP).

Exchange values are defined as:

“The values at which goods, services, labor or assets are in fact exchanged or else could be exchanged for cash”

(United Nations et al. 2008, 2021).

For most entries in the national accounts compiled using the SNA, exchange values are measured using data from actual transactions involving market prices. However, there are also several types of transactions for which market prices are not observed and therefore need to be estimated. Thus, alternative methods are used to estimate observed market prices when exchange values are not observable. This allows aggregation across market and non-market goods and services in the measurement of production and consumption.

The use of alternative methods in the SNA to estimate exchange values highlights that the estimation of the monetary value of a transaction does not require actual exchange of money (cash or equivalent) (NCAVES and MAIA 2022). Another consequence of using a transaction-based approach is that national accounts do not include consumer surplus, as consumer surplus cannot be transferred between agents (NCAVES and MAIA 2022). Consumer surplus is the difference between what is actually paid for a good or service (exchange price) and what a person would be willing to pay at the maximum.

The SEEA EA describes the order of methodological preference for the ecosystem service valuation methods (United Nations et al. 2021):

- I. Methods where the price for the ecosystem service is directly observable.
- II. Methods where the price for the ecosystem service is obtained from markets for similar goods and services.
- III. Methods where the price for the ecosystem service is embodied in a market transaction.
- IV. Methods where the price for the ecosystem services is based on revealed expenditures (costs) for related goods and services.
- V. Methods where the price for the ecosystem service is based on expected expenditures or markets, i.e., cost of replacing an ecosystem service using a process that provides the same benefit but for which there are established

costs or prices; cost of the damages that would occur due to the loss of these services; or estimates of price and quantity that would prevail if the ecosystem service would be traded in a hypothetical market.

Table 2.1 lists the methods in order of methodological preference in the SEEA EA (NCAVES and MAIA 2022). Table 2.2 lists the number of value estimates by valuation method in our database. Fifty-one percent of the value estimates in the database are based on preferred methods for the SEEA EA by NCAVES and MAIA (2022). This rises to 94 percent for non-wood forest products, where market prices are directly observable, and 78 percent for water services, where avoided cost and production function methods are applied in several cases.

TABLE 2.1: TYPOLOGY OF VALUATION METHODS BY SEEA EA METHODOLOGICAL PREFERENCE

PRICE OBSERVATION	VALUATION METHOD	ALTERNATIVE DESCRIPTION/ RELATED METHODS
I. Prices are directly observable	Market prices	Gross revenue; public pricing; monetary incentives
II. Prices from similar markets	Market prices in similar markets	
III. Prices embodied in market transactions	Residual value; resource rent Hedonic pricing Productivity change	Net factor income Production function method
IV. Prices from revealed expenditure on related goods and services	Averting behavior Travel expenditure	Defensive expenditure; averting cost Consumer expenditure method; zonal based models; random utility model studies
V. Prices from expected or simulated expenditures or expected markets	Replacement cost Avoided damage cost Simulated exchange value	Substitute cost; alternative cost Cost of illness; human capital

Source: NCAVES and MAIA (2022).

TABLE 2.2: NUMBER OF VALUES BY METHOD AND LINKAGES WITH SEEA EA

METHOD	SEEA EA CATEGORY	RECREATION, HUNTING, AND FISHING	HABITAT AND SPECIES PROTECTION	NWFP	WATER SERVICES	TOTAL
Avoided cost	V.	2	1	1	20	24
Market price	I.	4	1	47	4	56
Production/cost function	III.	0	1	5	11	17
Travel cost	IV.	71	0	8	0	79
Hedonic pricing	III.	1	0	0	0	1
Transfer		8	1	2	1	12
Contingent valuation		42	59	2	6	109
Choice experiment		10	34	0	3	47
Total		138	97	65	45	345
% values using methods preferred by SEEA EA		56.5%	3.1%	93.8%	77.8%	51.3%

In the case of recreation, hunting, and fishing, 56 percent of the value estimates are produced by methods preferred by the SEEA EA. Finally, only 3 percent of the value estimates for habitat and species protection are produced using revealed preference methods. We will discuss habitat and species protection later in this section. The remaining estimates for recreation, hunting, and fishing; non-wood forest products; and water services in our database are produced mainly stated preference methods (contingent valuation and choice experiments). NCAVES and MAIA (2022) notes when these methods are considered for compilation purposes, they should be checked for consistency with exchange value principles and adjusted as required before their use for the accounts.

For example, the simulated exchange value method (SEEA EA category V) uses stated preference methods (contingent valuation or choice experiment) to obtain a demand curve for a certain ecosystem service that is later combined with a supply curve to identify the exchange market.

In many studies in the literature on recreation, hunting, and fishing, stated preference approaches are used to elicit data on new recreational opportunities, using a similar conceptual and empirical model as one uses when conducting revealed preference recreational site choice travel cost studies, eliciting data by using surveys. We include stated preference studies when they are carefully designed to estimate the demand curve

for the ecosystem service in question. As such, they involve estimation of marginal values, as needed for this study. We note that the value estimates for recreation, hunting, and fishing derived using stated preference methods always lay within the range of value estimates derived using other methods suggested in NCAVES and MAIA (2022).

The setting in the valuation of habitat and species protection is different from the other three services considered here, in that most of the estimates from the literature address the total value of an ecosystem, including its non-use value. The SEEA EA explains that non-use values are not within the scope of the value of ecosystem services included in the accounts, as there are typically no transactions associated with these values. However, where there is interest in estimating these values, a common approach is to use stated preference methods (such as choice experiment, contingent valuation) (NCAVES and MAIA 2022). Ninety-seven percent of the value estimates for habitat and species protection in our database are produced using stated preferences methods (Table 2.5). While the estimates of habitat and species protection can be useful to inform measurements and decisions that go beyond the SEEA EA, they at least partially comprise non-use values that cannot be allocated to specific transactions. That is, there is no physical flow of ecosystem service that corresponds to the value. Moreover, because stated preference methods regularly estimate the combined total value of ecosystem services, separating out use versus non-use values is not feasible.

Disentangling contributions by nature from contributions by manufactured and human capital

The generation of ecosystem services, and their delivery to final beneficiaries, requires contributions by ecosystems, but also regularly draws inputs from manufactured and human capital. For example,

water provision services to urban populations requires the availability of raw water regulated in quantity and quality by ecosystems, but also needs a water treatment facility, plant operators, and variable inputs, such as electricity and chemicals for water purification, along with a distribution network to deliver water to the customers. This combination of inputs from ecosystems (natural capital) and produced capital enables water supply services that are transacted and yield the exchange prices observed in practice.

Ecosystem service valuation requires that the contribution of ecosystems to the final exchange price of the ecosystem service flow is disentangled from other forms of contributions, such as produced or human capital. All methods in our database, described in Table 2.5, are designed to disentangle the contribution of nature from the overall value of benefit. This means that our value estimates consistently correspond to the contribution of ecosystems to the economic benefits associated with a certain ecosystem service flow.

Consistency with the SEEA EA ecosystem services reference list

The SEEA EA provides a general typology of ecosystem services by using 27 relatively high-level categories that form a basis for less or more detailed classifications in specific applications (United Nations et al. 2021). Table 2.3 shows the linkages between the ecosystem services classification used in this report and the SEEA EA ecosystem services reference list, including the number of studies in the database developed in this study by ecosystem service.

Value estimates for recreation, hunting, and fishing; habitat and species protection; and non-wood forest products are linked one-to-one with a specific ecosystem service category in the SEEA EA.

The situation is different for water services, which have seven different ecosystem services in the SEEA EA reference list, including services related to water quantity and quality, erosion control, and flood control. Moreover, many of the value estimates individually address more than one of the ecosystem services in the SEEA EA reference list. This is the case, for example, for studies that jointly examine water quantity and quality. While a few studies

specifically focus on water quality or quantity, most of the studies assess this service as joint production. The same is true for flood control services, where valuation estimates often use data on avoided damage from flood events, but do not disentangle what part of the benefit is related to baseline flow maintenance service, peak flow mitigation services, or river flood mitigation services.

TABLE 2.3: LINKAGES BETWEEN ECOSYSTEM SERVICES CLASSIFICATION AND SEEA EA ECOSYSTEM SERVICES REFERENCES LIST

ECOSYSTEM SERVICE CATEGORY IN THIS STUDY	SEEA EA REFERENCE LIST	ALTERNATIVE DESCRIPTION/ RELATED METHODS	NUMBER OF VALUES IN THE DATABASE
Recreation, hunting, and fishing	Recreation-related services	Recreation-related services are the ecosystem contributions, in particular through the biophysical characteristics and qualities of ecosystems, that enable people to use and enjoy the environment through direct, in-situ, physical and experiential interactions with the environment. This includes services to both locals and non-locals (i.e., visitors, including tourists). Recreation-related services may also be supplied to those undertaking recreational fishing and hunting. This is a final ecosystem service.	139
Habitat and species protection	Ecosystem and species appreciation	Ecosystem and species appreciation concerns the wellbeing that people derive from the existence and preservation of the environment for current and future generations, irrespective of any direct or indirect use.	97
Non-wood forest products	Wild animals, plants and other biomass provisioning services	Wild animals, plants and other biomass provisioning services are the ecosystem contributions to the growth of wild animals, plants and other biomass that are captured and harvested in uncultivated production contexts by economic units for various uses. The scope includes non-wood forest products (NWFP) and services related to hunting, trapping and bio-prospecting activities; but excludes wild fish and other natural aquatic biomass (included in previous class). This is a final ecosystem service.	65

ECOSYSTEM SERVICE CATEGORY IN THIS STUDY	SEEA EA REFERENCE LIST	ALTERNATIVE DESCRIPTION/ RELATED METHODS	NUMBER OF VALUES IN THE DATABASE
Water services	Water supply	Water supply services reflect the combined ecosystem contributions of water flow regulation, water purification, and other ecosystem services to the supply of water of appropriate quality to users for various uses including household consumption. This is a final ecosystem service.	26
	Water purification services (water quality regulation)	Water purification services are the ecosystem contributions to the restoration and maintenance of the chemical condition of surface water and groundwater bodies through the breakdown or removal of nutrients and other pollutants by ecosystem components that mitigate the harmful effects of the pollutants on human use or health. This may be recorded as a final or intermediate ecosystem service.	
	Rainfall pattern regulation services (at sub-continental scale)	Rainfall pattern regulation services are the ecosystem contributions of vegetation, in particular forests, in maintaining rainfall patterns through evapotranspiration at the sub-continental scale. Forests and other vegetation recycle moisture back to the atmosphere where it is available for the generation of rainfall. Rainfall in interior parts of continents fully depends upon this recycling. This may be a final or intermediate service.	1
	Soil erosion control services	Soil erosion control services are the ecosystem contributions, particularly the stabilizing effects of vegetation that reduce the loss of soil (and sediment) and support use of the environment (e.g., agricultural activity, water supply). This may be recorded as a final or intermediate service.	7
	Baseline flow maintenance services	Water regulation services are the ecosystem contributions to the regulation of river flows and groundwater and lake water tables. They are derived from the ability of ecosystems to absorb and store water, and gradually release water during dry seasons or periods through evapotranspiration and hence secure a regular flow of water. This may be recorded as a final or intermediate ecosystem service.	11
	Peak flow mitigation services	Water regulation services are the ecosystem contributions to the regulation of river flows and groundwater and lake water tables. They are derived from the ability of ecosystems to absorb and store water, and hence mitigate the effects of flood and other extreme water-related events. Peak flow mitigation services will be supplied together with river flood mitigation services in providing the benefit of flood protection. This is a final ecosystem service.	
	River flood mitigation services	River flood mitigation services are the ecosystem contributions of riparian vegetation that provides structure and a physical barrier to high water levels and thus mitigates the impacts of floods on local communities. River flood mitigation services will be supplied together with peak flow mitigation services in providing the benefit of flood protection. This is a final ecosystem service.	

3 Methods for the Spatial Estimation of the Value of Non-Wood Forest Ecosystem Services Globally

3.1 OVERVIEW

Figure 3.1 illustrates the general conceptual approach developed here to construct spatial estimates of the economic value of non-wood forest ecosystem services worldwide. As explained in the previous sections, we identified the latitude and longitude of each study area included in the database of value estimates developed from the primary literature. We then divided the world's forests into a 0.1° by 0.1° (approximately 10km by 10km) world grid. We compiled data on several socioeconomic, ecological, biophysical, and climatic features at the grid cell level using GIS and linked the data to the studies included by using their latitude and longitude (Figure 3.1, left panel). The construction of spatial data is described in Section 4.

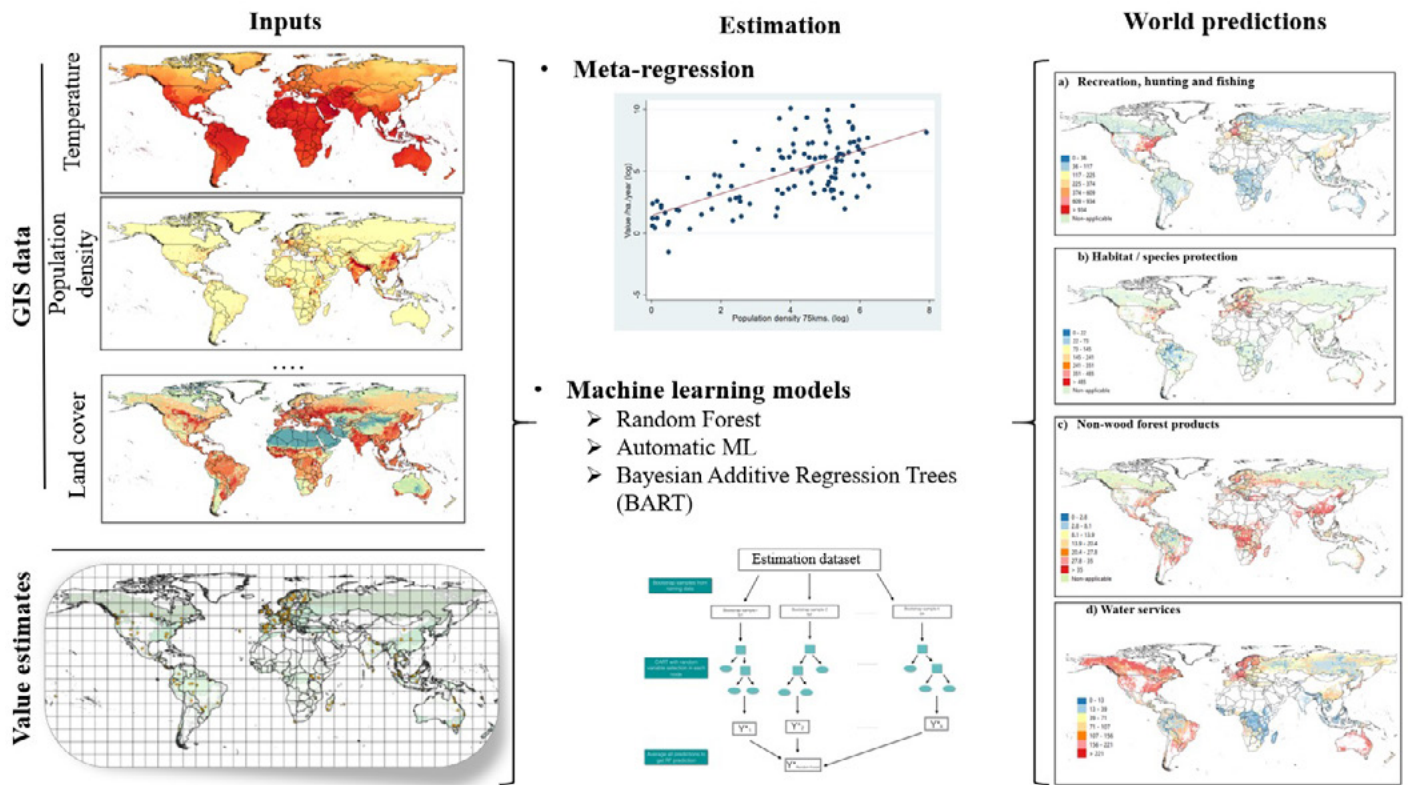
Using the data compiled, we then built alternative predictive models of the local value of forest non-wood ecosystem services by statistically examining the characteristics of the study areas as determinants of the value of non-wood forest ecosystem services. To do so, we used two alternative statistical approaches: (1) meta-regression and (2) machine learning (Figure 3.1, central panel). This is explained in Section 3.2.

Finally, we selected a model to produce global predictions and develop global predictions in two stages. First, we defined the service area for each ecosystem service, i.e., those cells that supply the service. Second, we used the selected model to produce global predictions of service areas. This is explained in Section 3.3.

3.2 ESTIMATION METHODS

We used meta-regression and machine learning methods as alternative approaches to statistical predictions. Meta-regression methods are widely used across different disciplines, including natural, health, and social sciences. Applications to environmental economics began in the early 1990s (for example, Smith and Kaoru 1990) and have since become prevalent (Nelson and Kennedy 2009; Johnston et al. 2015, 2018). Machine learning algorithms are a family of statistical methods widely used for prediction problems in agricultural sciences (Knapp and van der Heijden 2018), robotics, neuroscience, speech processing, and image recognition (Jordan and Mitchell 2015). The increasing availability of remote sensing data during the last decades and the power of machine learning methods to deal with large datasets has

FIGURE 3.1: GENERAL METHODOLOGICAL APPROACH



Source: Note: own elaboration using data from (Willmott and Matsuura 2015) for temperature, (Center for International Earth Science Information Network – CIESIN – Columbia University 2018) for population density, and (ESA 2017a) for land cover.

boosted their use to create global datasets on forest cover (Hansen et al. 2013); biomass and land productivity (Bai et al. 2008, 2015); mangrove soil carbon (Jardin and Siikamäki 2013); and weather (Matsuura and Willmott 2015), among others.

We developed separate predictive models for each of the four services considered: recreation, hunting, and fishing; habitat and species protection; non-wood forest products; and water services, assuming that studies within each category are sufficiently similar to be meaningfully combined as a group, which is one of the assumptions required for meta-regressions

(Nelson and Kennedy 2009; Borenstein et al. 2009; Cochrane 2019). For each service, we selected models by using both conceptual and statistical criteria. These models are then used to predict the economic value of different non-wood forest ecosystem services locally at the grid-cell level, across the entire world grid (Figure 3.1, right panel).

To compile local predictions of the value of non-wood forest ecosystem services, we depart from a conditional expectation function that characterizes their value (per hectare) as a function of socioeconomic (income per capita,

population density), biophysical (latitude), ecological (ecosystem type, species richness, land cover, forest degradation), and climatic (rainfall and temperature) attributes of each study site (Equation 1):

Equation 1:

$$E(\$ ha^{-1} | X = \text{socioeconomic, biophysical, ecological, climatic}) = f(X)$$

Regression analysis and machine learning methods involve tradeoffs between flexibility and interpretability (Figure 3.2). A method is less flexible, or more restrictive, when it can produce a relatively small range of shapes of the function f (James et al. 2016). For example, linear regression is relatively inflexible, because it generates single linear functions (or their non-linear transformations). Machine learning methods are considerably more

flexible because they can generate a wide range of possible shapes to predict f .

More restrictive models have the advantage that they are generally more interpretable, making it easier to understand the relationship between the predicted (dependent) and predictor (independent) variables. In contrast, highly flexible approaches can incorporate complex relationships between the predicted and predictor variables that make it difficult to evaluate how any individual predictor is associated with the response in the predicted variable. If one is only interested in prediction, and not in the interpretability of the relationship between the predicted variable and its predictors, then this flexibility can help obtain statistically powerful predictions.

In all models, we used weighted estimations to account for the fact that different studies contribute

FIGURE 3.2: TRADEOFFS BETWEEN FLEXIBILITY AND INTERPRETABILITY USING DIFFERENT STATISTICAL METHODS



different numbers of observations into the estimation dataset. We weighed the observations in the estimation dataset so that each study, not value estimate, is given equal overall weight in the estimations. To do so, we determined the weight of each value estimate as $1/z$, where z is the total number of value estimates derived from the study. Accordingly, the estimation weight equals 1 for value estimates that come from studies that contribute one value estimate to the estimation dataset. For studies contributing two value estimates, each of them received a weight of $1/2$, and so forth. Finally, we rescaled the weights so that they sum up to the number of observations in the estimation dataset. Because we estimated separate models for four ecosystem services, we determined separate weights for each service.

3.2.1 Meta-Regression Analysis

The meta-regression analyses conducted assume that the relationship in Equation 2 between the dependent variables and the determinants is linear (or a non-monotonous transformation of the variables is linear), as shown in Equation 2:

Equation 2:

$$\ln y_i = \alpha + \beta X_{ij} + \varepsilon_i$$

where $\ln y_i$ is the natural logarithm of the value estimate i of ecosystem services (dollars per hectare) identified from the literature, α is a constant, X_{ij} is a vector of J (indexed by $j=1,2,\dots,J$) independent variables to characterize the study and study area, β is a vector of J coefficients estimated on independent variables X , and ε_i is a random error term. We used a logarithmic transformation of the dependent variable. It is commonly adopted to help ensure that the distribution of ε_i is consistent with the underlying assumption of normality.

Table 4.1 in the next section lists the variables examined as potential predictors of the value of each ecosystem service. The list includes a range of variables to describe socioeconomic characteristics of the study sites, such as gross national income (GNI) per capita, population density, distance to urban center, road density, and the protection status, and the ecosystem characteristics, such as the biome, temperature, precipitation, forest area, wetland cover, and species richness of the study area.

We evaluated the inclusion of different predictor variables using statistical and conceptual criteria. For example, it is conceptually intuitive that income-level and the economic value of ecosystem services are linked, keeping everything else constant. Therefore, we generally included GNI per capita in the model regardless of statistical performance.

3.2.2 Machine Learning

We used three general strategies for machine learning, including random forest (RF) ensemble learning, automated machine learning (AML) (LeDell et al. 2019), and Bayesian Additive Regression Trees (BART).

Random forest

RF is an ensemble learning method, built on randomized trees (Breiman 2001), to incorporate two sources of randomness in the tree: random bootstrap samples and random variable selection (Figure 3.3).

First, the estimation dataset is divided into k samples with replacement (bootstrap samples). Then, a classification and regression tree (CART) is built for each sample (Breiman et al. 1984). Tree-based methods partition the feature space into a set of rectangles, and then fit a simple model in each one (Hastie et al. 2009). Figure A5.2 in Appendix 5

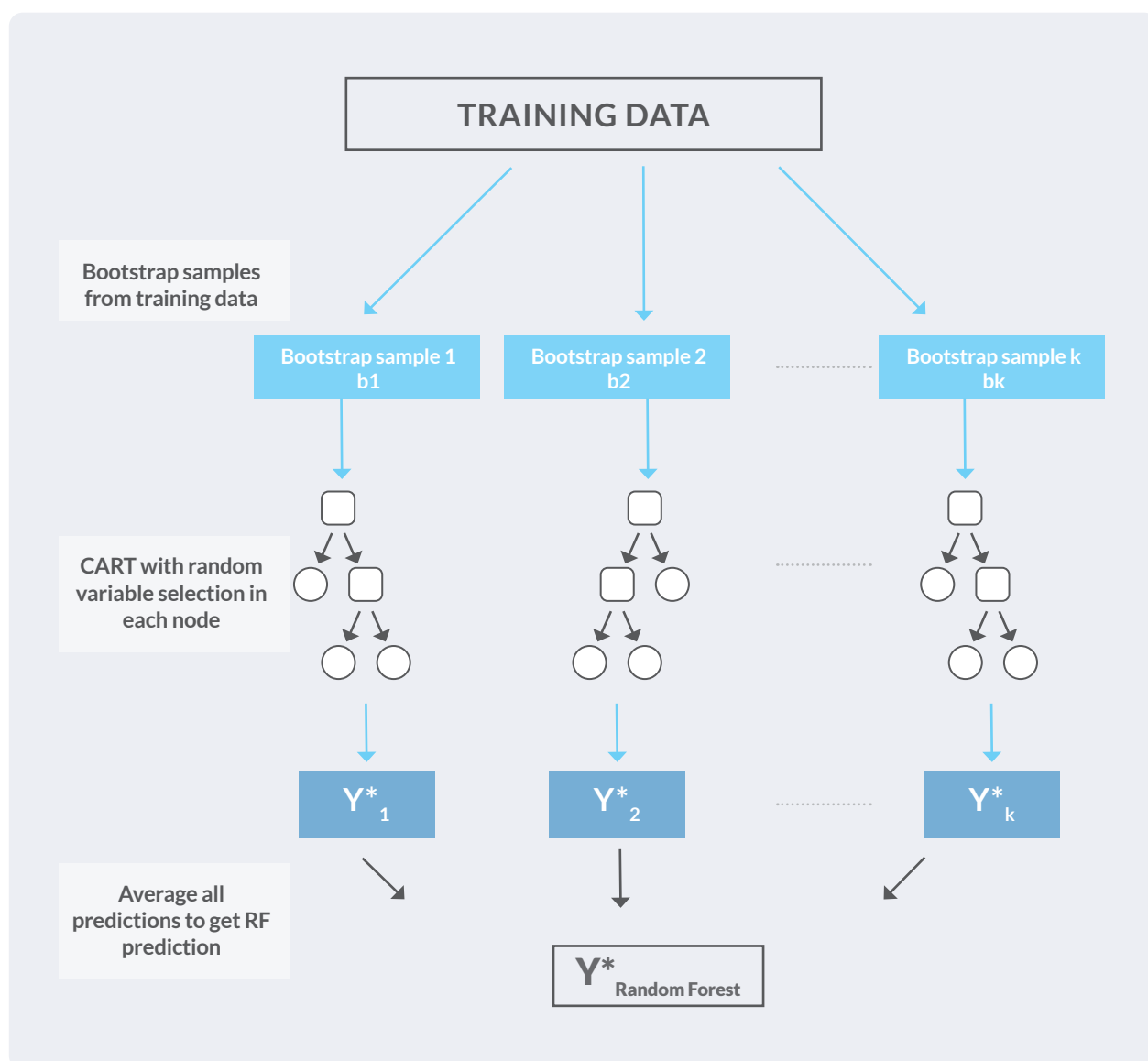
shows an example of a construction of a tree model with one variable. The CART decision tree is a type of tree model that uses binary recursive partitioning with axis-parallel splits. This allows for the inclusion of continuous and categorical attributes as targets and predictors.

The second source of randomness consists of randomly selected predictor variables to use in

each node partition. That is, each node partition is conducted only with a randomly selected subset of predictors, instead of all available possible predictors.

The RF model is run first with all the relevant variables in the dataset and later keeps only the most important variables. Variable selection is an important step in the construction of statistical learning models.

FIGURE 3.3: RANDOM FOREST ALGORITHM DESCRIPTION



Even if modern algorithms are designed to perform well in high dimensions when there are more predictors than observations, it is possible to improve performance by discarding unimportant variables in a specific problem. There are many techniques to compute variable importance in statistical learning models. In this study, we use the Variable Selection Using Random Forests procedure to select important variables in RF models (Genuer and Poggi 2020), implemented in the R package following Genuer et al. (2015) (see Appendix 5).

The main advantage of decision trees is that they are relatively easy to interpret and quick to implement. The main disadvantage is that the model may vary substantially from one sample to another. The inclusion of bootstrap aggregated trees and random selection of the predictor variables performed by random forests provides a more robust method that often better predicts data outside the training data (out-of-sample).

The result of the process described above is a collection of randomized regression trees, where each one of them has information on which variables of the subset of variables in the partition are important predictors of the variation in the predicted variable. The predicted variable, in this case, are value estimates for non-wood forest ecosystem services developed from the literature. A random forest predictor is then constructed by averaging randomized trees. See Appendix 5 for more information.

Automated machine learning

The second machine learning approach used is AML. AML includes several families of machine learning algorithms, including RF. AML is the process of setting an automatic workflow to construct a machine learning model. We used the open-source platform h2o (H2O.ai 2017). It

contains an AML algorithm to perform automatic model training and comparison across a fixed set of models to obtain the most appropriate model for each problem.

The main advantage of AML is that it simplifies model selection by reducing the number of parameters defined by the user. The drawback is the “black-box” type procedures that AML uses to choose combinations of models that are difficult to interpret. However, AML helps set a benchmark against which to compare other methods, given that AML selects the model with the best performance out of sample. Here we used AML primarily as a benchmark to analyze the performance of meta-regression and RF models.

Bayesian Additive Regression Trees

The third machine learning approach we used is BART, an approach introduced by Chipman et. al. (2007, 2010) that combines regression tree models with a Bayesian inferential framework and provides a flexible approach to fitting a variety of regression models.

A Bayesian tree model is like CART (see above) but uses prior distributions for two sets of parameters: leaves response values and tree structure. The BART model consists of a sum of Bayesian trees built in a boosting-like model. A Markov Chain Monte Carlo (MCMC) algorithm is used to obtain posterior samples at each prediction point.

Several approaches exist for variable selection in BART models (Kapelner and Bleich 2016). In this report we used the dbarts-package in R (Dorie 2023) to select a small set of important variables in the BART model. The basic measure of variable importance in BART is variable inclusion proportion, in other words, the number of times a variable is used by the algorithm to make the predictions. However, this measure on its own

can be misleading, as the choice of variables is random within the algorithm. Variable selection constructs a distribution for the variable inclusion proportion in a model without important variables and uses it as a “distribution under the null” to test the inclusion of each variable (see Appendix 5 for a detailed description).

As with other machine learning methods, BART avoids strong parametric assumptions. However, BART uses a probabilistic model (priors, errors) for uncertainty quantification of predicted values. Including measures of uncertainty constitutes an important advantage over other machine learning models, so BART can be used to construct prediction intervals for individual predictions or transformations of many predictions (for example, total forest value of a specific country).

3.2.3 Model Comparison and Statistical Criteria for Model Selection

For meta-regression analysis, we initially estimated a wide range of alternative model specifications (Appendix 7). By ecosystem service analyzed, we selected models that yielded the lowest out-of-sample prediction errors and were conceptually meaningful regarding the variables that drive the value of different ecosystem services, such as GNI per capita, population density, or distinct biophysical and climate data. We conducted further model selection by evaluating the out-of-sample predictions of each estimation model on the basis of the accuracy of out-of-sample predictions produced by cross-validation (Hastie et al. 2009; James et al. 2016), along with analyzing predictions using the global grid.

Cross-validation using out-of-sample predictions

Cross-validation using out-of-sample predictions involves splitting the set of observations into

two parts. First, we removed all value estimates belonging to a single study from the estimation dataset and fit the model with the remaining observations. Second, we used the model to predict the observations removed, and computed the mean square error for them.

The mean square error for each study $k = 1 \dots K$ is defined as

$$MSE_k = \frac{1}{Z} \sum_{z=1}^Z (y_{kz} - \hat{y}_{kz})^2$$

where $z = 1 \dots Z$ are the value estimates belonging to study k . This procedure is repeated for each of the k studies in the sample. The cross-validated estimate is the average of these K error estimates:

$$CV_{(K)} = \frac{1}{K} \sum_{k=1}^K MSE_k$$

and the root mean square error is computed as

$$RMSE = \sqrt{CV_{(K)}}.$$

This approach adapts the traditional leave-one-observation-out cross-validation, where K equals the number of observations in the estimation dataset. Here, we leave all the observations belonging to the same study out at the same time. That is, if there are five values belonging to the same study, we remove five observations, while if there is only one value of a specific study, we remove only one observation. The advantage of this approach is that it incorporates the sensitivity of the results to a specific study. After looping over every study, we calculated the average cross-validated prediction error (Appendix 5).

Assessing distribution of global predictions

Besides examining out-of-sample predictions in the estimation dataset, we found it important to assess models by assessing their global predictions. Although a model can perform well in out-of-sample cross-validation, predictions for the world grid may be unstable due to differences between the estimation and global datasets used

for predictions. Accordingly, we examined the distribution of the predictions in the global grid, especially regarding potential tendencies for the model to produce outliers.

Assessing different model selection criteria

A priori, there is no clear expectation for which family of methods, meta-regression or machine learning, would best fit the estimation dataset when evaluated using out-of-sample prediction power. The main advantage of meta-regression is that it uses pre-determined structural relationships between the dependent and the independent variables that give direct interpretability to the results.

Machine learning methods regularly statistically outperform meta-regression, as they are more flexible in modeling the relationship between the predicted and predictor variables. However, this may not always be the case, as more restrictive (structured) models may perform better out-of-sample because of the potential for overfitting by more flexible methods (James et al. 2016). Essentially, the statistical learning procedure of machine learning may go too far in finding patterns in the estimation dataset, including picking up patterns caused by random chances rather than by true properties of the unknown function f .

In addition, machine learning methods tend to increase in predictive power, especially when working with large samples. However, our analysis uses datasets that could be considered small or medium-sized. In addition, machine learning methods, by their structure, usually bound predictions to the range of values found in the estimation dataset (training dataset). On the other hand, regression analysis does not bound the prediction outcome unless constraints are imposed post hoc.

In the context of this assessment, there may be forests around the globe that are highly dissimilar with the value estimates in the estimation dataset. As a result, especially when using machine learning, the value predictions in some of the global grid cells could lack the necessary support (overlap) in the estimation dataset. On the other hand, meta-regression analysis estimates a structural relationship between the dependent and independent variables, so any extrapolation out-of-sample also takes place under the assumption that this relationship remains unchanged. While the meta-regression analysis facilitates predictions outside of the support in the estimation dataset, it may produce estimates that are unrealistically high or low for particular locations.

In conclusion, each method has pros and cons, including trade-offs between interpretability and flexibility and robustness of out-of-sample predictions. Section 5.1.3 discusses the different criteria for the empirical application. The two different approaches can be complementary in helping to understand the relationship between the value of non-wood forest ecosystem services and its determinants and to predict values across the globe. The final selection of the model for global predictions was determined empirically, based on multiple criteria, including statistical criteria for out-of-sample predictions and analyses of the distribution of the global predictions.

3.3 GLOBAL PREDICTIONS

To develop global predictions of the value of forest non-wood ecosystem services (per ha), we first constructed a 0.1° by 0.1° (about 10km by 10km) world grid of terrestrial areas (about 1.9 million terrestrial grid cells) (Figure 3.4). Then, we used

data on land cover from ESA-CCI (ESA 2017b) between 1992 and 2020 to determine year by year which grid cells comprised forests. The number of grid cells including forest area varies between years, ranging between 1,209,690 (2007) and 1,214,776 (1992). These grid cells form the global prediction dataset. In other words, the dataset varies between years depending on which grid cells have forests each year.

Global predictions are developed in two stages. First, we note that not all forests necessarily support all ecosystem services. There are many possible reasons for this, including, for example, the inaccessibility of some forests for recreation, hunting, and fishing or non-wood forest product collection, or the fact that only the forests that are protected fully support habitat and species protection. One important reason to define service areas is that the original valuation studies are conducted for sites that are known to supply specific services. As a result, using these values to estimate the ecosystem service value in sites that do not supply the service would artificially increase the estimated value by country. To address

this issue, we determined at the outset what types of forests are relevant for the provision of each different ecosystem services considered in this assessment (Table 3.1).

For ecosystem services that require physical presence in the forest, including recreation, hunting, and fishing, and collection of non-wood forest products, we designated service areas as forests that are accessible to potential users (panel a in Figure 3.4). Following FAO, we specified accessible forests as forests “within reach of exploitation by existing waterways, roads, railways or other means of transportation”, defined here as forests within 10km or less of roads or navigable waterways (FAO 2001; Sohngen et al. 2009). We used global data on road networks and rivers to determine the accessibility of each grid cell (see Appendix 6). Figure 3.4 maps all global forests and accessible forest using the grid cell data. In addition, collection of non-wood forest products also includes protected areas under IUCN protection category V or VI, because they allow for the sustainable extraction of goods.

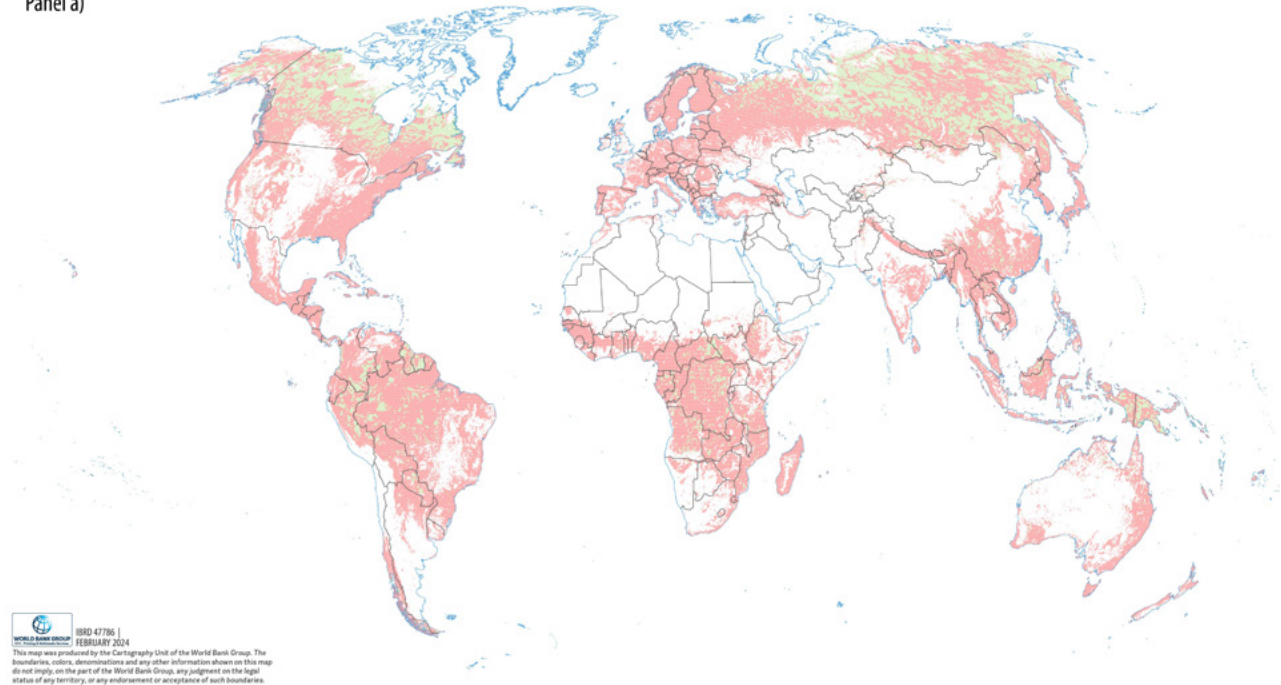
TABLE 3.1: SERVICE AREA FOR DIFFERENT ECOSYSTEM SERVICES

SERVICE	SERVICE AREA	% OF TOTAL GRID CELLS
Recreation	Accessible forests	59%
Habitat/species protection	All protected forests	16.5%
NWFPs	Accessible forests and IUCN category V and VI protected forests*	67%
Water services	Accessible forests	59%

*Category V: protected landscape or seascape; Category VI: protected area with sustainable use of natural resources

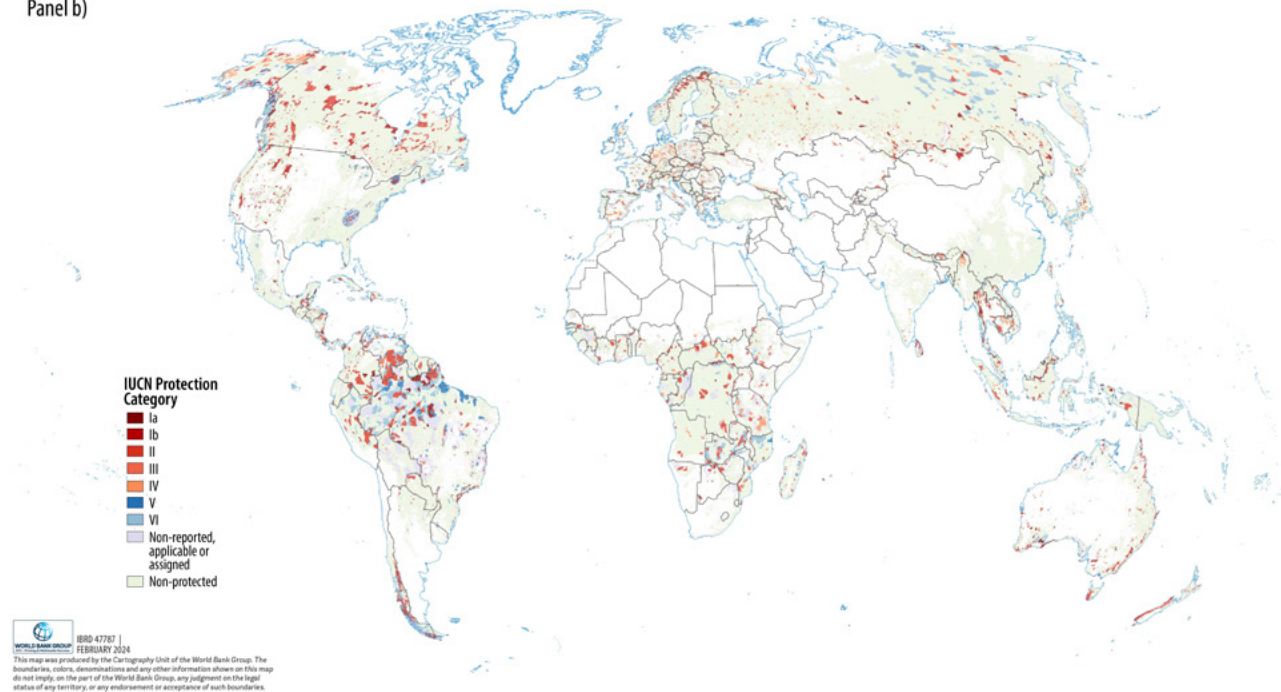
FIGURE 3.4: MAP OF GLOBAL FORESTS, INCLUDING ACCESSIBLE FORESTS (PANEL A) AND PROTECTED FOREST (PANEL B)

Panel a)



Note: Map generated using 1,279,660 grid cells ($0.1^\circ \times 0.1^\circ$), from which 562,498 (44%, red) are accessible (>50% of the cell area is accessible) and have forest area >10%, 362,203 (28.3%, green) are not accessible (<50% of the cell area is accessible and have forest area >10% cell), and 354,959 (27.7%, not colored) have forest area <10%.

Panel b)



Note: Map generated using 1,279,660 grid cells ($0.1^\circ \times 0.1^\circ$), from which 170,422 (13%, red, blue, purple, depending on IUCN protection category) are protected (>50% of the cell area is protected) and have forest area >10%, 754,279 (60%, green) are not protected (<50% of the cell area is protected and have forest area >10% cell), and 354,959 (27.7%, not colored) have forest area <10%.

Fifty-nine percent of the grid cells are accessible and hence designated for the provision of recreation values, and 67 percent provide non-wood forest products (Table 3.1).

Studies valuing habitat and species protection typically examine forests either already protected or considered for protection (panel b in Figure 3.4). Therefore, their value estimates are conditional on protection to perpetuity, so habitat and species protection applies only to protected areas. This approach excludes values from habitat and species protection associated with unprotected forests, which can be substantial. As such, the value estimates from this study for habitat and species protection may be considered underestimates at the country level. A total of 16.5 percent of the grid cells support habitat and species protection (Table 3.1).³

Water services are usually supplied by forests near waterways and beneficiaries. Forests further away from population and waterways can also produce valuable ecosystem services, such as hydrological control that can help to protect against disasters. However, most of the valuation studies represent areas near waterways and populated areas, so for consistency with the estimation dataset, we also restricted the water service area to the area of accessible forest (59 percent of the total forested grid cells).

Finally, in a second stage we used the selected model to produce global predictions of service areas. The result of this step is globally explicit ecosystem services valuation per hectare for the corresponding service areas.

3 In this study, we used publicly available data on the World Database on Protected Areas (WDPA), merging the dataset available in October 2019 and February 2022. Using publicly available data can mean underestimation of protected areas for several countries for which protected area data is not public, including China, India, New Zealand, or Türkiye. Hence, our estimates related to the geographic extent of protected area benefits should be interpreted as a lower bound.

4 Database Construction and Descriptive Analysis

4.1 CONSTRUCTION OF GLOBAL VARIABLES

Table 4.1 lists the variables examined as potential determinants to estimate a global, spatially explicit prediction of non-wood forest products. We constructed 17 variables to characterize socioeconomic, biophysical, ecological, and climate characteristics of each cell in the world grid using ArcGIS and spatial data. Appendix 6 describes the data sources and the GIS processing for each variable. All variables in Siikamäki et al. (2021) were updated for this report whenever new data became available. In addition, data on some new variables was added and the data sources for some variables were changed because better data had become available, as discussed below.

Socioeconomic characteristics

Socioeconomic characteristics of the study area are conceptually plausible determinants of ecosystem service values. For example, available income typically affects demand for market goods and services, so a similar relationship may emerge for ecosystem services. Moreover, income may be associated with preferences for ecosystem services. We use country-level data on PPP-adjusted GNI per capita, obtained for the World Development Indicators database, to measure income at each cell (World Bank 2020). When GNI data from a country was not available, we used data from the United Nations National Accounts Main Aggregates Database (United Nations 2020).

We used ArcGIS and spatial data to compile data on population density, density of road network, and the percentage of urban area in each grid cell. In addition, we computed the distance to the nearest urban center from the centroid of each cell. Population density and urban area are potentially important determinants of the value of ecosystem services. Although population density and urban area may be associated with human pressure that could depress local values for ecosystem services, areas of greater population density and urbanization also feature more beneficiaries that may increase the value of ecosystem services on a per unit area basis. This is especially true for ecosystem services that are not purely exclusive (rival) in consumption, such as recreation or hydrological services. In addition, we included a variable measuring the year of the value estimate so that possible time trends in the value estimates can be examined.

Road density is potentially relevant, especially for direct use values such as recreation and non-wood forest products. Increasing road density could also relate to increasing landscape fragmentation, hence, environmental degradation, but it also increases the accessibility of forests to potential users. In the end, the relationship between these variables and ecosystem service values is an empirical matter. The data source for estimating roads length in this report is the Global Roads Inventory Project (GRIP) by Meijer et al. (2018), while Siikamäki et al. (2021) used CIESIN-ITOS (2013). The GRIP dataset is a more recent data source with wide geographical coverage.

TABLE 4.1: VARIABLES EXAMINED AS POTENTIAL DETERMINANTS OF THE VALUE OF ECOSYSTEM SERVICES

	VARIABLE	SCALE	TIME PERIOD	SOURCE
Socioeconomic	Gross national income	Country	1960–2020	World Bank (2020); United Nations, (2020)
	Population density	Cells, 75, 200, and 400km round buffers	2000, 2005, 2010, 2015, 2020	Center for International Earth Science Information Network (CIESIN), Columbia University (2018)
	Urban area (fraction)	Cells, 75, 200, and 400km round buffers	1992–2020	ESA (2017a)
	Distance to nearest urban area	Study site and cell centroid	1992–2020	SA (2017a)
	Road density	Cells, 75, 200, and 400km round buffers	1 layer with data from sources published in 2010 or later	Meijer et al. (2018)
	Protected Areas and their IUCN category	Study sites and cells	2 merged layers published in 2020 and 2022	UNEP-WCMC and IUCN (2016)
	Forest area per capita per country	Country	1990–2020	World Bank (2020)
	Time trend			
Ecological and biophysical	Forest biome	Study sites and cells	1 layer published in 2010	Hansen, Stehman, and Potapov (2010)
	Forest area (fraction)	Cells, 75, 200, and 400km round buffers	1992–2020	ESA (2017a)
		Country	1990–2020	World Bank (2020)
	Species count (total, mammals, and bird)	Cell	1 layer last published 2022	BirdLife International and Handbook of the Birds of the World (2019) and IUCN (2019)
	Distance to the Equator (latitude)	Cell centroid		
Climate	Temperature and rainfall	Cells	1900–2017	Matsuura and Willmott (2018b, 2018a)
Forest degradation	Normalized Difference Vegetation Index (NDVI) trend 1982–2018 (Theil-Sen median)	Cells	1982–2020	Own elaboration based on Vermote and NOAA CDR Program (2019)
	Forest cover change 1992–2020	Cells	1992–2020	ESA (2017a)
	Threatened species (fraction of all species, mammals, and birds)	Cells	1 layer last published 2022	BirdLife International and Handbook of the Birds of the World (2019) and IUCN (2019)
	N° of threatened species (all species, mammals, birds)	Cells	1 layer last published 2022	BirdLife International and Handbook of the Birds of the World (2019) and IUCN (2019)
	STAR (Species Threat Abatement and Recovery) metric per ha	Cells	1 layer published in 2021	IUCN (Mair et al. 2021)

Socioeconomic determinants might relate to demand for non-wood forest ecosystem services also at a larger scale than the grid cell. For example, many of the beneficiaries may live outside the grid cell of the study area. To examine these types of relationships, we constructed multiple measures of local population density, road density, and urban area fraction. We measured each of these variables within 25km, 50km, 75km, 100km, 200km, and 400km circular buffers from the centroid of each grid cell. After exploratory analyses of the correlations between these variables, we decided to work with four scales: grid cell, 75km, 200km, and 400km.

Ecological and other biophysical characteristics

We processed several variables to characterize the biophysical and ecological characteristics of forests. We used ArcGIS and spatial data to compile data on the forest biome and land use, including the fraction of grid cell covered by forests. These data help examine whether the magnitude of ecosystem service values is related to the scarcity of these ecosystems in the study area. In addition, we computed the total forest area per person per country. We included this variable as an indicator of scarcity of forests that may drive the demand for forest ecosystem services.

Biodiversity may also drive the value of ecosystem services. We processed data from IUCN and Birdlife International to measure species richness (total number of species extant) at each cell in the world grid (BirdLife International and Handbook of the Birds of the World 2019; IUCN 2019). The species data from IUCN and BirdLife International comprises overlapping polygons that denote species ranges for mammals, amphibians, and reptiles. We used ArcGIS to count the number of extant species in each study location. We also measured the distance of the study locations from the equator so that any

latitudinal gradient (typical for biodiversity) in the value of ecosystem services can be examined.

The protection status of a forest area could be a relevant determinant of the value of non-wood forest ecosystem services. The degree of protection might relate to the level of supply of ecosystem services, as well as the types of uses that the beneficiaries may engage in. We compiled data on protected areas using the World Database on Protected Areas (IUCN 2016). We computed two measures regarding protected area: (1) the percentage of a cell that is protected, and (2) the area of protected areas intersected with the cell. In addition, we recorded the IUCN protection category of the protection area intersected with a cell. When more than one protected area intersected a cell, we recorded the strictest protection category.

Climate

We constructed data on monthly temperature and rainfall in each grid cell between 1970 and 2017 based on Matsuura and Willmott (2018b, 2018a). Because our objective is to characterize climatic conditions, not short-term weather, we used this data to estimate the average annual temperature and rainfall for the period 1970 to 2017.

Most of the data we used to characterize ecological and biophysical features and climate are modeled data. As a result, data is generally smooth across cells, and does not change drastically between adjacent cells. For this reason, we did not construct any of these variables for the buffers mentioned above; rather, we used values specific for each grid cell.

Forest degradation

Forest degradation follows the definition of the Food and Agriculture Organization of the United Nations (FAO), considered as the reduction of the capacity of a forest to provide goods and services (FAO 2012).

Forest degradation can be approached through changes on productivity, biomass, or biodiversity, as well as the drivers of degradation, including human pressures (IPBES 2018; DeFries et al. 2020). For the prediction of values globally, we consider variables related to changes in productivity, biomass, or biodiversity. For measures of the drivers of degradation, including human pressure, variables such as human density and road and urban area fraction are already included in the database in the form of socioeconomic variables. Their role and interpretation mixes with other factors that can involve countervailing effects. For example, population density can be a driver of both forest degradation (pressure) and demand (number of beneficiaries) for ecosystem services.

Normalized Difference Vegetation Index (NDVI) summarizes the level of “vegetation greenness” (Vermote and NOAA CDR Program 2019). NDVI can be interpreted as an indicator of vegetation health, because degradation of ecosystem vegetation, or a decrease in green, would be reflected in a decrease in NDVI (Meneses-Tovar 2011). We used NDVI to proxy forest degradation by measuring the trend of the variable between 1982 and 2020 (discussed below), as a proxy of the biomass and structure change. We used the Theil-Sen median trend estimator, commonly applied to measuring NDVI trends because of its robustness relative to outliers and accuracy for skewed and heteroscedastic data (Liu et al. 2015), to estimate the trend per cell (see Appendix 6).

Loss of forest cover can be a significant form of degradation. To measure it, we computed forest cover change per cell between 1992 and 2020 using the ESA (2017a) land cover dataset. We assessed the total change during a period of 29 years to assess degradation relative to a longer-term benchmark. As with the NDVI trend, this measure requires

interpretation with caution, because the baseline year can be a point in time where the ecosystem is already degraded. In other words, an area where forest cover does not change remains in whatever state of the baseline years, be it pristine or degraded.

In addition, we used the number of threatened species and the fraction of all species that are threatened as proxies of impoverished species composition. We measured them by grid cell across all comprehensively assessed taxonomic groups, including mammals, birds, amphibians, and reptiles. We also examined mammals and birds separately for their potentially distinct impact on some ecosystem services, such as recreation and non-wood forest products. We computed the total number of species per taxonomic group at the centroid of each grid cell using data from BirdLife International and IUCN (BirdLife International and Handbook of the Birds of the World 2019; IUCN 2019).

Finally, the Species Threat Abatement and Recovery (STAR) metric assesses the potential of threat abatement actions at specific locations to contribute to global sustainability targets (Mair et al. 2021). STAR draws on data on the distribution, threats, and extinction risk of threatened species derived from the IUCN Red List of Threatened Species (IUCN 2019) to produce estimates of the potential for species extinction risk reduction broken out over a global 5km × 5km grid. For each pixel within this grid, STAR estimates the contribution of the threats affecting species present in the grid to the total value for the pixel. The STAR value of a pixel is calculated using the number of threatened species that occur in a pixel, their level of threat (from 100 for a near threatened species, up to 400 for a critically endangered species), and the fraction of all threatened species’ area of habitat represented by the pixel. The values on each pixel are scalable across species, threats, and geographies.

We calculated the average STAR value for each of the cells in our global grid, and then computed STAR per hectare, for comparison across sites. This is a new variable added to the dataset, as it was not available when Siikamäki et al. (2021) was conducted.

Because the aim of this study is to produce annual estimates of the value of forest ecosystem services between 1995 and 2020, we sought to include data on the potential determinants of the value of ecosystem services that are observed annually during this period. Variables that only have one snapshot (road density, species richness, protected areas, forest biome, and wetlands area) are treated as time invariant. These variables change slowly, so the assumption is not critically limiting.

Appendix 6 describes the data sources processed and the processing details. In total, we processed 28 GIS datasets, of which 14 were used in the modeling. Some of the variables were discarded because they were redundant. For example, we processed forest cover using the 2009 GlobeCover land cover map (ESA and UCLouvain 2010) as in Siikamäki et al. (2015) and for 1992 and 2020 using ESA-CCI land cover map (ESA 2017b) as in Siikamäki et al. (2021). In the end, we used only ESA-CCI for estimations, because it provides annual time series 1992 to 2020. Other data was discarded because of the lack of complete global coverage, or the lack of availability of time series. For example, this is the case of wetland area (WWF) and net primary productivity (Running et al., 1999). In addition, some variables were not included because they were aggregate indexes summarizing many environmental pressures, including human footprint (Venter et al. 2016, 2018), human modification map (Kennedy et al. 2019), or biodiversity intactness (Newbold et al. 2016). We decided to incorporate in the models the direct pressure drivers, including variables such as road length and the extent of urban area, instead of aggregate indexes, which are difficult

to interpret. The datasets set aside were discarded for various reasons discussed in Siikamäki et al. (2021).

4.2 LINKING THE WORLD GRID TO THE STUDY SITE LOCATIONS

Each value estimate was linked to a grid cell in the world grid using its latitude and longitude so that other data from the grid cell could be linked to each study (Figure 2.6). Some studies come from years for which data on specific predictor variables is not available. This is the case for urban area fraction and distance to nearest urban area for years prior to 1992, and population density, as these were only available in five-year intervals starting from 2000. We interpolated these variables by computing the annual average change between periods. We used a similar approach for data on forest cover from FAO, gathered by the World Bank (2020). See Appendix 6 for details.

4.3 DESCRIPTIVE ANALYSIS

4.3.1 Descriptive Statistics Estimation Dataset

Table 4.2 lists the summary statistics for the variables in the estimation dataset, including value estimates derived from the original primary studies and the set of potential explanatory variables developed as predictors of the primary value estimates. The value estimates in the dataset range between US\$0.007 and US\$29,695 (US dollars PPP 2017 per hectare per year) and are, on average, US\$1,125.8 per hectare per year. The value estimates show a wide variation across ecosystem services. On average, the highest values are for recreation, hunting, and fishing; and habitat and species protection (about US\$1,500/ha/year), followed by water services (about US\$500/ha/year). Non-wood forest products have the lowest average value (about US\$110/ha/year). However, there is a very wide range

of estimates within each category, and categories with relatively fewer estimates are more likely to be affected by extreme values. Only 13 percent of all available estimates are for water services, for example, while 40 percent are for recreation, hunting, and fishing. In all cases, the median value is significantly lower than the mean value, indicating the presence of outliers in the right-hand tail of the distribution.

Socioeconomic characteristics

GNI per capita ranges widely in the estimation dataset, with the minimum at \$712.83 (Ethiopia) and the maximum at \$67,800 (Switzerland). About 60 percent of the value estimates come from high-income countries, 31 percent come from middle-

income countries, and the rest (8 percent) are from low-income countries. Population density at the study sites ranges from zero to 14,060 per km², which indicates the inclusion of highly urbanized areas. The maximum values for population density and urban area decreases with the size of the buffer around the valuation site. The summary statistics of distance to urban centers and road density within the study area show wide variation in the estimation dataset.

On average, 43 percent of the grid cells of study sites are protected, and about 82 percent of the study sites come from a grid cell that includes at least some protected areas.

TABLE 4.2: DESCRIPTIVE STATISTICS OF THE ESTIMATION DATASET

VARIABLE			N	MEAN	STD. DEV.	DISTRIBUTION		
						MIN	MEDIAN	MAX
Study	Value (USD PPP 2017/ hectare)	Total	346	1,125.84	3,450.15	0.007	95.55	29,695.61
		Recreation, hunting, and fishing	139	1,531.33	4,240.55	0.22	148.86	28,436.15
		Habitat and species protection	97	1,518.13	3,880.08	0.01	209.76	29,695.61
		Non-wood forest products	65	110.70	272.36	0.01	11.35	1,664.96
		Water services	45	494.05	1,091.31	0.01	63.53	6,048.20
	Ecosystem service	Recreation, hunting, and fishing (0/1)	346	0.40	0.49	0.0	0.00	1
		Habitat and species protection (0/1)	346	0.28	0.45	0.0	0.00	1
		Non-wood forest products (0/1)	346	0.19	0.39	0.0	0.00	1
		Water services (0/1)	346	0.13	0.34	0.0	0.00	1
Socioeconomic	GNI per capita (USD PPP 2017)Cells		346	28,788	17,977	712.83	31,917	67,800
	Continent	Africa (0/1)	346	0.09	0.29	0		1
		Americas (0/1)	346	0.27	0.45	0		1
		Asia (0/1)	346	0.17	0.38	0		1
		Europe (0/1)	346	0.42	0.50	0		1
		Oceania (0/1)	346	0.04	0.20	0		1
	Income level	High (0/1)	346	0.61	0.49	0		1
		Middle (0/1)	346	0.31	0.46	0		1
		Low (0/1)	346	0.08	0.27	0		1

VARIABLE			N	MEAN	STD. DEV.	DISTRIBUTION		
					MIN	MEDIAN	MAX	
Socioeconomic	Population density (people/km2)	Cell	346	199.773	876.370	0	19.540	14060.140
		75km buffer around the centroid of the grid cell	346	195.97	580.76	0.00	34.64	8,212.94
		200km buffer around the centroid of the grid cell	346	132.10	211.42	0.02	59.55	2,048.41
		400km buffer around the centroid of the grid cell	346	101.74	97.25	0.44	78.73	507.75
	Road density (km roads/ha)	Cell	346	0.0052	0.0110	0	0.0019	0.0898
		75km buffer around the centroid of the grid cell	346	0.01	0.01	0	0	0.09
		200km buffer around the centroid of the grid cell	346	0.00	0.00	0	0	0.03
		400km buffer around the centroid of the grid cell	346	0.00	0.00	0	0	0.02
	Urban area (fraction of grid cell/ buffer)	Grid cell	346	0.02	0.05	0	0	0.45
		75km buffer around the centroid of the grid cell	346	0.02	0.05	0	0	0.37
		200km buffer around the centroid of the grid cell	346	0.01	0.02	0	0	0.15
		400km buffer around the centroid of the grid cell	346	0.01	0.01	0	0	0.07
	Distance to nearest urban area (km)							
	IUCN protection category (0/1)	I	346	0.17	0.38	0		1
		II	346	0.23	0.42	0		1
		III	346	0.03	0.17	0		1
		IV	346	0.16	0.37	0		1
		V	346	0.06	0.24	0		1
		VI	346	0.03	0.18	0		1
		Not Reported/Not Applicable/Not Assigned	346	0.14	0.34	0		1
		Non-protected	346	0.18	0.39	0		1
	PA fraction of the grid cell		346	0.43	0.41	0		1
	PA area (ha)		346	0.31	3,374	0	2,154	9,963
Biophysical and ecological	Species richness		346	0.08	222.65	28	258.00	1,059.00
	N° mammal species		346	67.12	43.37	1	53.00	197.00
	N° bird species		346	228.47	125.14	20.00	181.00	606.00
	Biome	Boreal (0/1)	346	0.14	0.35	0		1
		Temperate (0/1)	346	0.51	0.50	0		1
		Tropical (0/1)	346	0.34	0.48	0		1

VARIABLE			N	MEAN	STD. DEV.	DISTRIBUTION		
					MIN	MEDIAN	MAX	
Biophysical and ecological	Forest area (fraction of grid cell/ buffer)	Cell	346	0.56	0.35	0	0.62	1
		75km buffer around the centroid of the grid cell	346	0.48	0.31	0	0.47	1
		200km buffer around the centroid of the grid cell	346	0.42	0.27	0	0.38	1
		400km buffer around the centroid of the grid cell	346	0.30	0.21	0	0.27	1
	Forest area country (fraction)		346	0.37	0.18	0.04	0.34	0.76
	Latitude (absolute value)		346	34.16	19.43	0.48	38.59	67.40
	Study site area (km2)*		346	110,937.00	609,906.90	0.01	1,066.00	5,500,002.00
Climate	Temperature average 1970–2018 (°C)		346	13.78	8.39	-4.74	12.44	27.38
	Rainfall average 1970–2018 (annual mm)		346	1,332.25	885.06	166.94	1,094.06	4,763.68
Degradation	NDVI trend 1982–2020		346	0.0019148	0.0015917	-0.0022668	0.0022693	0.0050939
	Forest area change cell 1992–2020 (p.p.)		346	0.0043	0.09	-0.68	0.00	0.41
	N° species threatened		346	14.00	14.34	1.00	9.00	63
	N° mammals threatened		346	4.91	6.68	0	3.00	31
	N° birds threatened		346	6.89	5.79	0	5.00	29
	Species threatened (fraction of all species)		346	0.04	0.03	0.01	0.03	0.27
	Mammals threatened (fraction of all mammals)		346	0.07	0.10	0	0.04	1
	Birds threatened (fraction of all birds)		346	0.03	0.03	0	0.03	0.27
	STAR per ha		346	0.0014121	0.0043634	8.71E-08	2.80E-05	0.0322795

The total area of the protected areas intersect with the grid cells of the value sites is on average 3,376 ha, reaching a maximum of 9,963 ha.

Ecological and biophysical characteristics

About 14 percent of the value estimates come from boreal forests, 51 percent temperate forests, and 34 percent tropical forests. The study area grid cells are, on average, about 56 percent forested. Species richness on the study sites ranges from 28 to 1,059 and is, on average, about 353.

Forest degradation

Forest degradation measures show considerable variation. The NDVI trend from 1982 to 2020 ranges between -0.0022 to 0.005, indicating that the study sites in the estimation dataset include areas where biomass and productivity decreased and areas where it increased. Forest area change per grid cell from 1992 to 2020 has a wide range, including a maximum loss of 68 percentage points and a maximum gain of 41 percentage points. On average, the fraction of the grid cell covered by forest increased by 0.43 percentage points. The median forest area change is zero, indicating that roughly equally many grid cells experienced forest cover increase and loss.

The number of threatened species varies widely between value estimates, ranging between 1 and 63. The fraction of threatened species over total species average is 0.04 (4 percent), with a maximum 27 percent of species threatened in a value site. The patterns of data on threatened mammals and birds are similar to those on all taxonomic groups. The average STAR per hectare is 0.0014, ranging between 8.71E-8 and 0.032, with a wide range expected based on the similarly wide ranges in data on threatened species.

4.3.2 Comparing the Estimation Dataset and the World Grid

When developing predictions for the world's forests, an important issue is how well the studies in the valuation database represent forests in the rest of the world. We assessed this by contrasting predictor variables between the grid cells in the valuation database (estimation dataset) and the world grid used for predictions (world dataset comprising all global grid cells that include forests).

Table A7.4 in Appendix 7 shows the descriptive statistics of the determinants used for global predictions for 2020. Contrasting these data with

the database of value estimates, forested grid cells have a population density of 52.73 persons per km² (using a 75km buffer), on average globally, whereas the population density for the grid cells of value estimates is much higher, at about 196 people per km². By continent, grid cells distribution is as follows: Africa, 13 percent (9 percent for the value estimates); Asia, 13 percent (17 percent); Europe, 33 percent (42 percent); Americas, 36 percent (27 percent); and Oceania, 2 percent (4 percent).

Data on GNI in the estimation dataset overlaps the world data, although the grid cells with low GNI are less prevalent in the estimation dataset than in the world dataset, except for non-wood forest products, for which low-income countries are well represented in the estimation data. Population density (when using a 75km buffer) has a generally high overlap between the estimation and world datasets for every ecosystem service, but coverage of very high population cells is limited in the estimation dataset. A similar case occurs with data on distance to the closest urban area. Finally, for temperature, we find that the estimation dataset has limited overlap with the world dataset in areas of very low temperatures. See Figure A7.5 in Appendix 7 for more details.

5 Estimation Results and Global Predictions

This section explains the results from the empirical analyses. We begin with the meta-regression analysis and continue with the machine learning models. Thereafter, we discuss the selection of the predictive model for generating global predictions. Finally, we show the results of the global prediction of the value of non-wood forest ecosystem services, per hectare per year, for the 0.1° by 0.1° world grid, as well as at country level.

5.1 ESTIMATION RESULTS

5.1.1 Meta-Regression Analysis

We estimated several meta-regression models separately for each service considered. Model selection, the process of choosing empirical specification for predicting the dependent variable, was then conducted using several criteria as discussed above. We estimated and compared a broad range of alternative model specifications by including and excluding potentially relevant socioeconomic, biophysical, ecological, climate, and forest degradation variables. For each model, we recorded the correlation between the observed values of the dependent variable and the predicted values produced by the regression model (R^2), information criteria (Akaike Information Criteria—AIC and Bayesian Information Criteria—BIC), and out-of-sample prediction power (root mean square error—RMSE).

Appendix 7 shows the range of the models estimated by ecosystem service and used in model selection.⁴ We note that the models that yield empirically the lowest out-of-sample prediction errors are also conceptually meaningful in that they include information on variables that drive the value of different ecosystem services, such as GNI, population density, or distinct biophysical data. Qualitatively, the estimated coefficients are also as expected and mostly statistically significant, as discussed below. We have also estimated many robustness checks using alternative specifications for each service, and the estimation results are robust considering those comparisons.

In addition, for regression analysis, we conducted preliminary analyses to guide model selection and evaluate the estimation dataset. For example, we examined (using Cook distance) whether there were observations in the estimation dataset so influential that their inclusion or exclusion would considerably alter the estimation results. To ensure robust estimation results, we removed observations that disproportionately affected the estimation results. This is not the case for machine learning models, where influential observations are directly considered within the model.

⁴ We also tested two potential functional forms: log-log and log-linear. In this report we show only the results for the log-log functional form, because they behave better and produced global predictions within reasonable boundaries.

TABLE 5.1: META-REGRESSION ESTIMATION RESULTS BY ECOSYSTEM SERVICE

VARIABLE	RECREATION, HUNTING, AND FISHING	HABITAT AND SPECIES PROTECTION	NWFP	WATER SERVICES
GNI per capita (log, USD PPP 2017)	0.67** (0.25)	0.79** (0.33)	-1.11*** (0.17)	2.02*** (0.63)
Population density grid cell (log, People/km2)			0.57*** (0.08)	
Population density 75km buffer (log, People/km2)	0.72*** (0.10)	0.85*** (0.20)		
Species richness (log)			1.45* (0.75)	
Species threatened (fraction of all species)	-12.48*** (3.82)	-20.83*** (5.30)		
Temperature average 1970–2018 (log, K°)	33.28*** (9.67)		-33.24*** (10.50)	29.92 (24.26)
Precipitation average 1970–2018 (log, annual mm)	0.28 (0.34)		0.20 (0.38)	0.34 (0.87)
Forest area country (fraction)			6.49*** (0.78)	
Forest area (fraction of grid cell)	1.36** (0.63)			
Forest area (fraction 400km buffer)		3.58*** (1.20)		
Urban area (fraction 75km buffer)				-50.29** (19.08)
Study site area (log, km2)		-0.22*** (0.08)		
Road density 75km buffer (log, km roads/Km2)			196.97*** (51.23)	254.19* (142.07)
Road density 400km buffer (log, km roads/km2)		-110.66 (78.46)		
Constant	-195.11*** (55.62)	-4.32 (3.66)	186.31*** (55.77)	-188.36 (137.45)
RMSE	1.74	2.00	1.22	2.43
Observations	110	88	57	39
R-squared	0.55	0.39	0.71	0.31
LL	-207.8	-177.5	-83.92	-81.81
Df	7	7	8	6
Prediction average study site (international \$/ha/year)	135.2	159.0	19.3	28.96

Robust standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 5.1 lists estimation results from the selected model specifications by service after the removal of influential observations. We selected specifications that yielded the lowest out-of-sample prediction error. The results are discussed by ecosystem service below.

Recreation, hunting, and fishing

The estimation results show that values for recreation, hunting, and fishing are determined by socioeconomic, biophysical, and climate factors, as well as forest degradation (Table 5.1). The socioeconomic determinants, GNI per capita and population density (using a 75km buffer), are positively and statistically significantly associated with the value of recreation, hunting, and fishing. The coefficient is about 0.67 for GNI and 0.72 for population density. Because both variables are log-transformed, the coefficient estimates directly correspond to the elasticity of the value of recreation services with respect to these variables. Accordingly, the value of recreation, hunting, and fishing per hectare of forest increases by roughly 6.7 percent per every 10 percent increase GNI per capita, keeping everything else constant.

The value of recreation, hunting, and fishing is also positively and statistically significantly associated with average temperature. This result is consistent with previous findings. For example, Ghermandi and Nunes (2013) find that coastal recreational values are systematically related to temperature. Note also that climate variables control not only for the climatic conditions but may also account for the impacts of any unobservable variables that are also correlated with latitude. We kept both temperature and rainfall as controls in the regressions, although rainfall is not significant.

The forest area fraction of the grid cell and the fraction of threatened species are significant

determinants of the value of recreation. The variable forest area fraction of the grid cell has a positive coefficient equal to 1.36. The fraction of threatened species shows a negative coefficient, equal to -12.5. Interpreting the results as semi-elasticities, if, for example, the fraction of threatened species increases one percentage point, the value of recreation, hunting, and fishing decreases 12.5 percent.

The last row in Table 5.1 shows that the predicted value for a value site showing the average features in the sample used for recreational values equals \$135.20 per hectare per year. This value is close to the median value in the sample. Note that these values are expressed in constant 2017 international dollars (PPP-adjusted) to maintain consistency with the estimation dataset; final predictions use nominal US dollars 2020 as explained earlier in this report.

Habitat and species protection

The estimated relationships are positive and statistically significant between the value of habitat and species protection and population density and GNI per capita (Table 5.1). The estimate indicates that the elasticity of the value of habitat and species protection relative to income is about 0.79. In other words, the value per hectare increases by about 7.9 percent as GNI increases by 10 percent. The results also show a positive and statistically significant relationship between habitat and species protection values and population density. This relationship can be interpreted both as an increase in the value of habitat and species protection when local demand for the benefits from protection increases, either through an increase in the number of people caring about species and habitat or, possibly, due to increased need for species and habitat conservation because of high exposure to human pressures.

In addition, the significance of the variable “study site area” indicates that marginal value per hectare

decreases when the area protected (or to be protected) increases. The coefficient is equal to -0.22, and can be interpreted as an elasticity, suggesting that the per-hectare value of species and habitat protection decreases 2.2 percent when the size of the protected area increases 10 percent.

The forest area fraction within a 400km buffer around the grid cell centroid is statistically significant, with a positive coefficient equal to 4.5. The coefficient can be interpreted as a semi-elasticity. That is, if the forest area fraction within a 400km buffer increases one percentage point, the value of habitat and species protection, on average per hectare, increases 4.5 percent. The model also includes road density within a 400km buffer. Although this variable is not statistically significant, it helps to improve the predictive performance of the model.

The predicted value of species and habitat protection for a site showing the average features in the estimation sample equals \$159 per hectare per year (constant 2017 international dollars). This value is slightly lower than the median value in the sample.

Non-wood forest products

The estimation results for non-wood forest products highlight the importance of the socioeconomic determinants of ecosystem service values, although with distinct differences relative to the value of recreation, hunting, and fishing and habitat and species protection (Table 5.1). The estimated coefficient for the GNI per capita (-1.11) suggests that the value of non-wood forest products, on average per hectare, is relatively high when GNI per capita is low, and that it declines by about 11.1 percent per every 10 percent increase in GNI per capita. An intuitive explanation for this is that low-income populations are more dependent on non-wood forest products for food and livelihoods, which then translates into a relatively high value of non-wood forest products per hectare. As income level increases, the importance

of forests for food and livelihoods decreases and so does the corresponding value of non-wood forest products, assuming all other determinants of value remain the same.

Population density at the grid cell level is relevant for the value of non-wood forest products, yielding a positive and statistically significant coefficient estimated at 0.57. It indicates that the value of non-wood forest products, on average per hectare, increases by about 5.7 percent for every 10 percent increase in population density at the value site. This is plausible as non-wood forest products are typically collected manually, so areas with low population density may be constrained by the lack of the local population available to collect non-wood forest products.

Another socioeconomic variable that is a statistically significant determinant of the value of non-wood forest products is road density within a 75km buffer. The coefficient is positive and equal to 196.8. This coefficient can be interpreted as an elasticity, in other words, the value of non-wood forest products, on average per hectare, increases by almost 19-fold per every 10 percent increase in road density. While this coefficient seems large, it needs to be interpreted jointly with the narrow actual range of values for these variables.

The forest area fraction per country is statistically significant, and the coefficient equals 6.49. The coefficient can be interpreted as a semi-elasticity, in other words, the value of non-wood forest products, on average per hectare, increases 0.65 percent when the forest area fraction of the country increases 0.1 units.

In addition, species richness is a variable measuring ecosystem condition that shows a significant positive coefficient equal to 1.45. This can be interpreted as an elasticity, in other words, the value of non-wood forest

products increases around 14.5 percent when the number of species increases by 10 percentage points. This might be an indicator of forest productivity.

The predicted value for a value site showing the average features in the sample used for the value of non-wood forest products values equals \$19.30 per hectare per year (constant 2017 international dollars). This value is slightly larger than the median value in the sample, and almost seven times smaller than the mean value. This shows that despite the high estimated value of the constant, predictions from the model are reasonable when used together with the explanatory variables set within the relevant range for the estimation data.

Water services

The selected model shows a statistically significant role for GNI, forest area, forest degradation, and climate as determinants of the value of water services (Table 5.1). The estimated elasticity of the value of water services with respect to GNI is positive and a large, with the coefficient estimated at 2.02. This means that if the income increases 10 percent, value for water services will increase by about 20 percent. We note that about 69 percent of the studies in the estimation dataset examine avoided costs or changes in water treatment costs using a production function approach. The estimation results therefore indicate that as income increases, additional expenses to address the loss of forest hydrological services increase at rates higher than the rate of income growth.

Urban area, measured as a fraction of urban land within a 75km buffer, yields a negative coefficient estimate. The magnitude of the coefficient indicates that the value of water services, on average per hectare, decreases by about 1 percent when urban fraction increases by 0.1 percent (which is around the median in the estimation dataset).

In addition, road density within a 75km buffer shows a statistically significant relationship. The coefficient is positive and equal to 254.2. This coefficient can be interpreted as an elasticity, in other words, the value of water services, on average per hectare, increases almost 25-fold per every 10 percent increase in road density. As discussed earlier with respect to other variables, while this coefficient seems large, it needs to be interpreted jointly with the narrow range of actual values for these variables. In addition, while the sign of the coefficient seems counterintuitive, this might be an indicator of forest scarcity. That is, the marginal value of forest, on a per hectare basis, for water services increases when forest is more fragmented and becomes scarcer.

The predicted value of water services for a value site showing the average features in the sample used for water services values equals \$36.70 per hectare per year (constant 2017 international dollars). This is about two-thirds of the median value in the estimation dataset, and well within the range of values in the dataset.

5.1.2 Machine Learning Models

We developed predictive models using three classes of machine learning algorithms: RF, BART, and AML. We used the AML models as a benchmark for comparisons based on out-of-sample prediction performance, but we do not use them for the main estimation model because their results are hard to interpret and understand (the approach works completely as a black-box model). Moreover, due to the AML model structure, it sometimes produces outlier predictions when using the global dataset. In the following section, we present the main results for RF and BART models.

Following recommended practices in the literature, the machine learning models incorporate all

variables in Table 4.1 that are potentially relevant for the analysis.⁵ When estimating the machine learning models, we used the same weights as in the regression models, except for some of the AML sub-algorithms that, by their construction, do not allow for the inclusion of weights. In addition, all the machine learning models were run with the full set of observations, without removing influential observations as in the regression analysis. This is because machine learning methods manage outliers more effectively, without allowing one or few observations to have a disproportionately large impact on the predictions.

RF models

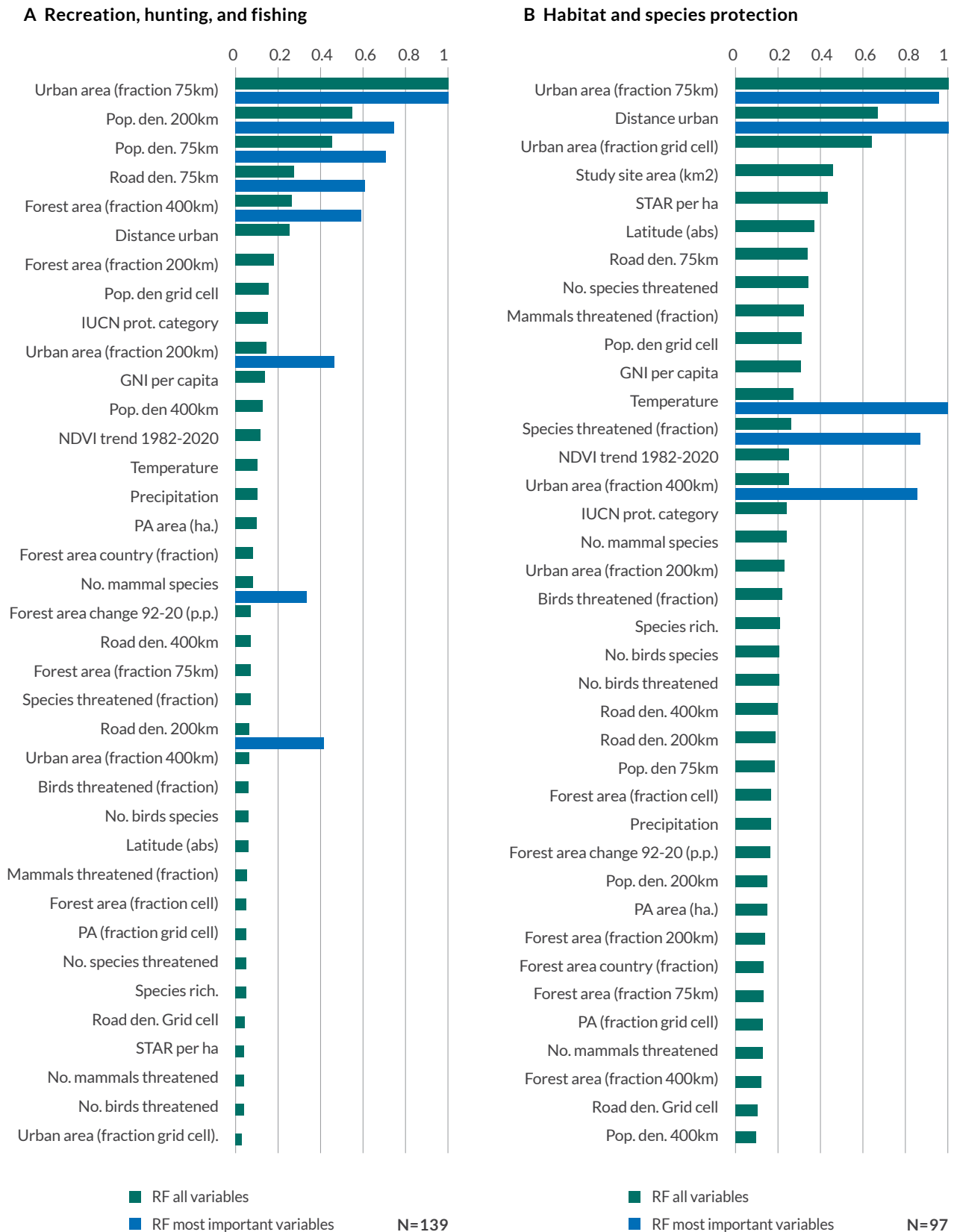
Figure 5.1 shows the relative importance of the predictors in the RF model for each ecosystem service, using both the whole set of variables and only the most important variables. Panel a in the figure shows that the urban area fraction within a 75km buffer and population density within 75km and 200km buffers are the most important variables

for predicting the value of recreation, hunting, and fishing. Other variables included in the model using the most important variables include road density within 75km and 200km buffers, forest area fraction within a 400km buffer, urban area fraction within a 200km buffer, and number of mammals species.

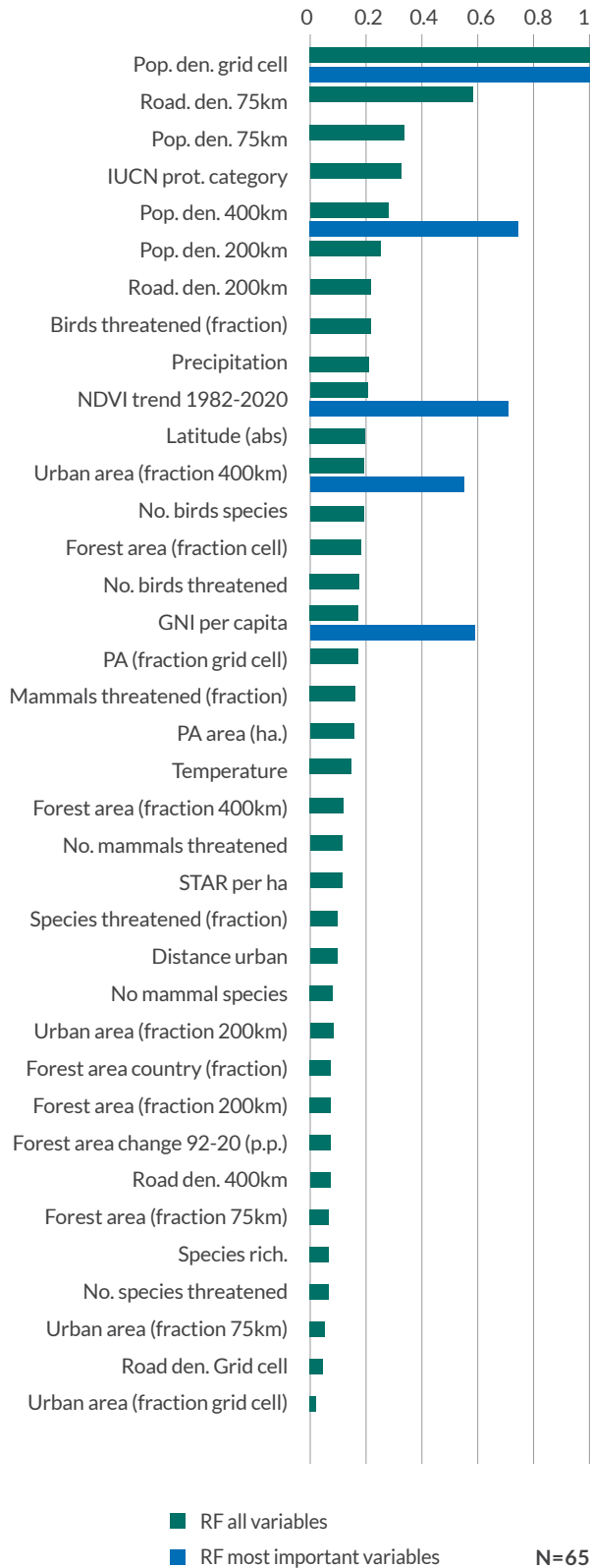
Panel b (Figure 5.1) shows the relative importance of the predictors for the value of habitat and species protection. Distance to nearest urban area (km), temperature, urban area fraction within a 75km and 400km buffer, and species threatened fraction are the variables selected by the model as the most important variables.

The relative importance of the predictors of the value of non-wood forest products are shown in panel c (Figure 5.1). Population density within the grid cell and a 400km buffer, NDVI trend, GNI per capita in the country, and urban area fraction within a 400km buffer are the most important variables selected by the model.

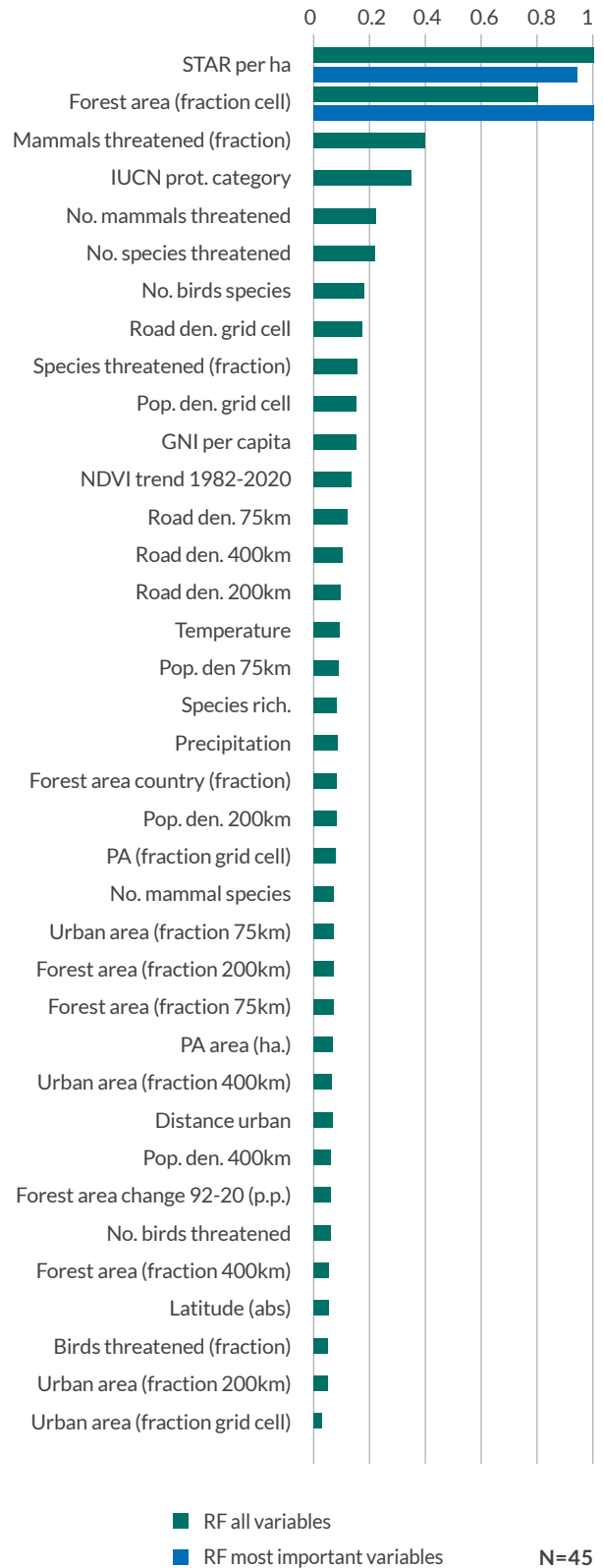
⁵ The variables included in the ML base models are : GNI per capita, population density (cell, 75km, 200km, and 400km), road density (grid cell, 75km, 200km, and 400km), urban fraction (grid cell, 75km, 200km, and 400km), distance to nearest urban area, species richness, number of mammal species, number of bird species, latitude (absolute value), protected fraction of the grid cell, size of the protected area intersected with the grid cell, IUCN protected area category, forest area fraction (cell, 75km, 200km, and 400km), forest fraction of the country, forest per capita in the country, temperature (annual average 1970–2018), rainfall (annual average 1970–2018), NDVI trend 1982–2020, forest change 1998–2020 (% cell), number of species threatened, number of mammals threatened, number of birds threatened, species threatened fraction of all species, mammals threatened fraction of all mammal species, birds threatened fraction of all bird species, and STAR per ha. ML models did not include a variable with the year of the value study, because it is used as a time fixed effect in these models. As a result, the variable does not have a direct interpretation as in linear regression.

FIGURE 5.1: PREDICTOR RELATIVE IMPORTANCE PER SERVICE USING BART MODELS

C Non-wood forest products



D Water services



Panel d (Figure 5.1) shows the relative importance of the predictors for water services. Forest area fraction of the grid cell and STAR metric per hectare are the most important variables selected by the model.

BART

Figure 5.2 shows the relative importance for the predictors in the BART model for each ecosystem service, both using the whole set of variables and the most important variables. In general, BART models tend to use information from more variables than RF when constructing the model.

Panel a shows that the urban area fraction within a 75km buffer, population density within 75km and 200km buffers, species richness, and grid cell protection category are the most important variables to predicting the value of recreation, hunting, and fishing. Many of the variables signal the importance of the demand for recreational services, and results are consistent with the findings from the regression models and RF models. In addition, habitat protection status is an important predictor in BART models.

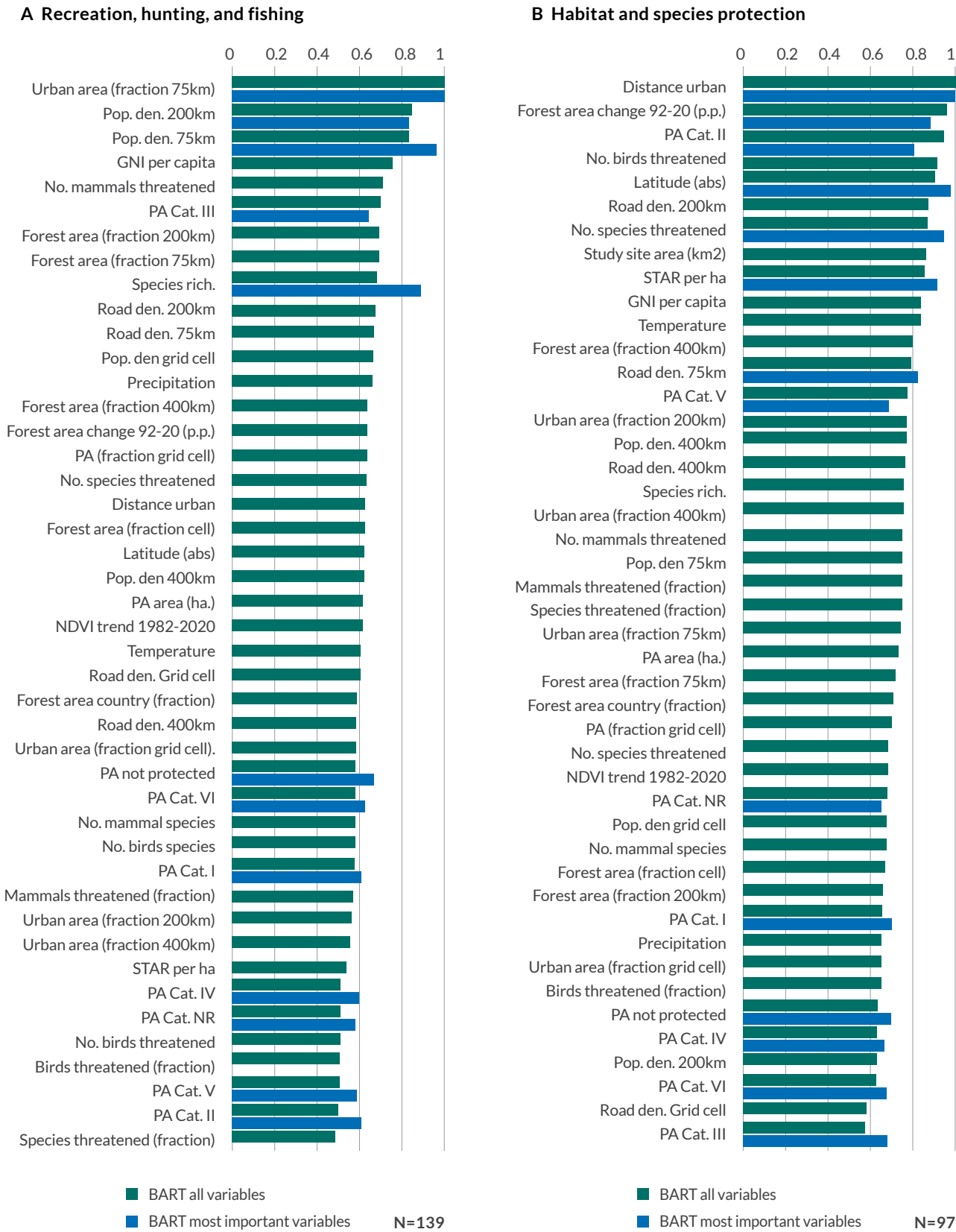
Panel b in Figure 5.2 shows the most important predictors for the value of habitat and species protection services. Distance to the nearest urban area, latitude in absolute terms, number of species threatened, STAR metric per ha, forest area change in the period 1992 to 2020, road density within a 75km buffer, and grid-cell protection category are the most important predictors.

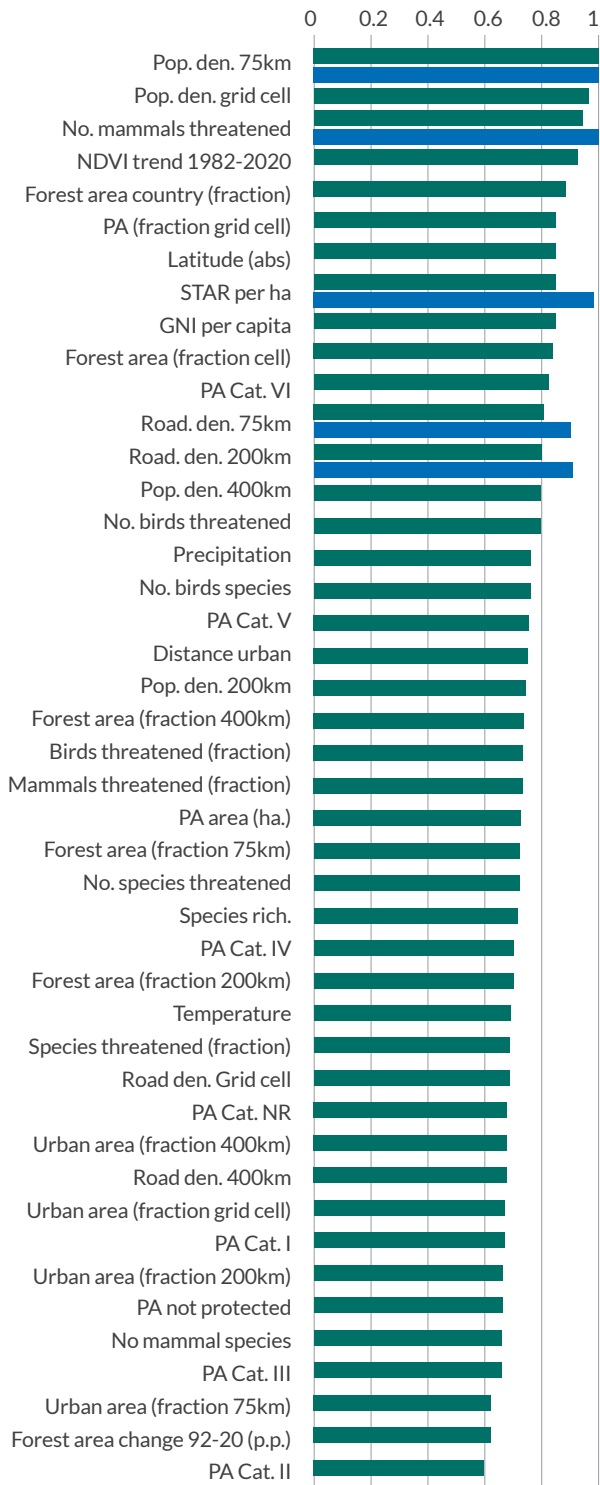
The most important predictors of the value of non-wood forest products are shown in panel c in Figure 5.2. Number of species of mammals threatened, population density in the grid within a 75km buffer, STAR metric per ha, and road density within 75km and 200km buffers are the most important variables. Latitude in absolute terms might summarize weather conditions and ecosystem productivity.

Panel d in Figure 5.2 shows the results for water services. The most important variables are forest area fraction in the grid cell, STAR metric per ha, mammal species threatened fraction of total mammal species, number of species of mammals threatened, and grid-cell protection category.

Machine learning models have the advantage of dealing better with the presence of outliers in the estimation dataset, and by identifying non-linear relationships. In addition, RF models, and BART models to some extent, assure that predictions are within the range of the estimation dataset, avoiding extreme low or high values in the prediction. The analysis above shows that the predictors of the value of forest ecosystem services recovered in the assessment are by and large consistent between the machine learning and the regression models. This also points to the use of regression models as helpful approaches to recover and interpret the relationships between different predictor variables and the value of different forest non-wood ecosystem services.

FIGURE 5.2: PREDICTOR RELATIVE IMPORTANCE PER SERVICE USING BART MODELS

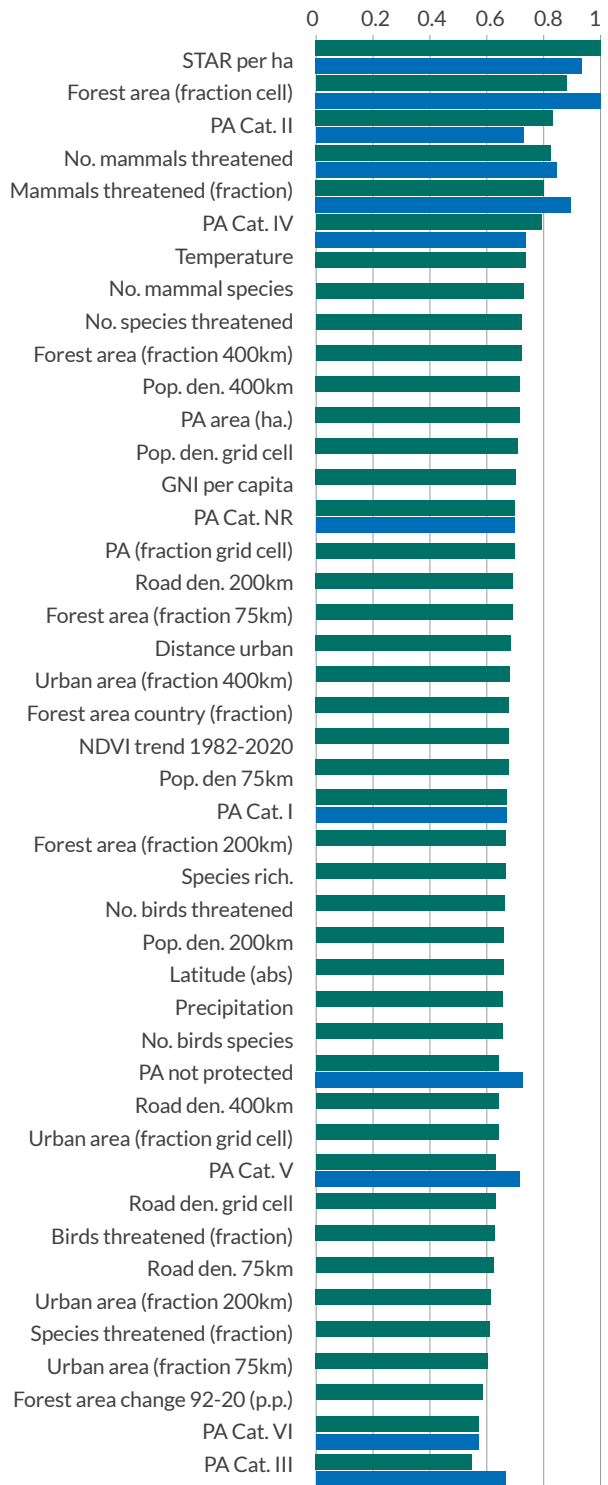


C Non-wood forest products

■ BART all variables

■ BART most important variables

N=65

D Water services

■ BART all variables

■ BART most important variables

N=45

5.1.3 Model Selection to Generate Global Predictions

We compare the performance of meta-regression models and alternative machine learning models by using out-of-sample prediction tests (Table 5.2). Within different machine learning models, the AML always has the lowest RMSE. Differences between the RF, BART, and meta-regressions are less clear cut. Using the most important variables, RF and BART always outperform the same model using all the variables. Meta-regressions generally attain lower RMSE than RF and BART, but the differences are minimal. One possible exception includes models to predict the value of non-wood forest products for which meta-regressions yield RMSE that is roughly 50 percent to 60 percent of the RMSE of RF and BART models. But, in general, differences between the machine learning and meta-regression models are almost negligible.

Meta-regression models may outperform RF and BART models in RMSE comparisons for different reasons. Many machine learning algorithms, by their nature, aggregate observations in clusters, and the predicted value for observations in a cluster

equals their average value within that cluster. When the sample size is small, machine learning might group variables that are quite dissimilar in value, increasing the error for the observations farthest from the average value of the cluster. This error gets smoothed in regression models, where the error of each observation is measured as the distance to its own prediction, and not the average of several observations. Another potential explanation is that the RF and BART models may be overfitting the model. The risk of overfitting is reduced by including only the most important predictors.

Differences in RMSE across the models in Table 5.2 are not sufficiently pronounced to unequivocally support choosing one model over others for global predictions. In general, the RF models have appeal over AML, because they allow evaluating variables that are important for predictions and consider their intuition. While AML works well as a benchmark to compare the performance of RF and regression models, we prefer to avoid using AML for global predictions because they could be driven by random features of the data that are difficult to explore and explain.

TABLE 5.2: META-REGRESSION ESTIMATION RESULTS BY ECOSYSTEM SERVICE

MODEL	RECREATION, HUNTING, AND FISHING	HABITAT AND SPECIES PROTECTION	NWFP	WATER SERVICES
Regression	1.74	2.00	1.22	2.43
RF all variables	2.12	2.97	2.36	2.79
RF most important variables*	2.00	2.64	2.07	2.57
BART all variables	2.28	2.88	2.41	2.80
BART most important variables	2.09	2.75	2.22	2.56
AML	1.83	2.43	1.83	2.15

*Selected model for global predictions

In addition, RF models have some advantages in reference to BART models. First, RF is a well-established and mature method, while the BART models are more incipient. Second, RF allows for missing values for explanatory variables in the prediction dataset, while the predictions for grid cells with missing values for at least one of the explanatory variables is predicted as missing by BART models, like in regression models. Third, BART models depend on the assumed distribution underlying the model, while RF is completely flexible. Finally, RF models are more conservative in the tails of the distribution, while BART model predictions are more wide ranging, given the distributional assumptions.

To further support the selection of models, we compared global predictions from different models. Appendix 8 shows the distribution of global predictions for each of the three main models per ecosystem services. Figure A8.1 in Appendix 8 graphs the kernel distribution of the regression and RF models by ecosystem service in 2020, as an illustrative year.

Examining global predictions at grid cell and country levels further strengthened the choice of RF as preferred models. Two observations led to this. First, differences in the out-of-sample prediction criteria between the modeling approaches are almost negligible, with some exceptions (such as predictions for NWFP). Second, although regression analyses show a smoother distribution of the predictions and allow for the prediction of values out of the range of values in the estimation dataset, they also show exceedingly high-value outliers in the right tail of the distribution. This is true even after truncating the predictions and the predictors in the regression analysis (see Siikamäki et al. 2021). This problem does

not emerge with the RF models; rather, the way RF model predictions are constructed directly controls for outliers in global predictions by effectively constraining the range of global predictions to match the range in the training (estimation) dataset. Because of the reasons above, we selected RF using the most important variables as the model for global predictions.

5.2 GLOBAL PREDICTIONS

In this section we first present global predictions by ecosystem service using the selected RF model with the most important variables. Next, we present aggregate values by grid cell and country, using only three ecosystem services: recreation, fishing, and hunting; non-wood forest products; and water services. This follows the approach by CWON to focus on value estimates that, where possible, are aligned with internationally accepted statistical standards and guidelines of the SNA and SEEA. That is, to use methods that can be considered consistent with exchange values, and that account only for use values.

5.2.1 Global Predictions by Ecosystem Service

Several maps illustrate value predictions. Note that the rest of results are computed for 2020 in nominal dollars (2020 US dollars). Also, note that the maps are colored according to variation for values within the service illustrated in the map, and not using the same scale across different services. This works well for geographically contrasting value predictions for each service but is less telling of differences between values for different service, as the same color in one map indicates a different value in another map.⁶

⁶ Using the same colors to indicate the same dollar values in each map is not practical, because the maps would show little, if any, variation in values for some services, such as NWFPs (as their geographic variation is more modest than the overall variation of values across different services).

Global predictions by grid cell

Figure 5.3 shows the value per ha, by service, mapped globally using 0.1° by 0.1° resolution for forested grid cells globally. Panel a in Figure 5.3 shows the predicted values for recreation, hunting, and fishing using the RF model with the most important predictor variables. The recreational values are mostly associated with population density, urban area fraction, and roads density at different scales, forest area fraction within a 400km buffer, and number of mammal species. Therefore, forests in areas of high income and populations, such as Eastern and West Coast United States, Central Europe and the south of the Northern European countries, Japan, and Eastern China, are valued highly for recreation. Note also that values

for recreation are supported only by forests that are accessible. This results in relatively low values in much of the boreal forests, especially in Russia and Canada, where inaccessible forests are prevalent. Tropical rain forests also get low values per hectare because of inaccessibility, especially in the Amazon.

The value of habitat and species protection, shown in panel b in Figure 5.3, is driven by urban area fraction at different scales, distance to nearest urban area, temperature, and fraction of threatened species. This service is projected only for protected forests. High values for habitat and species protection concentrate in Europe, Japan, the Republic of Korea, and parts of North America and Australia.

FIGURE 5.3: PREDICTED VALUES PER ECOSYSTEM SERVICE BY GRID CELL, PER HECTARE (CURRENT USD 2020)

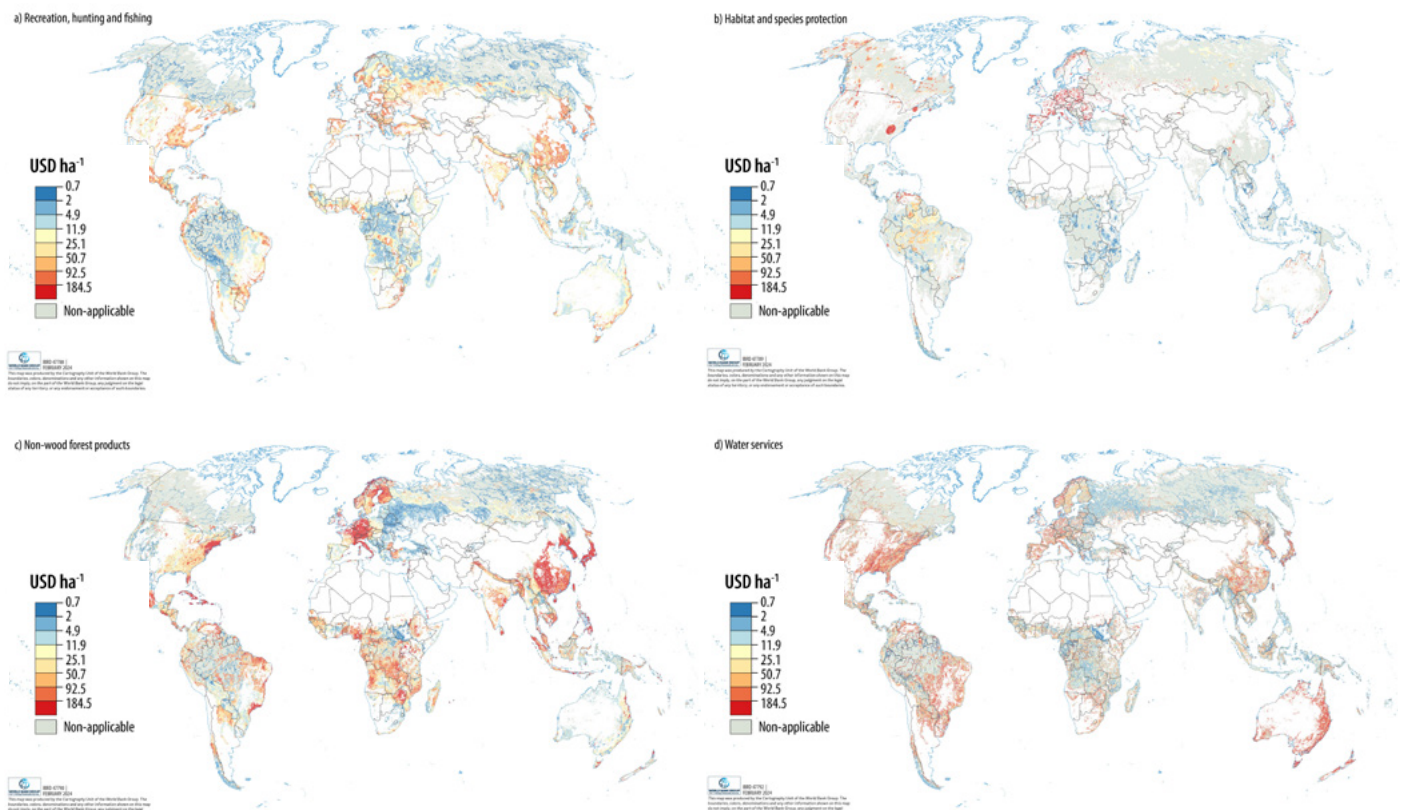
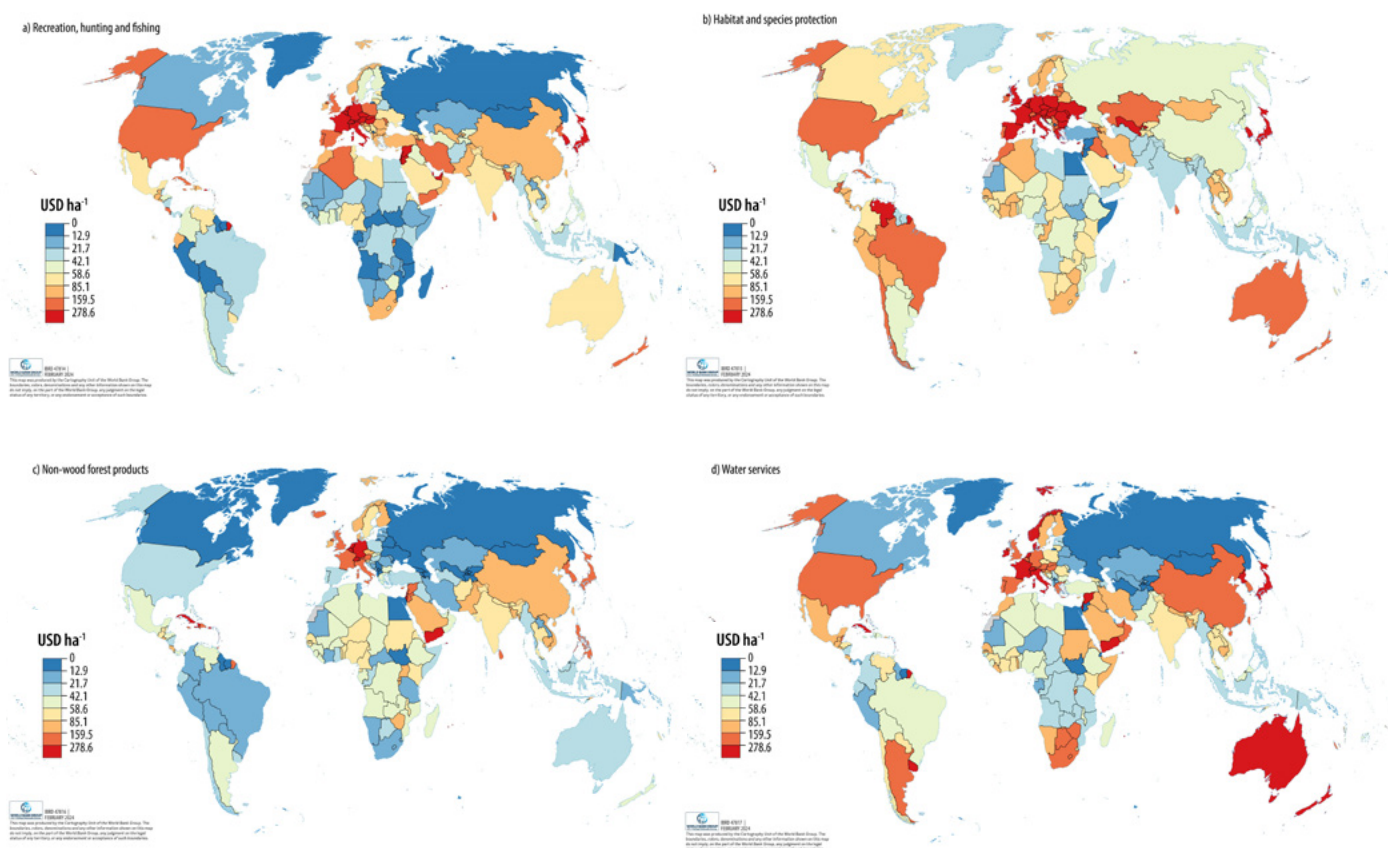


FIGURE 5.4: PREDICTED VALUES 2020 PER ECOSYSTEM SERVICE BY COUNTRY, AVERAGE VALUE PER HECTARE (CONSTANT USD 2020)



The value of non-wood forest products is supported only by forests that are accessible or are under IUCN protected area categories V or VI that allow for sustainable extraction of goods (panel c, Figure 5.3). Value of NWFP tends to be explained by population density at different scales, NDVI trends 1982 to 2020, urban area within a 200km buffer, and GNI per capita in the country. Results are similar to high values for recreation, but also extend to regions with lower GNI, such as Central Africa and Central America.

Finally, water services (panel d in Figure 5.3) are also supported only by accessible forests. The value is explained mainly by forest area fraction in the grid

cell and STAR per ha. High values are concentrated in North America, Central and Western Europe, Australia, and some locations in South America.

Country-level predictions

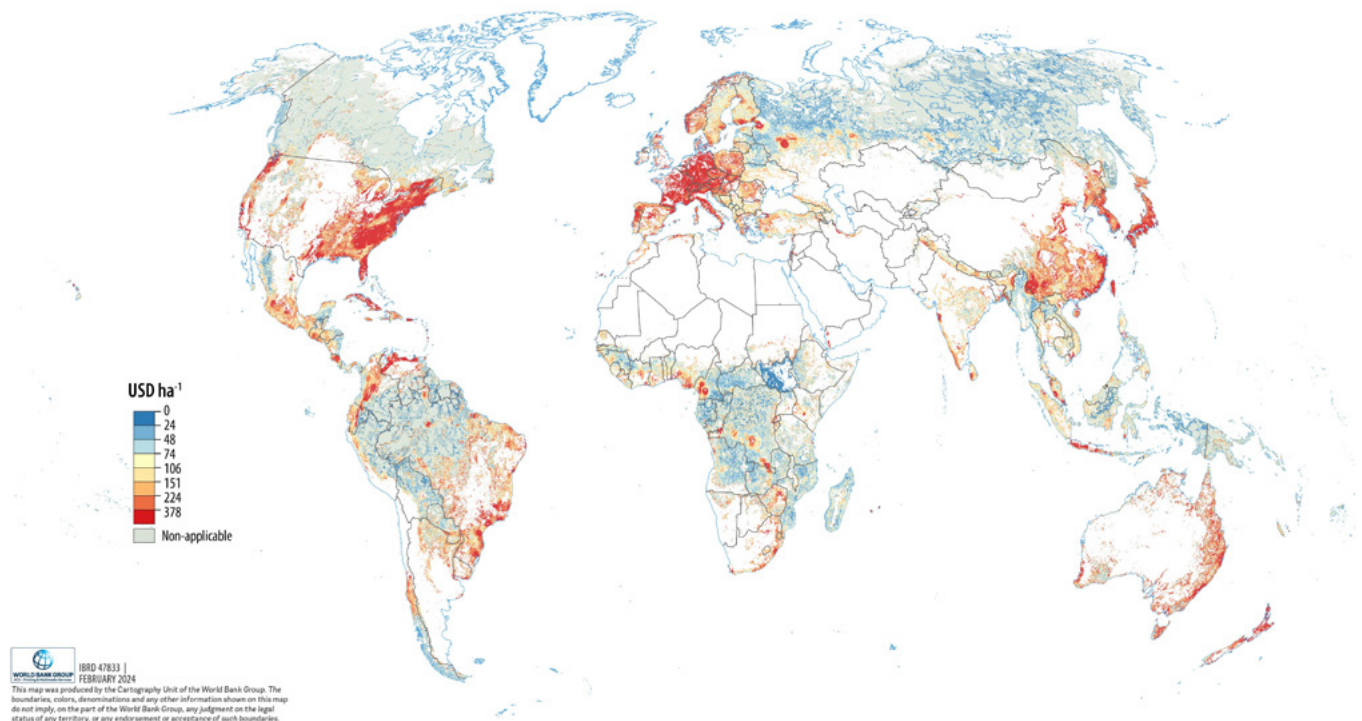
The CWON assessment measures country-level wealth, so the next set of results aggregates grid-cell predictions by country. To account for the fact that not all grid cells are fully forested, we weighted the predicted value of ecosystem service, per hectare, in the grid cell, by the forest area in the grid cell over the total forest area in the country. Figure 5.4 presents the country-level estimates by ecosystem service.

5.2.2 Aggregate Global Predictions

The CWON assessment aggregates country-level wealth for ecosystem services that use valuation methods aligned with internationally accepted statistical standards and guidelines of the SNA and SEEA. That is, to use methods that can be considered consistent with exchange values, and that account only for use values. As discussed in Section 2.5, this is the case for three ecosystem services: recreation, fishing, and hunting; non-wood forest products; and water services. Habitat and species protection valuation studies consider non-use values and are sometimes inconsistent with the SEEA principle of using exchange values (see Section 2.5).

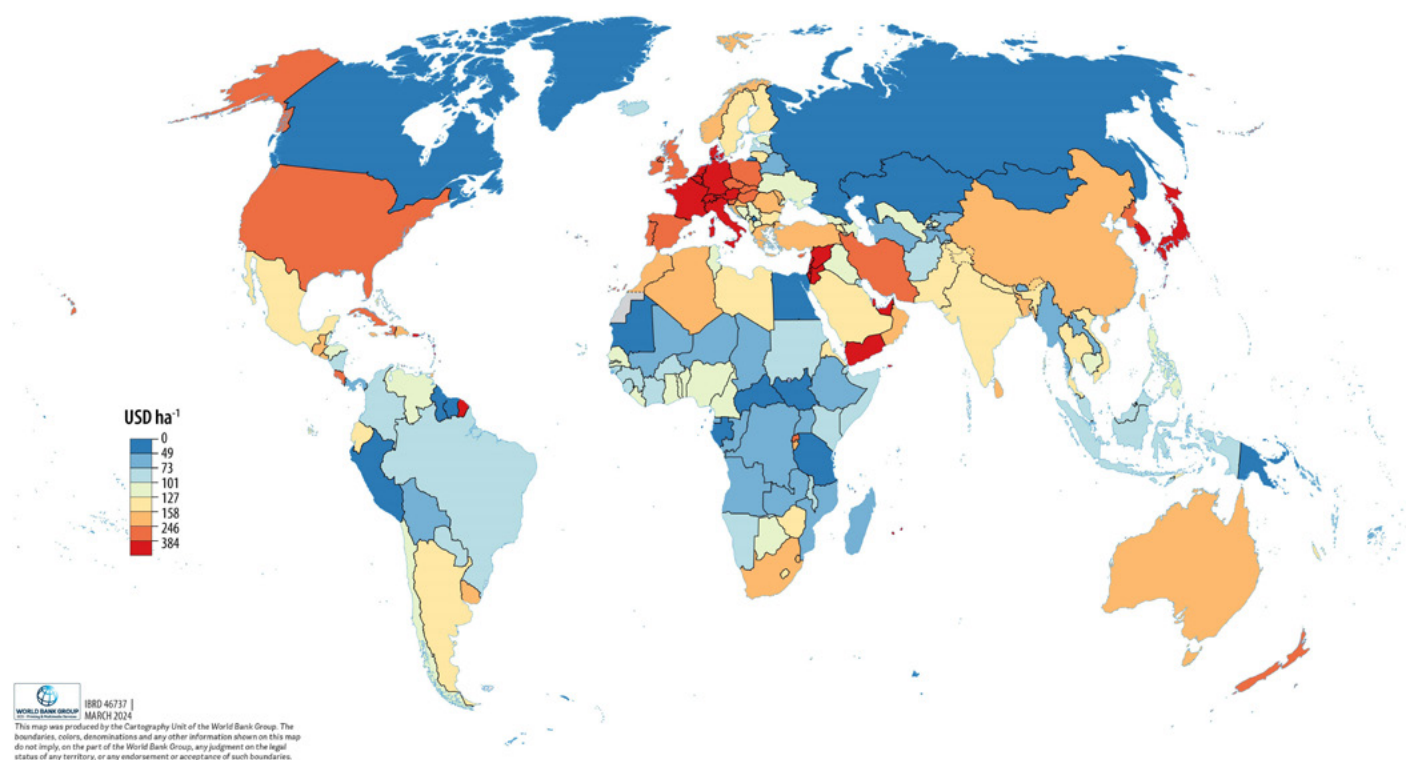
Figure 5.5 maps the combined value of forest ecosystem services for recreation, hunting, and fishing; non-wood forest products; and water services on average per hectare in 2020. The value is mapped globally in 0.1° by 0.1° resolution for forested grid cells. Several interesting trends emerge. First, there is considerable variation in the values by biome. Industrialized areas, including North America, Europe, Japan, and Australia, feature particularly high value estimates. On the other hand, several developing countries also have high values, including parts of Brazil, parts of Mesoamerica, and several areas in Asia, such as the densely populated areas in Indonesia and China. Africa, in general, has relatively low predicted

FIGURE 5.5: COMBINED PREDICTED VALUE OF ALL RECREATION, HUNTING, AND FISHING; NON-WOOD FOREST PRODUCTS; AND WATER SERVICES, PER HECTARE IN 2020 (USD 2020)



Note: The services considered include recreation, NWFPs, and water services.

FIGURE 5.6: COUNTRY-LEVEL PREDICTIONS OF COMBINED VALUE OF RECREATION, NWFPS, AND WATER SERVICES PER HECTARE IN 2020 (CURRENT USD 2020)



values, but some spots in Southern and Western Africa, such as South Africa, Côte d'Ivoire, Ghana, and Nigeria, are relatively high.

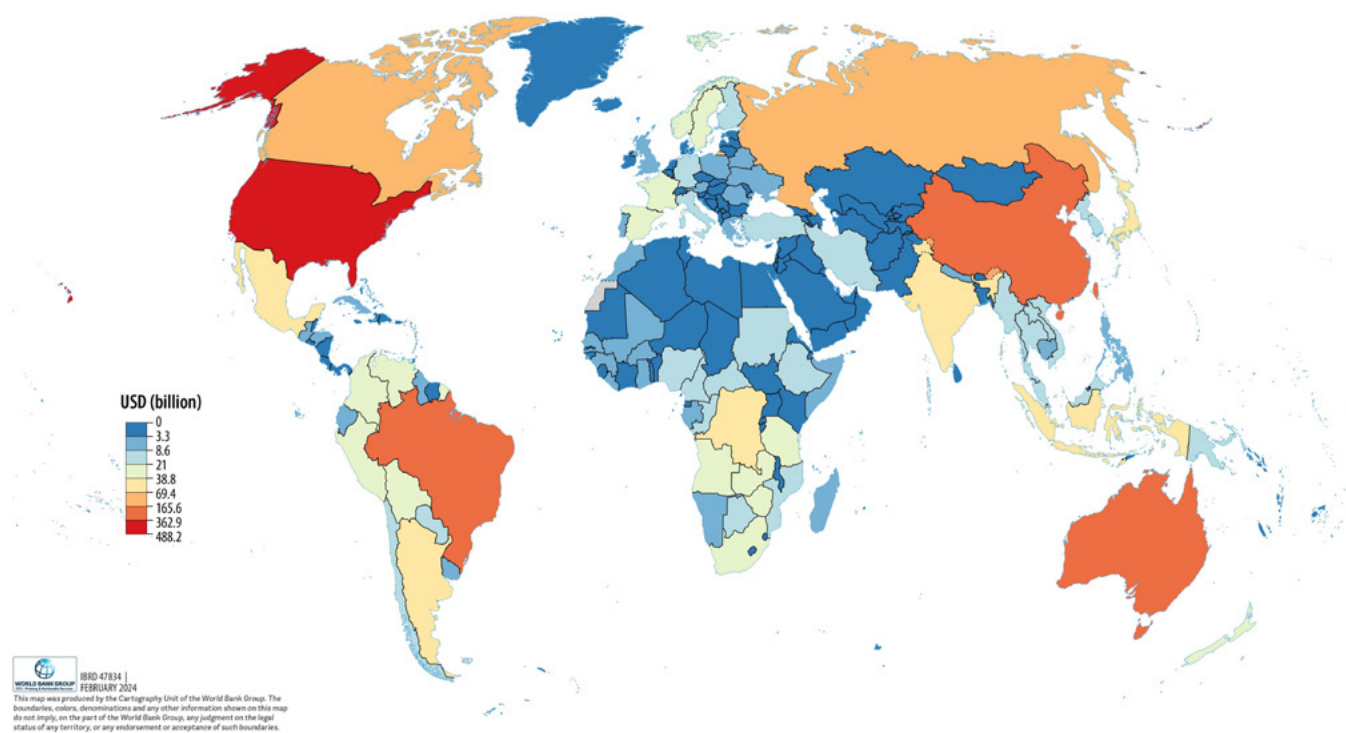
Country-level aggregate predictions

For country-level estimates of the value of forest non-wood ecosystem services, on a per-hectare basis, we again combined the value of recreation, hunting, fishing, non-wood forest products, and water services (Figure 5.6). The results are shown in Table A9.1 in Appendix 9, which lists the predicted value for recreation, hunting, and fishing; non-wood forest products; and water services on average per hectare, by country, continent, World Bank region, and world level estimates for 2020. This information supports the World Bank assessment of forest wealth. In addition, we compiled supplementary spreadsheets listing the average value per hectare by country, continent, World Bank region, and world-level estimates for 2020 for habitat and

species protection. These estimates may be useful in applications that go beyond CWON, including assessments that consider non-use values.

The total forest wealth of non-wood forest ecosystem services by country is shown in Figure 5.7 (Table A9.1 in Appendix 9 shows the estimates by country). It is computed by multiplying the combined value of recreation, hunting, and fishing; non-wood forest products; and water services on average per hectare by the total forest area per country, as measured using official international forest statistics from the FAO, extracted from the World Bank World Development Indicators (World Bank 2020), and computing the net present value using a 25-year time horizon and 4 percent discount rate. The use of FAO data also helps maintain consistency with the rest of the World Bank wealth assessment and facilitates future updating of the country-level estimates of wealth.

FIGURE 5.7: TOTAL FOREST WEALTH BY COUNTRY OF COMBINED VALUE OF RECREATION, NWFPS, AND WATER SERVICES (CURRENT USD BILLION 2020)



Annual predictions by country

We produced annual values per cell and country for the time period between 1995 and 2020 (25 years). The estimates are listed in an auxiliary spreadsheet file attached to the report.

5.3 RESULTS COMPARISON WITH THE PREVIOUS ASSESSMENTS

Tables 5.3 and 5.4 summarize value predictions from this assessment and contrasts them with estimates obtained in the previous assessments by Siikamäki et al. (2015, 2021). The tables allow comparisons of average value per hectare as well as total wealth in 2013 (current dollars). The updated total value of non-wood forest ecosystem services, globally, is about 7.5 percent larger than the estimate derived in Siikamäki et al. (2015), and 65 percent of the estimate in (Siikamäki et al. 2021) (Table 5.3).

When contrasting the results by ecosystem services to the 2021 report, Table 5.4 shows that the value predictions for recreation, hunting, and fishing are about 45 percent of those developed in the 2021 report; about 67 percent of those developed for non-wood forest products in the 2021 report; and some 52 percent higher than those developed for water services in the 2021 report.

There are multiple explanations for these differences. Perhaps most importantly, we have considerably expanded the dataset of primary estimates derived from the current literature, including studies published from 2020 to 2022. We have also added several new studies identified for years prior to 2020. This report added 79 new values to the estimation dataset: 28 new estimates for recreation, hunting, and fishing (20.1 percent of all the values for this service); 20 new estimates for habitat and species protections (20.6 percent);

17 new estimates for non-wood forest products (26.2 percent); and 14 new estimates for water services (31.1 percent). While most of the new value estimates are within the range of value estimates in Siikamäki et al. (2015, 2021), this is a major change in the estimation dataset.

Moreover, the current study uses a more updated and comprehensive dataset for roads, changing the area of accessible forest (determined by the road network). To understand the implications of this change, we ran again the regression models for the study by Siikamäki et al. (2021) with the old and new GIS data, and changes in the results were minor. However, this still does not discard that differences in aggregate values are because of the new area of accessible forest.

In addition, we used machine learning techniques, similar to Siikamäki et al. (2021), but using different methods for variable selection. Also, the method is different from the meta-regressions used in Siikamäki et al. (2015). As explained before, meta-regression analysis allows predictions out of the range of the values in the estimation dataset, while machine learning bounds predictions between the values included in the estimation dataset. Therefore, many of the grid cells in previous assessments may have imputed a lower or higher value than in the current report because of the statistical method.

Finally, we included the STAR metric as an additional explanatory variable, which may also play a potentially important role in the predictions.

TABLE 5.3: ESTIMATED VALUE OF NON-WOOD FOREST ECOSYSTEM SERVICES BY WORLD BANK REGION, AND COMPARISON WITH PREVIOUS REPORTS (2021, 2015) (CURRENT USD 2013)

	THIS ASSESSMENT			STUDY 2021			STUDY 2015	
	Annual value ha ⁻¹ (rec. + NWFPs + water services)	Total forest wealth ha ⁻¹ (NPV)	Total forest wealth (NPV, billion)	Annual value ha ⁻¹ (rec. + NWFPs + water services)	Total forest wealth ha ⁻¹ (NPV)	Total forest wealth (NPV, billion)	Annual value ha ⁻¹ (rec. + NWFPs + water services)	Total forest wealth (NPV, billion)
East Asia & Pacific	150	2,443.4	1,562.8	161	2,615.4	1,672.8	148	1,537.9
Europe & Central Asia	60	973.8	1,015.1	78	1,268.2	1,322.0	47	796.0
Latin America & Caribbean	76	1,237.8	1,153.1	92	1,486.8	1,385.0	103	1,559.0
Middle East & North Africa	212	3,451.2	80.0	227	3,694.2	85.6	42	15.8
North America	141	2,298.7	1,509.6	327	5,316.1	3,491.1	128	1,365.7
South Asia	118	1,916.1	159.3	154	2,509.7	208.6	29	39.2
Sub-Saharan Africa	56	905.6	561.5	77	1,254.6	777.9	13	131.0
World	90	1,468.2	5,881.1	136.99	2,225.7	8,915.4	84	5,466.8

TABLE 5.4: ESTIMATED VALUE OF NON-WOOD FOREST ECOSYSTEM SERVICES, ANNUALLY PER HECTARE, AND COMPARISON WITH PREVIOUS REPORT (2021), IN CURRENT USD 2013, BY WORLD BANK REGION AND ECOSYSTEM SERVICE

REGION	RECREATION, HUNTING, AND FISHING			NWFP			WATER SERVICES		
	This study 2023	Siikamäki et al. (2021)	2023/ 2021	This study 2023	Siikamäki et al. (2021)	2023/ 2021	This study 2023	Siikamäki et al. (2021)	2023/ 2021
East Asia & Pacific	74.4	127.1	0.58	11.6	10.5	1.11	64.4	23.4	2.75
Europe & Central Asia	34.8	42.5	0.82	4.4	4.8	0.91	20.8	30.8	0.67
Latin America & Caribbean	29.9	68.3	0.44	6.7	6.7	1.00	39.5	16.6	2.38
Middle East & North Africa	140.0	193.9	0.72	10.6	14.5	0.73	61.8	19.0	3.25
North America	92.8	276.7	0.34	4.3	4.9	0.88	44.4	45.6	0.97
South Asia	59.0	127.4	0.46	14.8	22.1	0.67	44.2	5.0	8.81
Sub-Saharan Africa	15.1	45.3	0.33	8.1	25.6	0.32	32.5	6.3	5.13
World	46.4	102.5	0.45	6.7	9.9	0.67	37.3	24.6	1.52

6 Contribution of Protected Areas to the Value of Non-Wood Forest Ecosystem Services

Protected areas cover about 15 percent of the world's terrestrial areas and some 7 percent of the ocean (UNEP-WCMC, IUCN 2022). Their coverage has steadily increased over time, and their current global extent nearly matches the Aichi Biodiversity Target 11 of 17 percent of terrestrial and 10 percent of coastal and marine areas protected by 2020. As such, protected areas constitute one of the key policy instruments to ensure the conservation of nature to support biodiversity and the provision of ecosystem services to people.

Although various ecological and ecosystem contributions of protected areas are widely recognized (King et al. 2023), information on the economic value of ecosystem services provided by protected areas is not comprehensively available. In this section we formulate an operational method to understand how much of the contribution of the ecosystem services to wealth is produced by protected forest areas. For full alignment with the SEEA, we predicted the contribution of protected areas for recreation, non-wood forest products, and water services in the grid cells that are protected. These results constitute the first available estimates of the economic value of these ecosystem service categories supported by protected areas, comprehensively generated by country and globally.

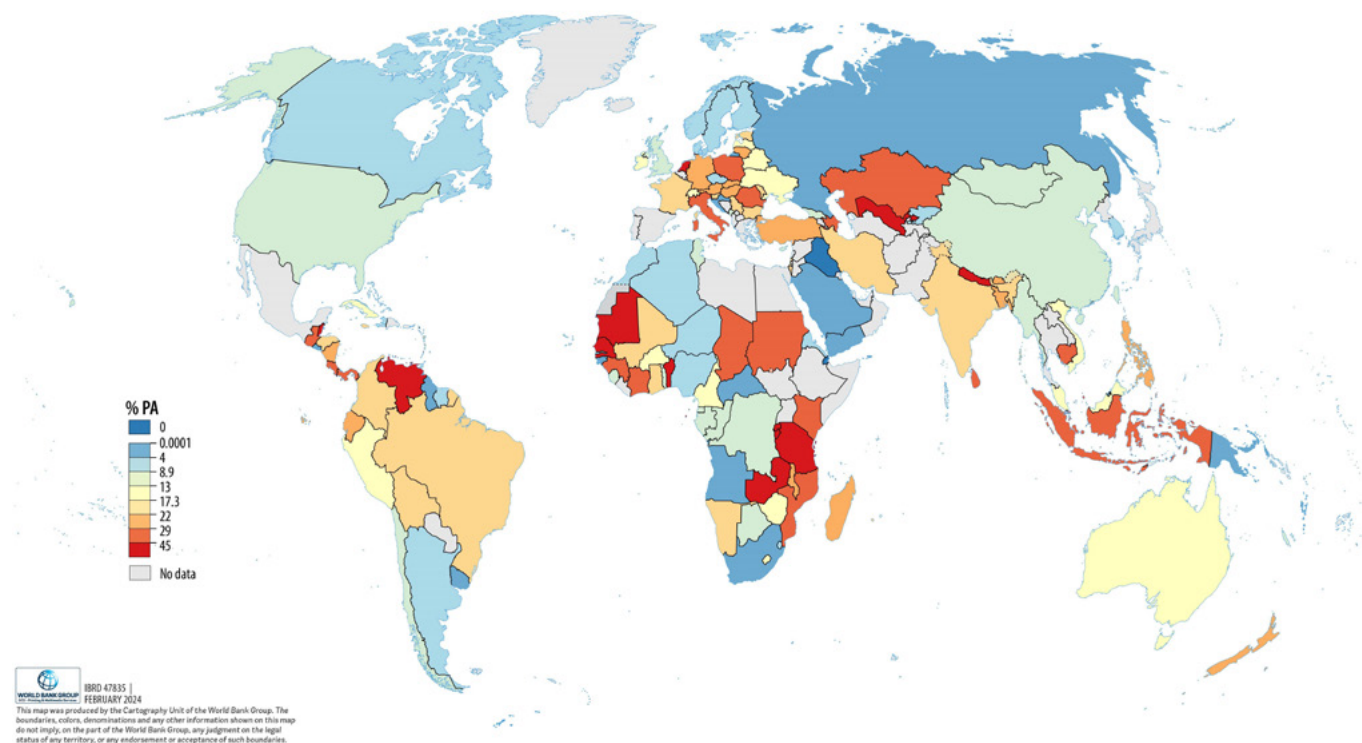
For each service, we estimate the average marginal value for cells that are in a protected area and

outside of a protected area. As before, a cell is defined to be in a protected area if 50 percent or more of its area is protected. In addition, we apply the service areas defined previously: forest that is accessible and protected for recreational and water services, and forest that is accessible and protected or within a protected area under IUCN category V or VI (classification used by the World Database of Protected Areas is used here to identify where protected areas exist) for non-wood forest products.

Note that data in this assessment on the spatial extent of protected areas come from the World Database on Protected Areas, maintained in partnership by UNEP World Conservation Monitoring and IUCN. Although it is the primary and most comprehensive source for protected area data, some countries, including China and India, offer restricted data on protected areas for public use. All data on protected areas in this assessment is based on publicly available data only. Consequently, the coverage of protected areas of forests likely underestimates their actual extent in countries that restrict data availability. Note also that the database corresponds to the current extent of protected areas and does not support construction of time-series data on protected areas.

Figure 6.1 shows the percentage of the total national economic value of forest non-wood ecosystem services provided by protected area forests, by country.

FIGURE 6.1: PERCENTAGE OF THE NATIONAL ECONOMIC VALUE OF RECREATION, HUNTING, AND FISHING; NON-WOOD FOREST PRODUCTS; AND WATER SERVICES PROVIDED BY PROTECTED AREAS, BY COUNTRY IN 2020



To estimate this, we first estimate aggregate forest value by country in 2020, as well as for areas that are protected. That is, first we multiply country-level predictions of combined average value per hectare of recreation, NWFPs, and water services 2020 in Figure 5.6 by the total forest area in the country reported by FAO Global Forest Resources Assessments (FAO 2021). Next, we multiply the combined average value per hectare country-level predictions for protected areas by the total area of forest that is protected by country reported by FAO (FAO 2021). Finally, we estimate the percentage of aggregate value by country that is contributed by protected areas. Note that this approach uses total forest area and protected area forest computed using the world grid designed for this study. These measurements show lack of data for several countries in the database, because not all countries report the area of protected forest.

However, this is the most robust approach to avoid discrepancies with official statistics on total area of forest and protected forest.

The contribution of protected areas to total value is highest in several African countries, Venezuela, Nepal, Uzbekistan, and many countries in Central Europe. This is a combination of the large share of forest being protected in those countries and the value of non-wood ecosystem services in the protected areas relative to non-protected areas.

Table 6.1 summarizes these results by world region, showing that protected areas provide in total more than one trillion in economic wealth through the provision of ecosystem services in recreation, hunting, and fishing, non-wood forest products, and water services.

Globally, this represents 16.3 percent of the total economic wealth contributed by forest non-wood ecosystem services. The share of national forest non-wood wealth provided by protected areas varies considerably by world region, with the highest percentage of wealth provided by protected areas

in Sub-Saharan Africa (21.8 percent), Latin America and Caribbean (21.5 percent), and South Asia (21.5 percent), and the lowest percentage of wealth provided by protected areas in Middle East and North Africa (8.5 percent), Europe and Central Asia (10.5 percent), and North America (10.9 percent).

TABLE 6.1: ECONOMIC WEALTH PROVIDED BY PROTECTED AREAS, BY ECOSYSTEM SERVICE AND IN TOTAL, IN ABSOLUTE (USD 2020) AND PERCENTAGE TERMS, BY WORLD REGION AND GLOBALLY

REGION	Total wealth provided by protected areas, by ecosystem service and in total (USD 2020)				Percentage total national wealth provided by protected areas, by ecosystem service and of total forest non-wood wealth (USD 2020)			
	Recreation, hunting, and fishing	NWFPs	Water services	Total	Recreation, hunting, and fishing	NWFPs	Water services	Total
East Asia & Pacific	149.8	21.1	133.4	304.3	17.0%	17.2%	19.1%	17.9%
Europe & Central Asia	81.3	7.5	31.5	120.3	12.1%	9.2%	8.1%	10.5%
Latin America & Caribbean	109.5	26.0	127.3	262.8	21.7%	25.4%	20.7%	21.5%
Middle East & North Africa	5.5	0.3	2.1	7.9	8.7%	6.5%	8.7%	8.6%
North America	120.4	3.5	41.4	165.3	12.9%	6.9%	7.8%	10.9%
South Asia	22.1	4.5	14.5	41.2	21.1%	23.0%	21.4%	21.4%
Sub-Saharan Africa	35.1	21.1	88.7	144.9	15.6%	23.0%	25.4%	21.8%
World	550.9	77.7	403.3	1,031.9	16.9%	16.7%	15.5%	16.3%

7 Discussion

In this study, we developed predictive models for the value of forest non-wood ecosystem services using spatial data analyses and meta-regression and machine learning approaches for four distinct non-wood forest ecosystem services: recreation, hunting, and fishing; habitat and species protection; non-wood forest products; and water services. Thereafter, we conducted statistical model selections and developed localized estimates of the values of these four non-wood forest ecosystem services throughout the global forests, including nearly 1.2 million grid cells in a $0.1^\circ \times 0.1^\circ$ grid. Using local predictions, we summarized the value of forest ecosystem services by country and ecosystem service, globally. We produced estimates of combined value of recreation, hunting, and fishing; non-wood forest products; and water services to achieve alignment with the SEEA by using methods to estimate exchange values and accounting only for use values. Finally, we developed an operational method to measure the contribution of protected areas to the value of non-wood forest ecosystem services.

The global average marginal value per hectare in 2020 ranges between US\$6.8 (non-wood forest products) and US\$48 (recreation) per year, depending on the service (constant US dollars 2020). The average value of forest ecosystem services is in general higher in Europe, United States, the Republic of Korea, Japan, and Australia. However, there is wide variation across services. The average marginal value of protected forest can be larger or lower than non-protected forest, depending on the ecosystem service and the share of protected forest in the countries.

The current report extends the previous assessment in Siikamäki et al. (2021) in several ways: First, we updated the studies database by incorporating newly available studies. Siikamäki et al. (2015, 2021) reviewed 659 studies, from which 164 values were used in the meta-analysis. The current report includes 79 additional values on the basis of identifying and reviewing 768 new studies. That is, the estimation dataset increased 21.7 percent. The largest increase in percentage terms are in Asia (34 percent, 20 additional estimates), Africa (32 percent, 10 additional estimates), and Europe (19 percent, 28 additional estimates). This highlights the importance of updating the database to increase geographical coverage, mostly in regions where data was scarce. New estimates include 28 new estimates for recreation (20.1 percent of all the values for this service), 20 new estimates for habitat and species protections (20.6 percent), 17 new estimates for non-wood forest products (26.2 percent) and 14 new estimates for water services (31.1 percent). Updating the estimation dataset with new studies allowed to significantly increase the number of estimates by service, mostly for services for which the number of observations was low.

Second, we extended the meta-regression and machine learning analyses in Siikamäki et al. (2021) by applying new machine learning algorithms (BART) to estimating the value of non-wood forest ecosystem services.

Third, the revised approach here extends the previous assessment by updating GIS databases and adding one more variable (the STAR metric) as potential predictors of the value of non-wood

forest ecosystem services. We expect that updated GIS datasets did not change estimation results significantly. We checked this by running the regression results in Siikamäki et al. (2021) using the new GIS data as explanatory variables. However, new data also has implications on the definition of accessible forest, which can have implications on the global predictions.

Fourth, we developed an operational method for estimating how protected area forests contribute to the economic value of ecosystem services. We allocate total value of protected areas for recreation, non-wood forest products, and water services, combining our results with the World Database on Protected Areas (UNEP-WCMC and IUCN 2022), which can be applied globally. Estimates show that, in 2020, protected area forests globally contributed 16 percent of the total value of recreation, hunting, and fishing; non-wood forest products; and water services.

Beyond supporting the development of estimates for CWON associated with forests, the results produced in this study on the value of forest ecosystem services, predicted locally at a global level, can support project design and evaluation, land use planning, and conservation assessments by the World Bank and other international agencies, as well as any similar assessments by government and nongovernment organizations around the world. So far, ecosystem service assessments typically rely on either globally or regionally uniform or near uniform value estimates or, alternatively, develop more customized estimates from the current literature. The advantage of the new estimates is that they draw information from all forest

valuation literature and develop estimates that are locally relevant, but globally consistent. As such, we view the estimates developed in this assessment as benchmark data that help with broad scale assessments, but can, and often should, be further refined using localized studies for evaluations of specific services in specific locations.

As with any meta-analysis, this assessment depends on the current literature, including the quality of studies and the coverage of the literature geographically and by ecosystem service. Moving forward, it would be important to increase the geographical coverage by conducting valuation studies in places that are not covered in the current literature, considering both the socioeconomic and biophysical aspects of forests. This could involve a concerted effort to conduct valuation studies for specific ecosystem services around the world, in locations strategically selected to develop data for meta-analytic assessments and using comparable methods aligned with the SEEA. Another possibility may be to augment existing data collection efforts to generate data to support assessment of forest non-wood ecosystem services. For example, the World Bank has developed a unique global database of more than 1,500 household surveys, which provides the foundation for a first-of-its-kind global implementation of a lifetime earnings approach to measure human capital. Using such data collection efforts could be considered to develop data to support the estimation of the non-wood ecosystem services supported by forests, including by collecting data on the amount and types of non-wood forest product collected by households. In addition, it would be important to improve the

measurement of protected areas over time. Current datasets by UNEP-WCMC and IUCN (2022) are the most comprehensive, publicly available dataset on protected areas globally. However, they do not track the creation of new protected areas over time.

In addition, this report relies heavily on spatial data that could be enhanced by building partnerships

with global initiatives on spatial data. For example, annual data could be generated on several potentially relevant determinants of the value of non-wood forest ecosystem services, such as the extent of road networks, that are currently available only in snapshots and not as time series required to empirically identify their relationships to the value of forest ecosystem services.

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Appendix 1

Update the metadata analysis by incorporating newly available studies

A1.1 IDENTIFYING POTENTIALLY RELEVANT STUDIES TO UPDATE THE PREVIOUS DATABASE

The first task in the revision was to summarize currently available literature on non-wood ecosystem service valuation. To identify relevant literature, we conducted systematic literature searches to find studies potentially relevant to our assessment. A first wave of the review was conducted in 2015 by Siikamäki et al. (2015). An update of the literature review was conducted in 2019, looking for studies conducted from 2015 to 2019. In both stages we followed the same criteria:

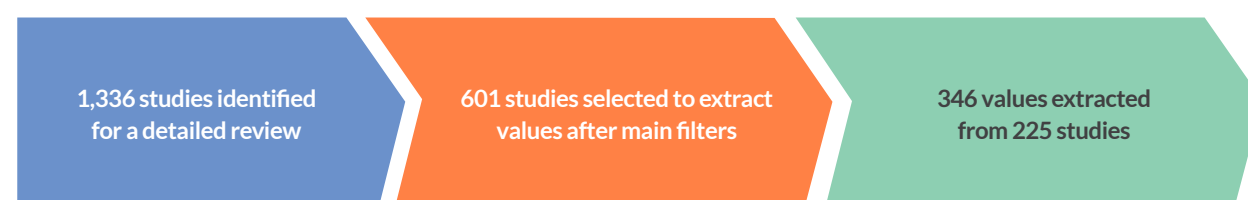
- Focus on non-wood ecosystem service valuation of forests.
- Provide primary estimates of non-wood forest values (as opposed to direct benefit transfer values based on generalizations of primary studies).
- Potentially enable estimation of values expressed in per-unit-area estimates (such as \$/ha).

The above criteria were purposefully general so that the first stage of the literature search was unlikely to exclude any potentially relevant studies. As a consequence, we identified many studies that were not applicable for the database. We detected such studies by conducting detailed reviews of each study initially identified, as explained below.

During the literature review update we mainly focused on four non-wood forest ecosystem services analyzed by Siikamäki et al. (2015): recreation, hunting, and fishing; non-wood forest products; water services; and habitat and species protection. In addition, we paid special attention to the potential to extend the analysis in previous reports to additional non-wood ecosystem services of forests, such as pollination, or disaggregation of services bundled in the water services category.

We used multiple sources to help find potentially relevant literature. We began by searching through two general ecosystem valuation literature databases: (1) The Economics of Ecosystems and Biodiversity (TEEB) and (2) the Environmental Valuation Reference Inventory (EVRI). Both databases are publicly available and comprise searchable collections of academic

FIGURE A1.1: STUDIES FOUND IN THE DIFFERENT STAGES OF THE SEARCH AND NUMBER OF VALUES EXTRACTED



and non-academic literature on environmental and ecosystem valuation studies. They include information on all ecosystems, not just forests. While EVRI is continuously updated, the TEEB database does not include studies after 2014.

In addition, we conducted a systematic search in the Research Papers in Economics (RePEc), a general economics database, for studies published after 2015. RePEc is a repository that allows not only the scanning of main journals in environmental economics, but also other journals less traditionally used by economists, such as *Ecosystem Services*, or *Sustainability*, as well as working papers and conferences' proceedings. The search was complemented by a specific search in multidisciplinary journals, like *Nature* (and all the journals in the *Nature* collection), *Science* (and all the journals in the *Science* collection), Proceedings of the National Academy of Sciences (*PNAS*), and *PLOS ONE*. The inclusion of these journals in particular is relevant for studies after 2015, given that ecosystem services' valuation publications are incipient in these type of journals before 2015.

Furthermore, we reviewed the studies cited in previous literature reviews and meta-analyses of ecosystem service valuation literature to help find any forest-related studies not yet included in our database.⁷ In addition, we conducted systematic searches using literature databases such as Google Scholar, EconLit, and Environment Complete, as well as RFF Library Resources and Journal databases. We added all potentially relevant studies not yet included in the database. Finally, we used a "snowballing" technique while conducting detailed reviews of studies already identified. We checked through the references of each study and added possibly relevant studies into our database if not

already included. We found this method highly effective in supplementing other searches.

We focused mostly on literature published in English. However, we also identified, reviewed, and included some studies in other languages, within the language skill limits of our study team, including Danish, French, German, Norwegian, Portuguese, Spanish, and Swedish. The review included mainly studies in English, but we also found studies in other languages. We included studies in English, Spanish, and French. In addition, we found three papers in Russian, Polish, and Ukrainian (Малашевич and Санкович 2012; Budziński 2015; Openko et al. 2016). A translation of the abstract of the studies conducted by Малашевич and Санкович (2012) and Openko, Shevchenko, and Tsvyah (2016) indicated these studies are focused on timber production, and therefore not relevant for the current review. An overview of the article by Budziński (2015) shows that the dataset used is the same one used by the author in papers published in journals in English, and hence was treated as a duplicated study.

Academic peer-reviewed literature, our key focus in the literature searches, offers relatively narrow representation of geographic regions and ecosystem services. Therefore, we also searched for and included any available grey literature (reports, books, theses, other non-journal publications), provided the studies were deemed relevant and methodologically sound.

Using the literature searches explained above, we identified 601 studies for more detailed reviews (Figure A1.1). However, we were unable to obtain 26 studies, despite efforts to locate them online, using interlibrary loan or direct purchase, and, in some cases, direct contact with the study authors.

7 These studies include (Ojea et al. 2016); (Barrio and Loureiro 2010); (Brander et al. 2006); (Chiabai et al. 2010); (Kuik et al. 2009); (Lindhjem 2007); (Shrestha and Loomis 2001); (Zandersen and Tol 2009); and (Zandersen and Tol 2009).

The studies we were unable to access were often grey literature and/or published a long time ago. They are listed in Appendix 2 along with all other studies included in the assessment. By and large, we were able to obtain any essential and relatively recent publications, especially those published in peer-reviewed academic journals.

A1.2 STUDY REVIEW PROTOCOL

After identifying and obtaining potentially relevant studies, we systematically reviewed them to develop a value database. When reviewing and summarizing each study, we conducted multiple rounds of reviews. In the first round, we extracted a range of relevant information to characterize the study and value estimates in it, including:

- Source used to identify the study.
- Study area ecological characteristics (biome, forest type, inland/coastal, other landscapes).
- Study location (country, country income group, protection status, study site area, scale of research, region continent and coordinates).
- Ecosystem service(s) addresses as well as classification as domestic/foreign value of service and as direct, indirect and non-use.
- Ecosystem service value information (year of value, valuation method, valuation type reported value, units, value currency).
- Other study variables (type of publication, publication year, and sample size, if applicable).

Our end goal in this study is to develop estimates of the value of forest ecosystem services on a per hectare basis. Therefore, a key task in the first review was to determine whether the study reports value estimates

on a per unit area basis (per hectare, per acre, per km², and so forth) or includes other information with which we would be able to derive such estimates. If any potentially relevant value estimates were found from the study, we recorded them in the database. After the first review, we identified 601 studies that could potentially feed into the dataset.

We use a value estimate as the unit of observation. However, we did not record every possible value estimate from each study, especially because journal articles often report many estimates addressing the same forest but derived under slightly different assumptions. In those situations, we determined a preferred or representative estimate, or averaged the listed estimates, if no preferred estimate could be identified. If the methodologies underpinning the different estimates were completely different (for example, travel cost methods and contingent valuation), we recorded multiple estimates instead of choosing a preferred estimate or taking an average. The final database contains 346 observations regarding values from 225 studies (Figure A1.1).

We included multiple records for studies that report value estimates for different services and/or target areas. For such studies, the study area characteristics may also vary by value estimate. To address such situations, we also recorded the location (latitude, longitude) of each value estimate. If a study shows multiple values that can be of interest to be recorded, but we can only identify one geographical location for the study (for example, has separate values for conservation of primary and secondary forest within the same park), we aggregated the values and included only one record in the dataset.

Many studies lack information necessary to develop value estimates on a per unit area basis. In such situations, we turned to external sources to search

for supplemental data. Typically, these efforts included retrieving data on variables such as study area size (when not mentioned in the study), study area location (coordinates), number of households or population addressed by value estimate (in order to calculate aggregate values), and ecological characteristics of study area (type of forest, biome).

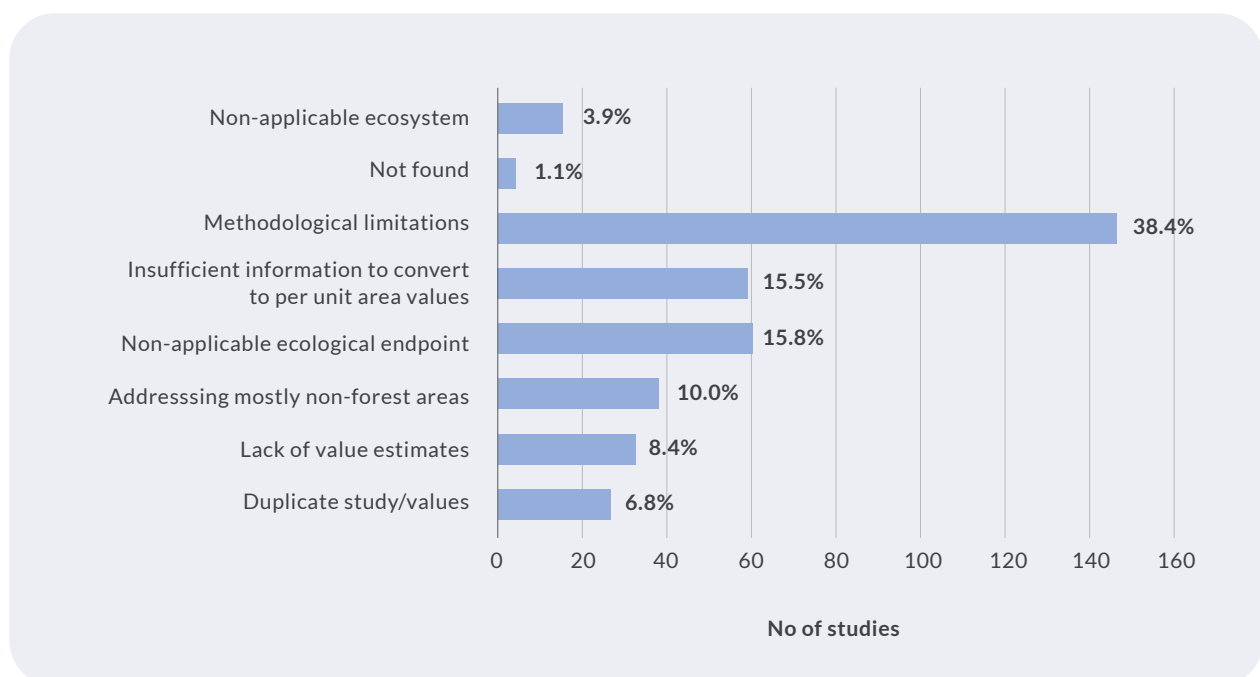
We used mostly online searches to find external data. However, we also used other approaches when online sources failed to provide the information needed. For example, in one case we contacted state park officials in Washington State (United States) to find out which state park areas permit the collection of non-wood forest products such as berries and mushrooms. Using a hard copy map mailed to us, we estimated the forest area applicable to a value estimate found in a study. In other cases, we contacted 23 study authors to request additional information. In many cases, the studies were conducted in small locations where the total number of households were not available online, or the total study area was not explicit, preventing us

from computing a value per hectare. By contacting the study authors directly, and with their help, we avoided excluding several studies.

A1.3 DETERMINING THE APPLICABILITY OF VALUE ESTIMATES FOR THIS ASSESSMENT

Many of the studies originally identified in the literature search are not applicable for this assessment. We recorded the primary reason for exclusion for each excluded study (Figure A1.2). In total, we excluded 376 studies (62 percent) out of the 601 studies originally identified to be potentially included in the analysis. The leading reason for exclusion was studies including methodological limitations. We reviewed the methodological approach taken by each study to ensure that values included in the database are derived using conceptually defensible approaches. When we identified methodological approaches inconsistent with the principles of ecosystem service valuation,

FIGURE A1.2: PRIMARY REASON FOR THE EXCLUSION OF STUDIES



we excluded the study. This criterion applied to 146 studies (38 percent of all excluded studies). When examining the methodological approach applied in each study, we primarily considered the suitability of the basic conceptual framework for the valuation of forest ecosystem services, not our subjective evaluation of the quality of the assessment. For example, certain methodological approaches, such as the travel cost or stated preference methods, are applicable to the valuation of specific services (such as recreation, habitat/species protection). Therefore, we included all studies that applied such methods using appropriate data and samples to develop findings usable for this study.

As an example of methodological considerations, when the study used survey-based approaches, we reviewed the survey methodology to evaluate its sample representativeness (for example, households in a region or recreational users of a forest area) and general suitability to generate a representative estimate of the value estimated. When sample representativeness was clearly not achieved, due to, for example, convenience sampling (for example, surveying park visitors or members of environmental organizations and then directly generalizing the results to the general population), we excluded the study. Another illustrative and relatively frequent case of methodological limitations includes studies to estimate local economic impacts of forests, such as employment associated with recreation activities or magnitude of expenditures by visitors to a park. These estimates can be informative, but generally do not represent conceptually accurate measures of the economic value of ecosystem services. Therefore, we excluded them from the database. Other examples of studies excluded because of this reason were those that asked farmers about willingness to accept payments for conservation, the analysis of the opportunity cost of non-forest land use to convert land to forest (not estimating the

benefits from forests, but the opportunity cost of an alternative activity), or stated-preferences method studies with poorly described scenarios.

This category also includes other specific cases. For example, a few value estimates in the database address global areas (such as all global tropical forests). Some other values concern large and discontinuous forest areas. When it was not possible to accurately determine the location of the study area, we excluded the corresponding value from the statistical analysis because no local spatial data could be developed for such estimates.

The second most prevalent reason for exclusion includes valuation studies for which there were not sufficient information to convert to per unit area values (59 studies), and those focused on non-applicable ecological endpoint (60 studies), each of them representing 15 percent of the total number of excluded studies. We excluded studies for which we were unable to develop value estimates on a per hectare basis, even after sometimes extensive efforts to draw from external data to complement data provided in the study.

In addition, we excluded studies that address values for ecological endpoints outside the scope of this assessment (non-wood benefits), such as timber or wood fuel or carbon sequestration. Non-applicable ecological endpoints also include studies that estimate aggregate wood and non-wood benefits without sufficient information to help separate out the non-wood portion of the benefits. Similarly, if the study explicitly addressed carbon and non-carbon value without separating them from one another, we excluded the estimate.

Initial summaries of the value database, in combination with insights gathered throughout the detailed study reviews, suggested that several types of ecosystem service valuation studies, such as those

addressing recreation, hunting, fishing, non-wood forest products, or habitat and species protection, are exceedingly comparable in objectives, methods, settings, and value estimates. However, some other ecosystem service valuation studies, especially those addressing seldom studied endpoints such as nutrient recycling or bioprospecting, entail so many idiosyncrasies in objectives, methods, data, and estimates that meaningful comparisons across different studies are difficult. In addition, there are only a few value estimates in these categories so statistical analyses are not meaningful. The case is similar for the pollination services and natural related (non-hydrological) disasters control. Therefore, we exclude from the meta-regression all value estimates addressing nutrient cycling, bioprospecting, pollination, and non-hydrological natural related disasters control. These studies are included in the category ecological endpoints outside the scope of this assessment (non-wood benefits).

Additionally, this category includes some non-wood forest product value estimates partly comprising fuel wood values. Initially, we included those estimates in the database and considered using statistical controls in the meta-regression to help isolate the non-wood portion of the value estimate. However, statistical controls may help only partially disentangle non-wood and wood values. Because wood fuel is out of scope for this assessment, we dropped from the meta-analysis all non-wood forest product value estimates with a potential wood component.

Our original literature database has studies that address mostly a non-forest ecosystem, such as savannah or agricultural landscape mosaics. We excluded such studies as not representative of forests in general. This excluded 38 studies (10 percent of all studies excluded).

The group of studies excluded because of “lack of value estimates” includes studies that initially were identified as potential studies but neither provided value estimates nor contained information to help us develop them. Examples of such studies include mostly theoretical journal articles, which do not develop empirical estimates, or studies conducting descriptive or qualitative analysis. This criterion applied to 32 studies (8.4 percent of all the excluded studies).

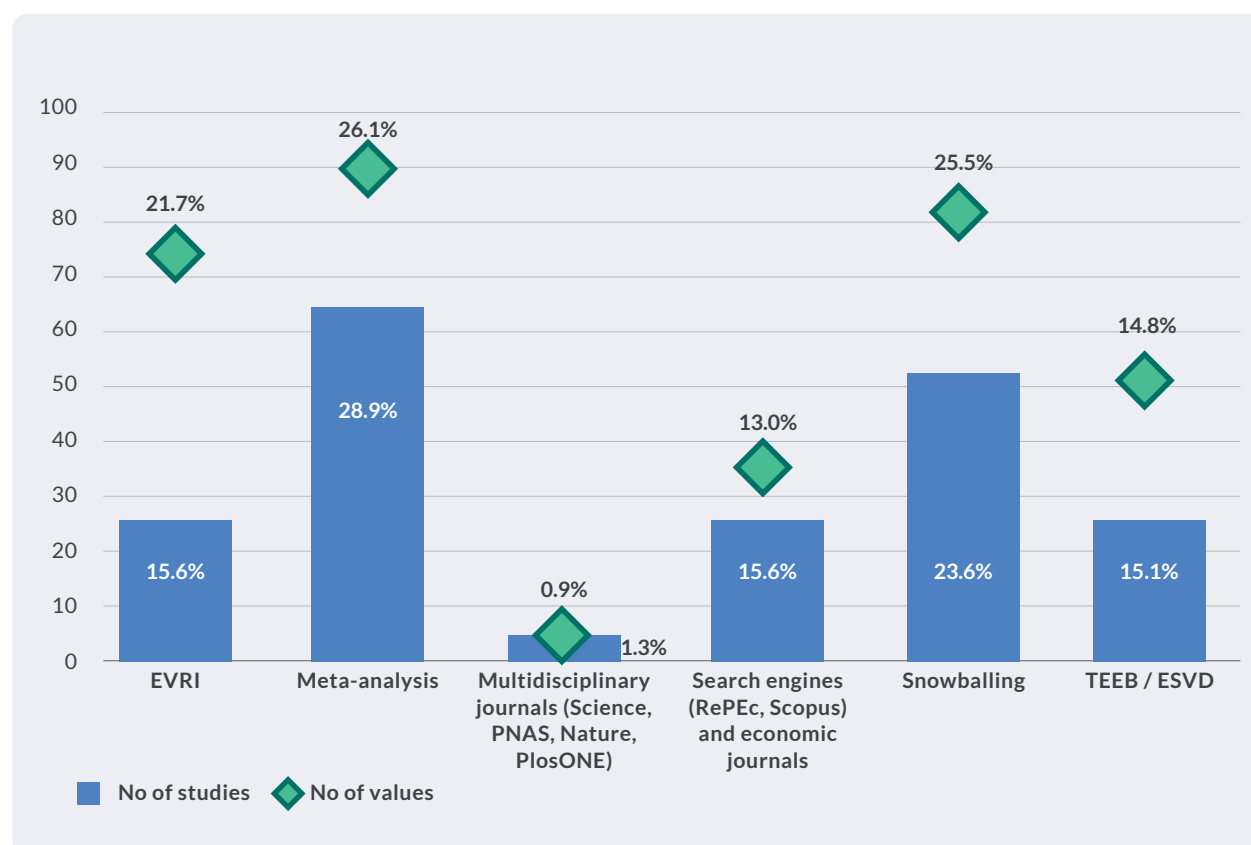
Finally, we also excluded studies that show duplicates of value estimates or studies already included in the database. This criterion applies to 32 studies, representing 7 percent of all recorded reasons for exclusions. When identifying duplicate studies, we did not only consider literal replicate studies (a discussion paper version of a later journal article). We also identified studies that use the same data to estimate essentially the same environmental values, with slight methodological differences between different the publications. This is not unusual; often, studies that focus on making distinct methodological contributions are accompanied by other publications that focus on the general findings and/or provide estimates to support policy assessments. When we identified such studies, we included the version that in our view was most applicable for the purposes of this study and excluded other publications representing the same study/data. Another relatively common occurrence involves graduate dissertations, which may be identified in our initial database both as a thesis and a later academic journal publication. In those cases, we generally included estimates from the peer-reviewed journal publications and excluded the thesis.

Figure A1.3 summarizes the number of studies and value estimates in the database by the source we originally used to find the study. In total, the value

database includes 346 value estimates developed from 225 studies. Among different sources, previous literature reviews and meta-analyses are most frequent. They account for 65 studies (29 percent of all studies) and 90 value estimates (26 percent of all value estimates). Snowballing—searching the reference lists of studies already reviewed—is the second most frequent method to find relevant studies. Although we used snowballing as the final method to supplement an already sizable literature database, snowballing produced 53 studies (24

percent of all) and 81 new value estimates (24 percent) into the database. EVRI and TEEB/ESVD helped identify 35 (15.6 percent) and 34 (15 percent) of the studies and 75 (21.7 percent) and 51 (15 percent) of the value estimates, respectively. Search engines, such as RePEc, Scopus, or specific environmental economics journals, worked as a good complement, adding 35 (15.6 percent) studies and 45 (13 percent) values to the database. Many of the studies found in RePEc were already found in EVRI, and because of that, are here only recorded in the EVRI database.

FIGURE A1.3: N° OF STUDIES AND VALUES PER DATA SOURCE INCLUDED IN THE FINAL DATABASE



Note: Only one data source by study and value is recorded, showing the first data source in which a study appears. A study can show up in more than one data source.

A1.4 VALUE ESTIMATES BY ECOSYSTEM SERVICES AND ESTIMATION METHOD

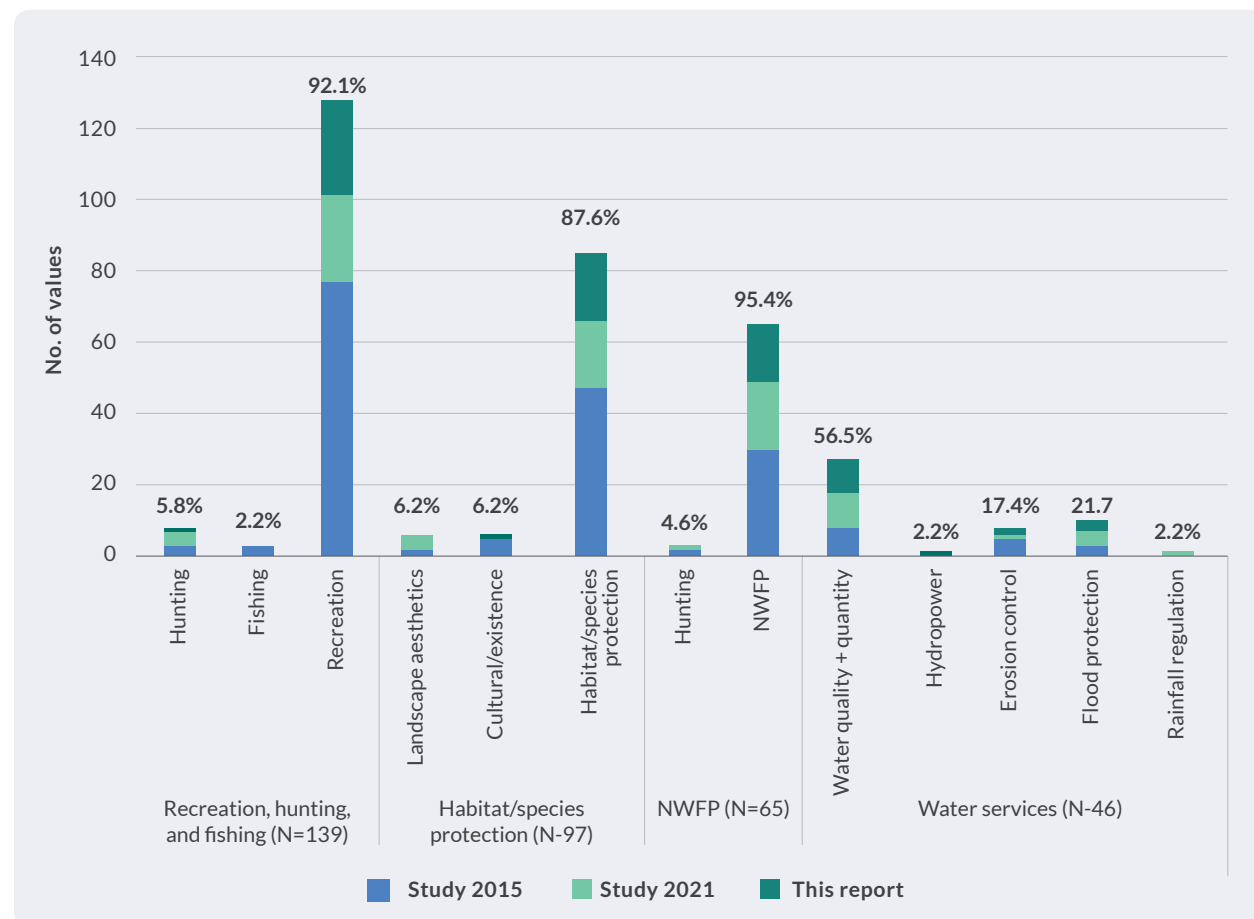
When recording the type of ecosystem service, we initially used a fine-grained classification, including cultural/existence value; erosion control; fishing; flood protection; habitat/species protection; hunting; landscape aesthetics; non-wood forest products; recreation; and various types of water-related services such as water quality or water quantity. We later aggregate these classifications into fewer but still meaningful aggregate categories, to help structure the empirical analysis with categories of non-wood forest ecosystem services that allow a significant

number of observations per service. The ecosystem services were aggregated into four main categories representative of the literature:

- Recreation, hunting, and fishing (denoted as “recreation” in most of this report)
- Habitat/species protection
- Non-wood forest products
- Water services.

Figure A1.4 shows the number of values per ecosystem service category and sub-category found during the three rounds of literature review. Recreation includes value estimates addressing recreation, hunting, and fishing.

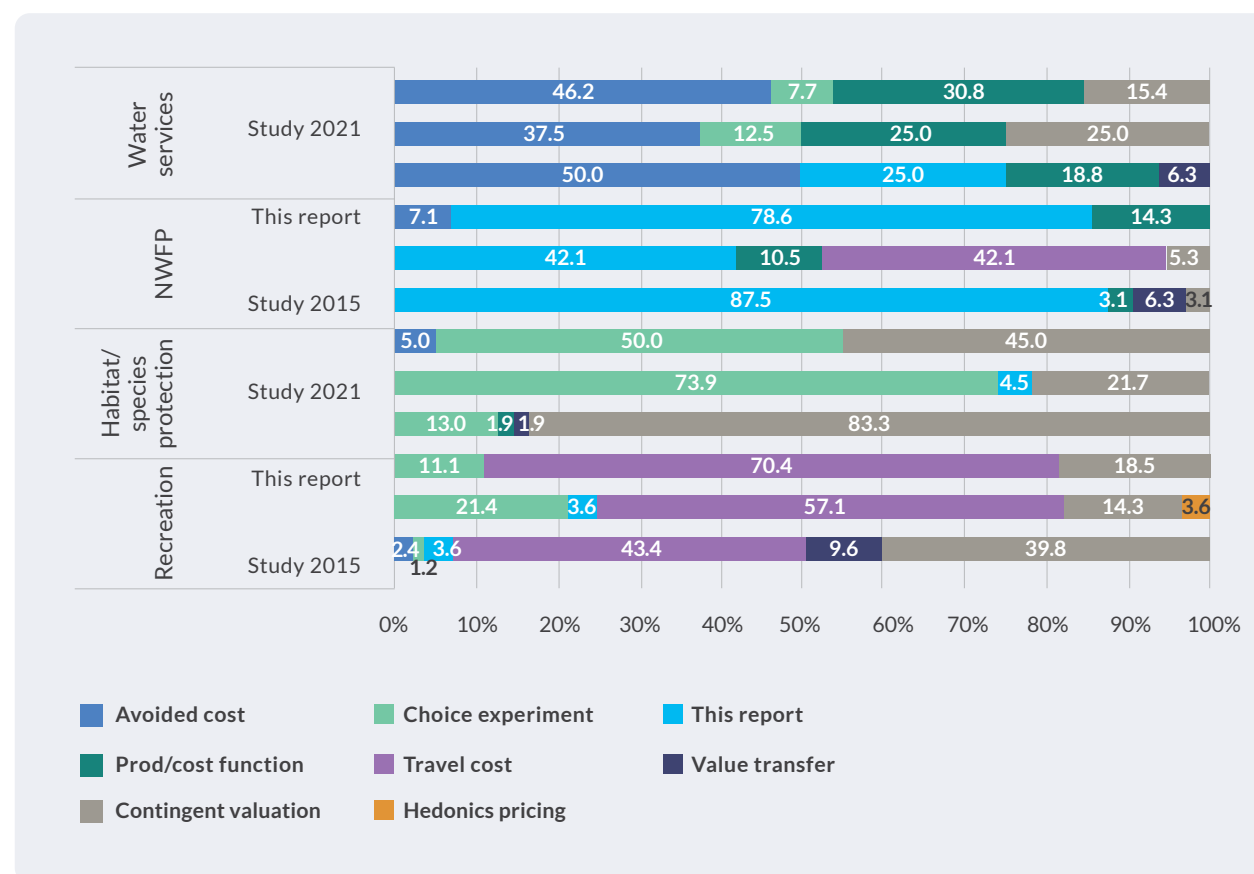
FIGURE A1.4: N° OF VALUES BY ECOSYSTEM SERVICES IN THE OLD REPORT AND THE NEW SEARCH



The estimation dataset includes 139 recreation-related value estimates. The literature review update increased by 27 percent the number of studies related to recreational values, and by almost 14 percent the number of studies regarding hunting activities. Value estimates regarding fishing recreational activities remained the same. Habitat/species protection includes values classified as habitat/species protection, cultural/existence values, or landscape aesthetics. There are 97 value estimates in this category in the estimation dataset. The literature survey update increased the number of value estimates regarding purely habitat and species protection by 298 percent, and the number of value estimates regarding cultural and existence by 20 percent.

Values addressing non-wood forest products include 65 estimates in the estimation dataset. The number of studies regarding non-wood forest products increased by 33 percent after the literature review, and the number of studies regarding hunting for subsistence increased by 50 percent. This is a significant increase given the small number of studies in this area found during the first two reports in 2015 and 2021. Values classified as “water services” come from studies that address benefits from forests on water quality/water quantity, often in the context of controlling water flow and pollution from erosion and other sources, enabling hydropower, avoiding disasters, or the impact on crop yields by controlling weather.

FIGURE A1.5: VALUATION METHOD BY ECOSYSTEM SERVICE AND REPORT (% PER REPORT AND SERVICE)



There are 46 value estimates for water services in the estimation dataset, having the number of value estimates increase 50 percent since the previous review. As in the case of non-wood forest products, this is a significant increase given the small number of studies found during the first two reports in 2015 and 2021.

Figure A1.5 shows the valuation methods used by the studies review per ecosystem service and wave of literature review. The valuation methods mostly used for habitat/species conservation are stated preferences methods, like choice experiments and the contingent valuation method. However, there is an increase in the percentage of studies using choice experiments in the new review. We can see the same phenomena regarding recreation and water services. This is in line with the increasing popularity of this method given its ability to disentangle the value of specific attributes of an environmental good or service.

Differences between the valuation studies in the above four categories are so substantial that their further aggregation is not justified. Moreover, the number of studies in each of the above four categories enables separate statistical assessments, in particular for recreation and habitat/species protection, which have 139 and 97 value estimates respectively. The number of value estimates for NWFPs (65) and water services (45) is more limited but, regardless, enables further analyses as a separate benefit category.

A1.5 GEOGRAPHICAL DISTRIBUTION OF VALUES BY ECOSYSTEM SERVICE

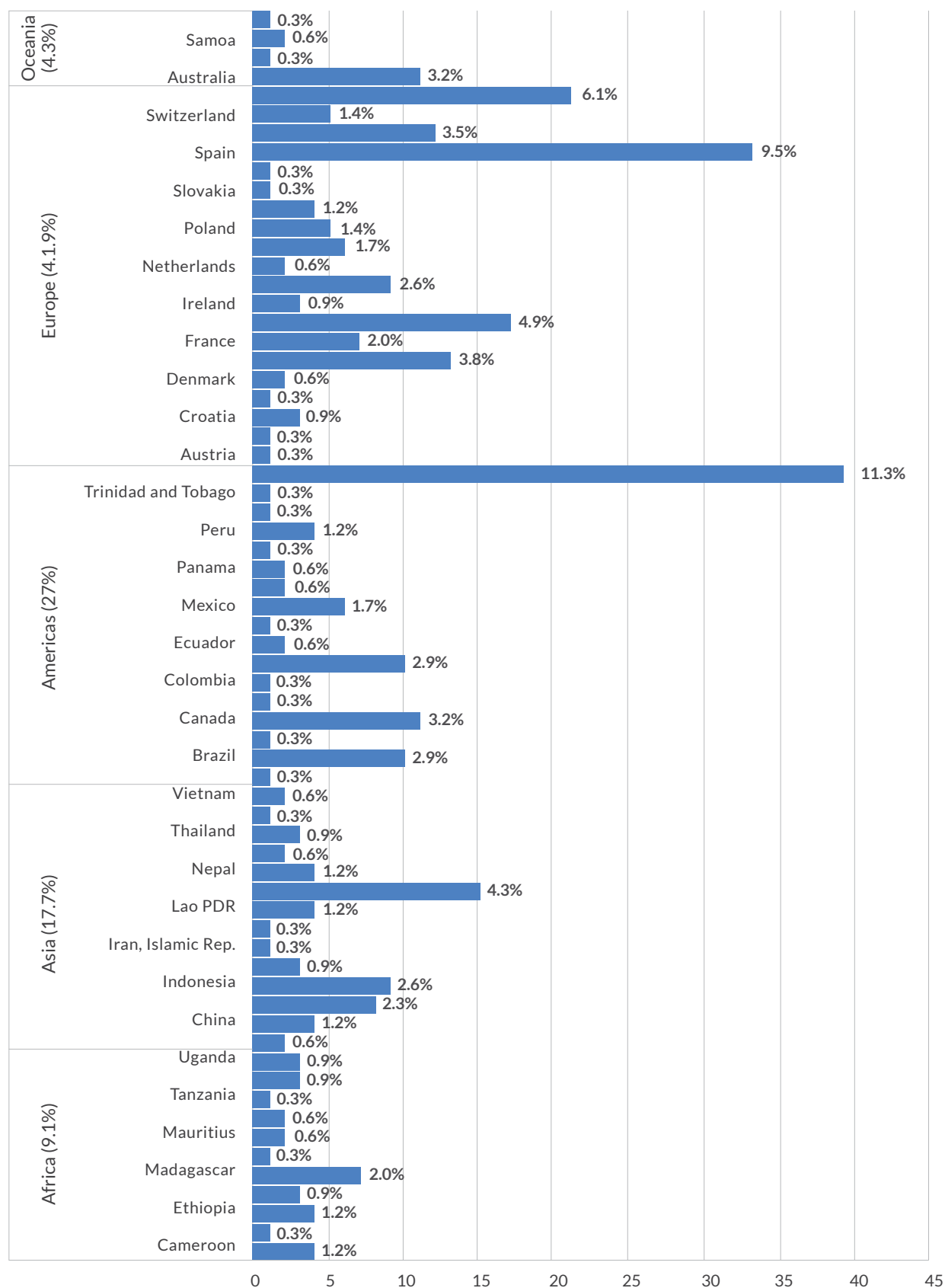
Figure AI.6 shows the geographical distribution of the values on forest ecosystems by country and continent. Figure AI.7 shows a map of the value sites

in previous report and the new data. The greatest number of value estimates comes from Europe, which has a total of 147 estimates (42 percent of all value estimates in the dataset). Within Europe, Spain is the country with more value estimates (33 value estimates, 9.5 percent of all value estimates), followed by the United Kingdom (21 estimates, 6.1 percent) and Germany (17 estimates, 5 percent). This indicates a broad representation of every sub-region within Europe.

The Americas have the second highest number of estimates in the dataset, including 94 estimates or 27 percent of the global total. Within America, 39 estimates belong to the United States, 11 to Canada, 10 to Costa Rica, and 6 to Mexico, showing a dominance of North and Central America within the continent. South America has 21 value estimates, of which 11 are conducted in Brazil.

Asia is the continent with the third highest number of value estimates. It has a total of 59 estimates (17 percent of the global total). Within Asia, Malaysia shows higher frequency in the number of study values (15 value estimates, 4.3 percent of the global total), followed by Indonesia (9 estimates, 2.6 percent), and India (8 estimates, 2.3 percent). This indicates a dominance of South-East and South Asia within the value estimates in the continent. However, there are studies from Iran, China, and Israel, showing a broad coverage of the continent.

The continents with the least number of value estimates are Africa (31 estimates, 9 percent of the global dataset) and Oceania (15 estimates, 4.3 percent). Within Africa, the majority of the value estimates address Eastern Africa, mostly from Madagascar (7 value estimates), Ethiopia (4), and Uganda (3). In Middle Africa, Cameroon has 4 estimates; in Southern Africa, South Africa has 2 value estimates; and Western Africa has none.

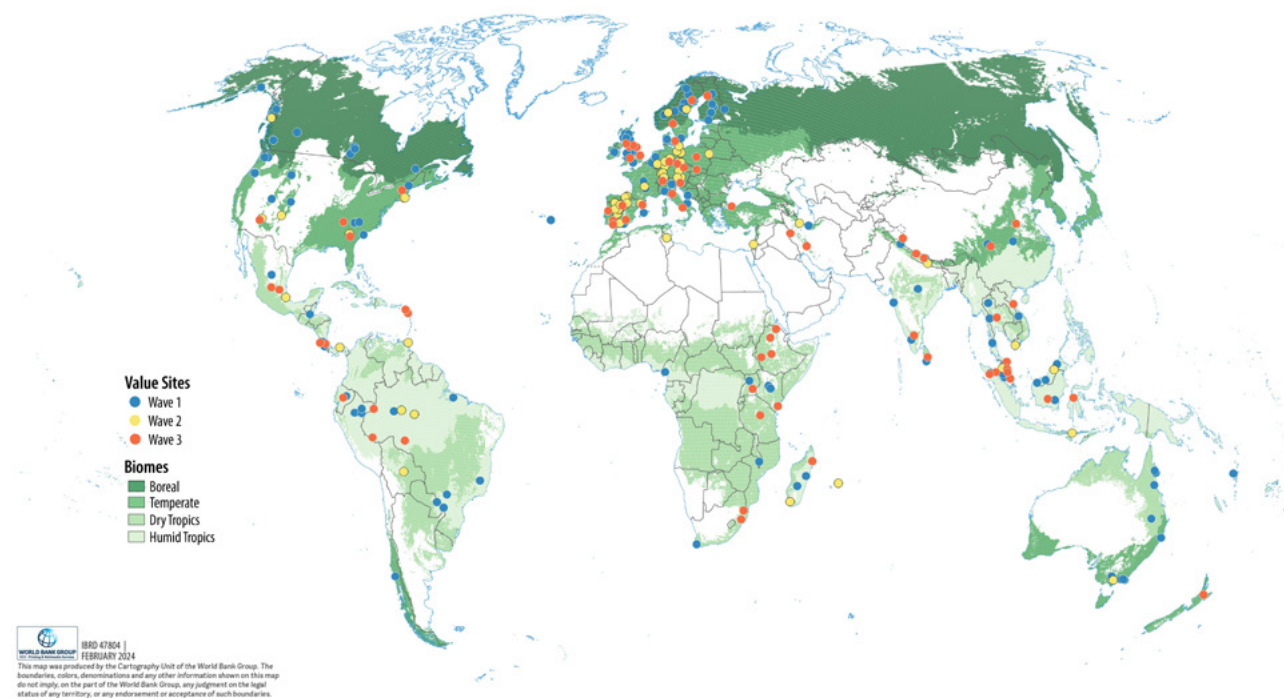
FIGURE A1.6: N° OF STUDIES PER COUNTRY AND CONTINENT

Within Oceania, most value estimates come from Australia (11 estimates, 73 percent of all estimates in Oceania); the rest are from Samoa (2 estimates; 13 percent), New Zealand, and Vanuatu (1 estimate each).

Figure A1.7 shows the geographical distribution of the studies by ecosystem service by report (wave 1 for the 2015 study, wave 2 for the 2021 study, and wave 3 for this study). Most of the studies valuing habitat and species protection and recreation

services are located in Europe. However, there are many value sites reviewed during the third wave in regions that were not covered before. We found 10 additional values in Africa, increasing the number of values from that continent by 33 percent, and 20 additional values in Asia, increasing the number of values to 34 percent. In total, the new review added 75 values to the database, increasing the number of values since the previous review by 21.7 percent.

FIGURE A1.7: MAP OF VALUE SITES BY REPORT (WAVE 1 IN 2015, WAVE 2 IN 2021, AND WAVE 3 IN THIS STUDY)



Source: Constructed by the authors based on the database constructed from primary valuation literature, forest biomes from Global Forest Watch, and country boundaries from the World Bank data bank.

FIGURE A1.8: MAP OF STUDIES LOCATION BY ECOSYSTEM SERVICE AND BY REPORT (WAVE 1 IN 2015, WAVE 2 IN 2021, AND WAVE 3 IN THIS STUDY)

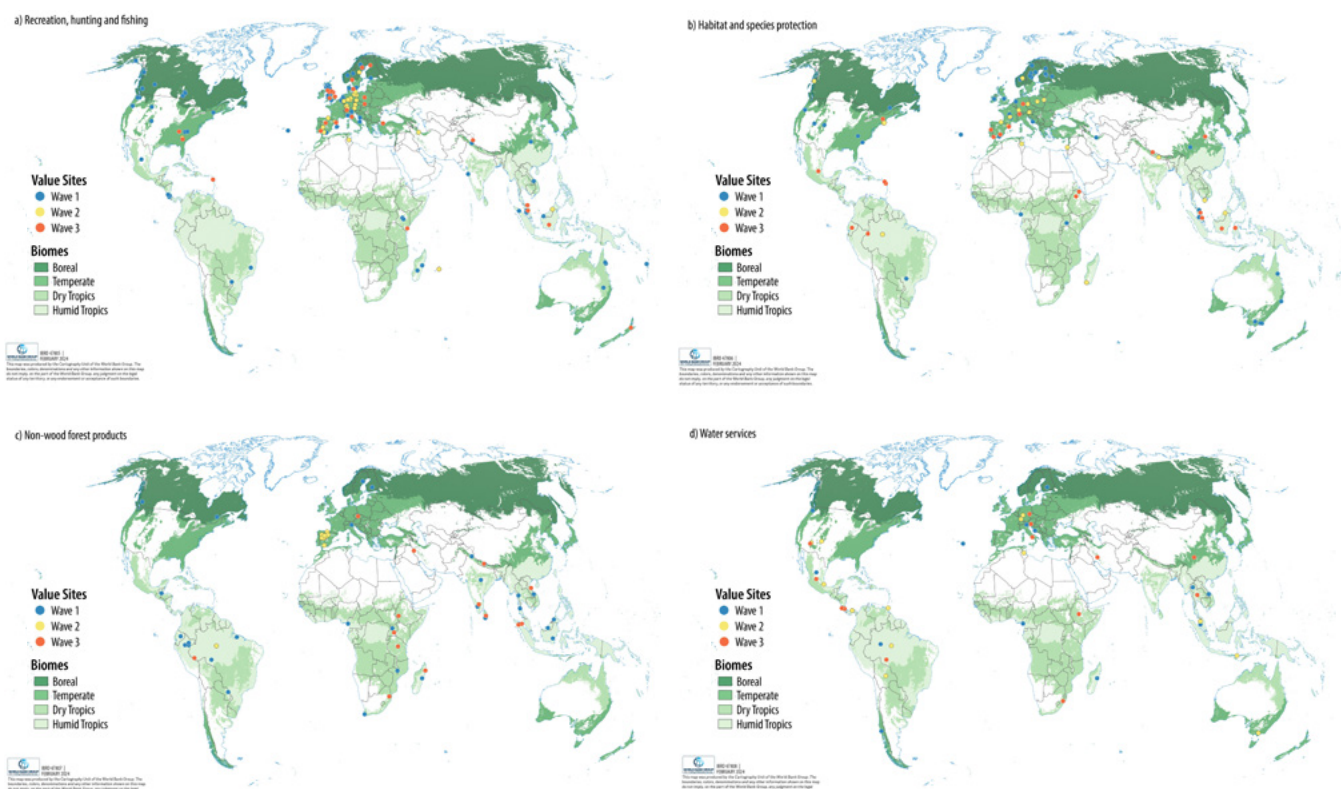
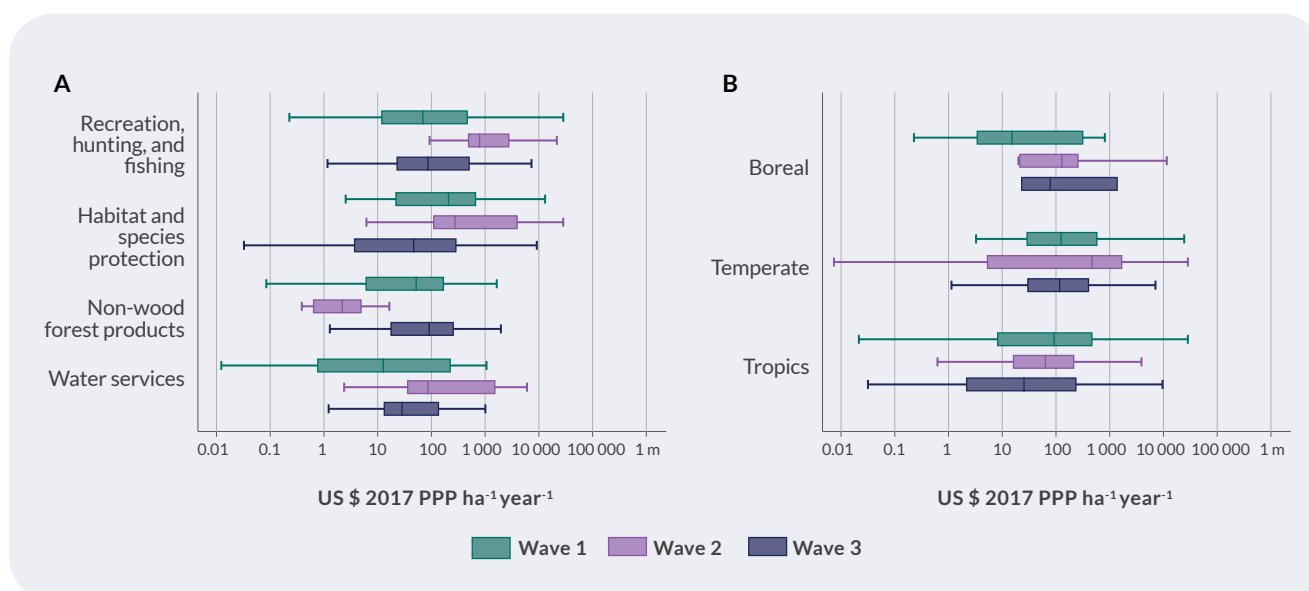
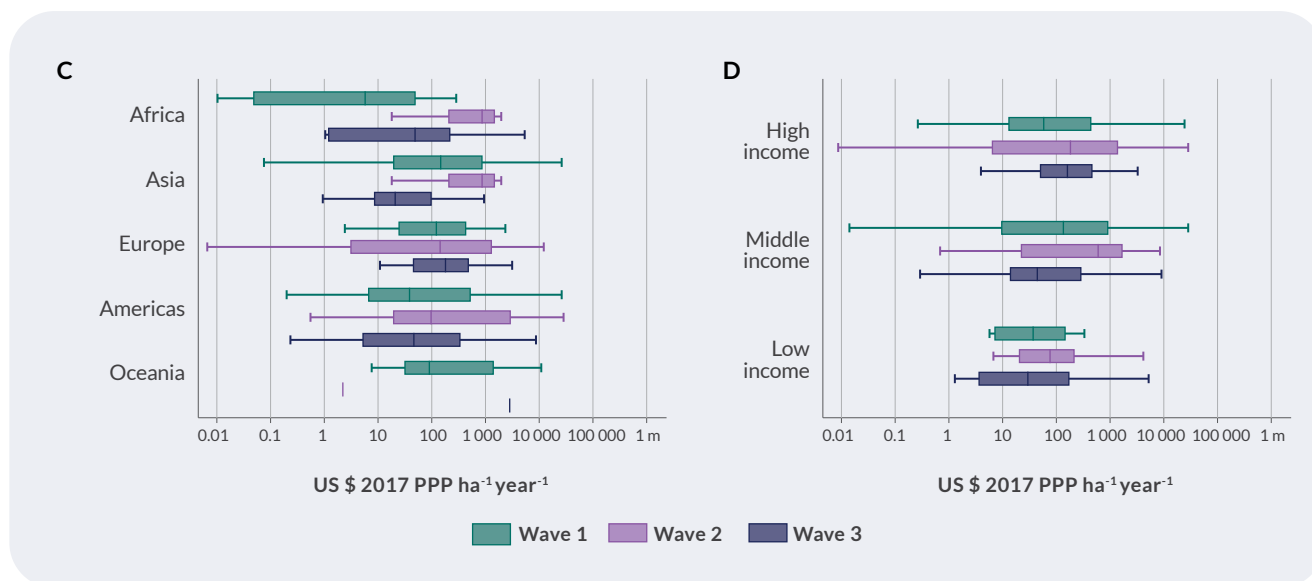


FIGURE A1.9: VALUE ESTIMATES BY REPORT (WAVE 1 IN 2015, WAVE 2 IN 2021, AND WAVE 3 IN THIS STUDY): BY ECOSYSTEM SERVICE (A), BIOME (B), CONTINENT (C), AND INCOME GROUP (D)





A1.6 SUMMARY OF VALUE ESTIMATES

Figure A1.9 shows the value estimates in the reports in 2015 (wave 1) and 2021 (wave 2) previous report and the new search (wave 3) using box-whisker plots by ecosystem service, biome, continent, and country income group (PPP US dollars 2017).⁸ PPP-adjusted exchange rates make estimates from different countries comparable as economic values. In the figures, the ends of “whiskers” denote the minimum and maximum of estimates; the box in the middle ranges from the 25th to 75th percentile of the estimates, and the line within the box shows the median.

The range of values is high, both within and between different ecosystem services (Figure A1.9, top-left). There is large overlap between the values of the different ecosystem services in the previous report

and in the new search. However, the median value in the new search is slightly higher for every ecosystem service except for NTFP. Differences in the median values by biome between the new search and the previous report are only significant for boreal forest (Figure A1.9, top-right). There is only one new study in the boreal forest, and its value overlapped with the box of the values for the original report.

When looking at the values by continent (Figure A1.9, bottom-left), we can see that the median values for America and Africa are higher in the new search than in the previous report. In addition, the distribution of the values per continent are highly overlapped between the original report and the new search. When classifying the values by the income classification by the World Bank (Figure A1.9, bottom-right), the distribution of values is highly overlapped between the original report and the new search.

8 To convert current local currency units (LCU) to constant PPP USD 2013, we first computed values in LCU 2013 constant prices using the GDP deflator. Then, the values were converted into purchasing power parity (PPP) US dollars 2013 using the PPP-conversion factor (LCU per international \$). When the values in the study were not in LCU, they were first converted to LCU using the exchange rate of the currency year. GDP deflator, PPP conversion rates, and exchange rates were extracted from the World Development Indicators database from the World Bank.

Appendix 2

List of studies (included and excluded)

A2.1 LIST OF STUDIES INCLUDED IN THE META-ANALYSIS

Recreation

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Appendix 3

Study review quality control/quality assurance protocol

We implemented several steps of quality assurance/quality control to help develop robust and consistent summaries of studies included in the database. One of the primary quality assurance protocols involved a duplicate review of each study by another reviewer. The second reviewer evaluated and confirmed information developed and recorded in the first review. When discrepancies appeared, they were resolved in a discussion among the team and the principal investigator (PI) Siikamäki.

In addition, each reviewer noted any missing details or questions relevant in the context of each study. The reviewers also recorded the method to develop each value estimate, including details on any calculations and external data required.

During the first wave of reviews in 2015, the group of researchers developing the database (three research assistants and the PI) met at least twice a week, each time typically for several hours, to review and examine studies and to discuss any complications

or open questions. The purpose of the meetings was to maximize consistency of different reviews and enable learning within the group. In addition to the meetings, each study review and value estimate was discussed, reviewed, and potentially revised jointly by the reviewer and the PI. The update of studies in 2019 was conducted by one researcher, with frequent meetings with the PI to discuss the review and any emerging issues. The update of studies in 2021 was done by one researcher and one research assistant, with frequent meetings with the PI.

Finally, at the conclusion of the literature reviews and database development, the value database and all variables constructed to support the analysis were once more reviewed and finalized in collaboration between the PI and the research assistant primarily responsible for a specific study/value. This helped ensure that all the study characteristics in the database were consistently and comprehensively developed and recorded.

Appendix 4

Currency conversion

Determining the year of value estimates

Information on the currency and currency year of the value estimate enables the use of deflators to develop comparable estimates from multiple study years and countries across the world. When recording the year of valuation, we searched for the currency year of value estimate from the publication. If the year was not listed, we searched for information on the year of data collection and used it for the year of currency.

If neither approach yielded the year, we approximated when the publication was prepared. However, we did not necessarily use the year of publication for the year of value. Instead, we looked for, for example, the year of initial submission, which is often listed for journal articles. Using the initial submission date and assuming a typical lag between data collection and manuscript preparation, we listed the year of currency as the year of the submission or the year before the submission. If the initial submission of a journal article was during the first six months of the year (such as February 2001), and the study listed no information on the year of the currency, then we recorded the year before as the currency year (2000). But for studies submitted in the last six months of the calendar year, we recorded the calendar year of the submission as the currency year. Note that these imputations are necessary only for studies that list no information, to determine the year of the currency more precisely (not a common occurrence).

Conversion of values into international dollars

For the statistical analysis we used the year 2017 PPP-adjusted US dollars, often referred to as “international dollars”, for the common denomination of value estimates. The global prediction values are reported in current US dollars.

The original value estimates come from many years and in many currencies. When the original value estimate is in local currency units (LCU), we first used a local GDP deflator to express the value in the year 2017 LCU. This value was then converted to international dollars by using PPP conversion.⁹ PPP-adjusted exchange rates make estimates from different countries comparable as economic values.¹⁰

Several studies address values in LCU but use US dollars in reporting the results. However, these estimates are typically not PPP-adjusted but use a conversion based on the currency exchange rate. To ensure consistent use of PPP-adjusted estimates, we first converted any original, non-US estimates expressed in US dollars back into LCU, using either the exchange rate reported in the publication or, in its absence, the reported exchange rate for the year of value estimates. The currency conversion was then conducted similarly as for value originally listed in LCU.

Finally, PPP conversion factors are not available for a few countries. In such cases, we first deflated the value into 2017 using a local GDP deflator and then adjusted the 2017 LCU value into international dollars using a regionally averaged PPP conversion factor (using UN sub-regions as regions).

⁹ We use GDP and PPP information from the World Bank (World Development Indicators, <http://databank.worldbank.org>).

¹⁰ For example, consider an original estimate 13.54 in Peruvian sols in 2008. The GDP deflator value is 225 in 2012 and 171 in 2008, so we convert the value into 2012 LCU as $13.54 \text{ sols} \times 225/171 = 17.81 \text{ sols}$. The PPP-adjusted exchange rate is 1 international \$ = 1.89 sols. The final value estimate is, therefore, $17.81 \text{ sols}/1.89 = 9.43 \text{ international dollars}$ (2012).

Conversion into value per hectare per year

We converted all value estimates into international dollars per hectare per year (international dollars 2017 PPP). When the original value estimates were expressed in other units, we converted them into per hectare per year values. For example, if the original value estimate addressed recreational benefits in a specific area of forest, expressed on a value per visit basis, we used information on the number of annual visitors to estimate total annual benefits from the forest. Then, we used the total forest area to estimate recreation benefits per year per hectare.

Some studies list value estimates in net present value (NPV). If the study listed the discount rate and the time horizon used in the NPV calculation, we converted it to annual value using the following relationship:

$$\text{Annual value} = \frac{NPV}{A_{t,r}}, \text{ where } A_{t,r} = \frac{1 - \left(\frac{1}{1+r}\right)^t}{r}$$

When the original value was listed in NPV but no information was given on the applicable discount rate and time horizon, we converted the value into annual anural terms using a 4 percent discount rate and 25-year time horizon.

World grid data and conversion factors

Most of the underlying data to predict the value of non-wood forest ecosystem services is produced globally processing GIS data. We also include country statistics, like gross national income (GNI). Sometimes, the GNI is not available for some countries from the main data source used in this study, the World Bank World Development Indicators (World Bank 2020). This is the case, for example, for the Democratic People's Republic of Korea, Croatia, or Taiwan. When this is the case, we used alternative data sources, like the United Nations National Accounts Main Aggregates Database (United Nations 2020) or national statistics bureaus.

To predict annual values at current US dollars, we first compiled GNI time series in local currency for 1995 to 2020. We converted it to 2017 USD PPP international dollars using the methods described here. Using this data, we predicted annual values for every year in 2017 USD PPP international dollars. To convert these values to annual current dollars we first convert them to 2017 LCU using the 2017 country PPP conversion factor. When the 2017 PPP conversion factor was not available, as for example, was the case for the Democratic People's Republic of Korea and Cuba, we used the 2011 PPP conversion factor as a proxy. 2011 is the also a base year for the PPP conversion factor, and available for almost every country. Second, we converted the 2017 LCU into the 2017 US dollar constant values using the average exchange rate for 2017. Exchange rate data was obtained from the World Bank World Development Indicators (World Bank 2020). Last, we convert from constant 2017 US dollars to annual current US dollars using the inflation deflator for the United States.

Appendix 5

Statistical methods

A5.1 GENERAL APPROACH

As explained in the main body of this report, this study uses two statistical approaches to predict the value of non-wood forest ecosystem services globally: (1) meta-regression and (2) machine learning. We depart from a conditional expectation function that characterizes their value (per hectare) as a function of socioeconomic (income per capita, population density), biophysical (latitude), ecological (ecosystem type, species richness, land cover, forest degradation), and climatic (rainfall and temperature) attributes of each study site (Equation A1).

Equation (A1)

$E(\$ ha^{-1} \mid X = \textit{socioeconomic, biophysical, ecological, climatic}) = f(X)$

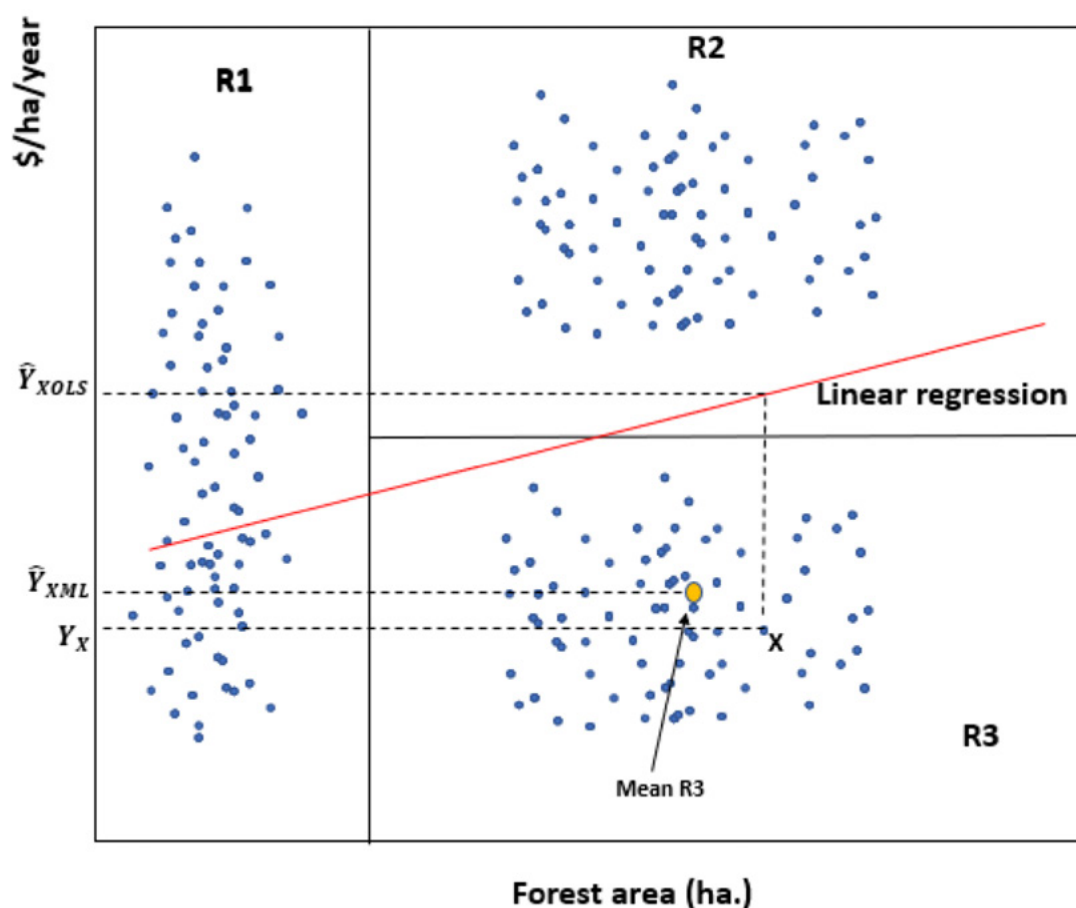
Regression analysis and machine learning methods show tradeoffs between flexibility and interpretability (Figure A5.1). A method is considered less flexible, or more restrictive, in the sense that they can produce just a relatively small range of shapes to estimate f (James et al. 2016). For example, linear regression is a relatively inflexible approach, because it can only generate linear functions. Machine learning methods, including random forest and boosting, are considerably more flexible because they can generate a much wider range of possible shapes to estimate f .

We estimate models using both more restrictive linear regression models and machine learning algorithms because of two reasons. First, we want to understand the relationship between the explanatory variables and the dependent variable and be sure that their

FIGURE A5.1: TRADEOFFS BETWEEN FLEXIBILITY AND INTERPRETABILITY USING DIFFERENT STATISTICAL METHODS



FIGURE A5.2: EXAMPLE COMPARING LINEAR REGRESSION AND A THREE-REGION PARTITION FOR PREDICTION THE VALUE/HA/YEAR REGARDING FOREST AREA



behavior is consistent with economic theory. The results of this analysis are going to be used to feed global estimates in the World Bank *The Changing Wealth of Nations* Report, therefore the relationship guiding the predictions need to be meaningful. Second, predictions that are more accurate are often obtained using a less flexible method, because of the potential for overfitting in highly flexible methods (James et al. 2016). Overfitting essentially means that a model follows the errors, or *noise*, too closely, perfectly fitting the observed data. That is, the statistical learning procedure is working too hard

to find patterns in the estimation dataset, that can be picking up some patterns that are just caused by random chance rather than by true properties of the unknown function f .

Figure A5.2 shows the result of a three-region decision tree to analyze the relationship between forest area and forest value per hectare using hypothetical data. Decision trees allocate each observation to a region based on their features. The predicted value for the forest value per hectare of an observation in Region 3 is Y_{XML} . That is, the decision tree splits the data

based on the value of the independent variables and allocates them to a specific region. Then, each observation (blue dot) in each region prediction is equal to the mean value of the dependent variable value of all the observations in the region.

We used leave-one-study-out cross-validation to compare the performance of the different models. This approach involves splitting the set of observations in two parts. First, we remove all the values belonging to a single study from the estimation dataset, and we fit the model again with the remaining observations. Second, we used the model to predict the values of the observations removed, and we compute the mean square error for them. The mean square error for each study $k = 1 \dots K$ is defined as:

Equation (A2)

$$MSE_k = \frac{1}{Z} \sum_{z=1}^Z (y_{kz} - \hat{y}_{kz})^2$$

where $z = 1 \dots Z$ are the value estimates belonging to study k . This procedure is repeated for each of the k studies in the sample. The cross-validation estimate is the average of these K error estimates:

Equation (A3)

$$CV_{(K)} = \frac{1}{K} \sum_{k=1}^K MSE_k$$

The root mean square error is computed as:

Equation (A4)

$$RMSE = \sqrt{CV_{(K)}}$$

Our approach is slightly different from traditional leave-one-observation-out cross-validation, where K equals the number of observations in the estimation dataset. Here, we leave all the observations belonging to the same study out at the same time. That is, if there are five values belonging to the same study, we remove five observations, while if there is only one value of a specific study, we remove only one

observation. The advantage of this approach is that it allows us to check the sensibility of the results to a specific study.

A5.2 META-REGRESSION ANALYSIS

The meta-regression analysis assumes that the relationship between the dependent variables and the determinants is linear (or a non-monotonous transformation of the variables is linear), as show in Equation (A5):

Equation (A5)

$$\ln y_i = \alpha + \beta X_i + \varepsilon_i$$

where $\ln y_i$ is the natural logarithm of the value estimate of ecosystem services (dollars per hectare) identified from the literature, α is a constant, X_i is a vector of J (indexed by $j=1,2,\dots, J$) independent variables to characterize the study and study area, β is a vector of J coefficients estimated on independent variables X , and ε_i is a random error term. The error term is assumed to be clustered by study, allowing correlation in the error of observations belonging to the same study.

In our study, we depart from the conventional logarithmic transformation of the dependent variable. Table 5 in the main body of the report lists the variables considered as potential determinants of the value of ecosystem service. We explore two potential functional forms between the dependent and the independent variables: log-log and log-level. In the log-log models all the independent variables were transformed using a natural logarithm transformation, except variables in percentages and indexes. In the log-level model, all the right-hand side variables enter the model in levels. All the models are estimated using a weighted estimation approach, as described in the main body of the report.

A5.3 MACHINE LEARNING ALGORITHMS

This section describes the machine learning methods used for value prediction for each ecosystem service. The two main methods are random forest (RF) and Bayesian Additive Regression Trees (BART). Each method is applied using all predictor variables available and using only a subset of important predictor variables. Variable selection is a very important step in the construction of statistical learning models. Even if modern algorithms are designed to perform well in high dimensions when there are more predictors than observations, is usually observed that is possible to improve performance by eliminating non-important variables in a specific problem. Finally, a fifth strategy is applied based on an automated machine learning (AML) algorithm.

A5.3.1 Classification and Regression Tree (CART)

The CART model (Breiman 2001) can be represented by a sequence of binary recursive partitions of the predictor variable space. Figure A5.2 above shows the value of forest per hectare variable. These kinds of trees use only one variable in each split and then define hyperplanes that are orthogonal to the axis. Let Y denote the numeric response variable and X a p dimensional random vector, which might contain discrete and continuous random variables. Furthermore let $\mathbf{d}_i = \{\mathbf{x}_i, y_i\}_{i=1}^n$, where $\mathbf{x}_i$ is a p -dimensional column vector of explanatory variables with $i = 1, \dots, n$, and $y_i \in \mathbb{R}$ is the numeric response variable.

The goal is to model the conditional expectation of the response as a function of the predictor variables (as shown in general terms in Equation (A1)).

Equation (A6) shows the structure of the conditional expectation function defined by a CART model:

Equation (A6)

$$E(Y|X = \mathbf{x}) = h(\mathbf{x}) = \sum_{s=1}^S c_s I_{R_s}(\mathbf{x})$$

where R_s represents a partition in the feature space (i.e., $R = \cup_{i=1}^S R_i$ and $R_s \cap R_i = \emptyset$), while $I_{R_s}(\mathbf{x}) = 1$ when $\mathbf{x} \in R_s$ and 0 otherwise.

Based on the estimation dataset, $\mathbf{d}_n$, a partition of the feature space, R_s , and coefficients c_s need to be estimated. The partition is obtain using a recursive partition algorithm.¹ The predicted value, c_s are computed as:

Equation (A7)

$$c_s = \frac{1}{\#R_s} \sum_{i/\mathbf{x}_i \in R_s} y_i$$

When $\mathbf{x} \in R_s$, the predicted value for Y is c_s , as regions are mutually exclusive. A CART model only produces a finite set of predicted different values.

A5.3.2 Random forest (RF)

RF is an ensemble learning method, built on randomized trees (Breiman 2001), incorporating two sources of randomness in the tree: random bootstrap samples and random variable selection. First, many samples with replacement are obtained from the estimation dataset, bootstrap samples, and a tree model is built for each bootstrap sample. The second source of randomness consists of randomly selecting predictor variables to use in each node partition.

Random forests then combine *randomized* trees predictors where each tree depends on the values of a random vector sampled independently and with the same distribution for all trees in the forest:

¹¹ We do not show the algorithm here. See James et al. (2016) for a detailed description of tree models.

Equation (A8)

$$E(Y|X = \mathbf{x}) = f(\mathbf{x}) = E(h(\mathbf{x}, \boldsymbol{\theta}))$$

where $h(\mathbf{x}, \boldsymbol{\theta})$ represents a randomized CART model. This consists of a tree model as described in the previous subsection but with some modifications in the tree construction. First, the model is not regularized as is usually done for CART. CART models use rules to avoid model overfitting, not allowing nodes with very low number of observations. RF does not use these kinds of rules in every individual tree. Second, each node partition is done only with m randomly selected subset of predictors, instead of using all p available explanatory variables, in regression problems. The default value is to set $m \approx p/3$, which has shown good overall performance (Genuer et al. 2008). Finally, the observation used in the individual tree construction constitutes a random sample with replacement from the original estimation dataset (bootstrap sample). The random vector $\boldsymbol{\theta}$ incorporates two sources of randomness in the tree: random variable selection in each node partition and random samples of cases.

The formal definition of the forest model described above is not useful in practice, as there is only one training dataset available. The actual predictive model is obtained by creating B bootstrap samples of the data $\mathbf{d}_n$, and growing a tree with each bootstrap sample. This process ends up with a collection of randomized regression trees $h(\mathbf{x}, \boldsymbol{\theta}_k), k = 1, \dots, B$ where each $\boldsymbol{\theta}_k$ contains information about which variables were selected in each partition and which cases were selected in the bootstrap sample. Equation (A9) shows how to construct the RF predictor, as the average of the randomized trees $h(\mathbf{x}, \boldsymbol{\theta}_k)$:

Equation (A9)

$$\hat{f}(\mathbf{x}) = \frac{1}{B} \sum_k h(\mathbf{x}, \boldsymbol{\theta}_k)$$

The RF construction algorithm can be described in three steps:

1. Take B bootstrap samples from $\mathbf{d}_n$
2. Grow a randomized tree $(h(\mathbf{x}, \boldsymbol{\theta}_k))$, in each bootstrap sample
3. Compute predictor as in equation (A9).

Figure 3.3 in the main body of the report illustrates the RF construction algorithm. From the estimation dataset, several samples are obtained with replacement, and a tree model is grown in each bootstrap sample. Finally fitted values are computed by averaging the individual model predictions. As with most non-parametric methods, RF has some tuning parameters that need to be optimized in order to improve its predictive performance. Tuning parameters include the number of decision trees in the forest and the number of features considered by each tree when splitting a node. The forest model is not too sensitive to the number of trees. The default value is $B = 10p$ for regression problems. The proposed default values for the number of trees (B) in the forest and the number of variables used in each split (m) are known to be rules with good performance properties across different applications (Genuer et al. 2008, 2010).

A5.3.3 Bayesian Additive Regression Trees (BART)

BART, originally proposed by Chipman et al. (2010) is increasingly studied and used in the machine learning community. In social sciences BART has been proposed to make causal inference (Hahn et al. 2020) and for analyzing data in observational studies (Dorie et al. 2019).

BART's main characteristics are described, but all descriptions here are superficial. Interested readers can look at Hill et al. (2020) and its references, which present a complete review of the BART model, its theoretical properties, and modeling extensions.

BART is a Bayesian statistical method. Bayesian inference consists of a probabilistic way to approach statistical tasks such as estimation and prediction. The main goal is to construct a probability distribution of any quantity of interest (parameters, predictions) that considers the observed data, this is called the posterior distribution. Let θ denote an unknown quantity and the goal is to obtain estimates (punctual, intervals, etc.) for θ . Then, very briefly Bayesian inference for θ can be described in three steps:

1. Complete probability model: $p(y|\theta)$ and $p(\theta)$
2. Get posterior using Bayes rule: $p(\theta|y, M) \propto p(y|\theta) \times p(\theta)$
3. Evaluate model performance.

In step 1, $p(y|\theta)$ represents the data-generating model, usually called likelihood. While $p(\theta)$ represents a model for the unobservable parameters, usually called the prior distribution. Then, the second step to obtain posterior distribution $p(\theta|y, M)$ is approximated with simulations, as in most of the problems there is no analytic form available or it is too computationally complex to obtain. There are many methods to approximate the posterior, the main class of them lies in the use of a Markov Chain Monte Carlo (MCMC) algorithm.² In practical terms, this means that the posterior distribution will consist in $(\theta^1, \theta^2, \dots, \theta^s)$, a finite set of simulated values from $p(\theta|y)$.

Rewriting equation (A6) in a Bayesian context might be done as follows:

Equation (A12)

$$E(y|x) = g(x|T, M) = \sum_k \mu_k I(x \in R_k)]$$

where T denotes the tree structure formed by a sequence of $\{X_k \leq c_k\}$ rules, and M denotes the vector of values at the tree leaves, $M = (\mu_1, \dots, \mu_b)$. A Bayesian tree model has the same approach as in CART but adds two main aspects: an explicit model for the data, and a prior model for the parameters of the tree. In a regression problem, a data model of a Bayesian tree is:

Equation (A13)

$$Y = g(x \| T, M) + \epsilon$$

where $\epsilon \sim N(0, \sigma^2)$.

The Bayesian tree model need a prior for (T, M) , this is topically done setting $p(T, M, \sigma^2) = p(M|T) \times p(T) \times p(\sigma^2)$, where the marginal distribution for tree structure is constructed as

$$p(d) \propto \alpha(1 + d)^{-\beta}, \text{ where } d \text{ is the tree depth}$$

X_k randomly selected among predictors

c_k randomly selected among X_k values

given a particular tree structure, leaves values, M , are normally distributed with mean m and standard deviation s . Additionally, the prior for the error variance parameter is $\sigma^2 \sim \nu \lambda \chi_\nu^{-2}$. Values for hyperparameters $\alpha, \beta, m_\mu, s_\mu, \nu$ and λ need to be provided by the user.

The model for data and the prior completes the Bayesian model for one tree. Next this model is used to construct a model:

Equation (A14)

$$Y = f(x) + \epsilon = \sum_j g_j(X|T_j, M_j) + \epsilon$$

¹² MCMC is a family of computational methods to obtain simulated values from complex multivariate distributions.

where each $g_j(\cdot)$ represents a single tree as described in previous section. Individual tree models are independently and identically distributed using the prior for a single tree. Default values for the hyper-parameters are calibrated so each individual tree favors smaller tree depth. The intuition for this is similar to boosting algorithms in machine learning where each individual model is a weak learner but together the model presents high flexibility and good predictive performance.

A5.3.4 Variable selection methods

Variable selection is a very important step in the construction of statistical learning models. Even if modern algorithms are designed to perform well in high dimensions when there are more predictors than observations, is usually observed that is possible to improve performance by discarding non-important variables in a specific problem. There are many techniques to compute variable importance in statistical learning models, and based on those measures, variable selection procedures have been proposed. In this subsection, the variable selection procedures used for RF and BART are briefly described.

The variable selection using RF procedure is used to select important variables in RF; an extensive explanation can be found in Genuer and Poggi (2020). This algorithm (implemented in Genuer, Poggi, and Tuleau-Malot (2015) package in R) can be outlined as follows:

1. Eliminate variables of low importance based on estimated variable importance measure and its variability. Variable importance is usually obtained using an average of 50 forests.
2. Construct a sequence of nested RF models, starting with the most important variable and adding variables one by one until all important

variables are in the model. Compute the out-of-bag error rate for each sub-model. Variables included in the model with the lowest out-of-bag errors are a list of variables recommended for interpretation.

3. Starting with a model using variables selected for interpretation, a new sequence of nested models is constructed. In increasing order of importance, new variables are introduced in the model and tested to see if the model improves. The variables of the last model in the sequence are selected for prediction.

The algorithm output consists of two sets of variables. First, a small set of variables is recommended to use if the main goal is interpretation, this is the result of step 2 in the algorithm. Secondly, a usually larger set of variables is added, including the previous ones plus other variables initially left out of the model but improve the model in terms of prediction error. This second set of variables is recommended when the main goal is prediction.

For BART models, there exist several approaches for variable selection (Kapelner and Bleich 2016). The `dbarts` package in R (Dorie 2023) is used to select a small set of important variables in the BART model. The basic measure of variable importance in BART is the variable inclusion proportion, i.e., the number of times a variable is used by the algorithm to make the predictions. However, this measure on its own can be misleading since the choice of variables is random within the algorithm. Variable selection constructs a distribution for the variable inclusion proportion in a model without important variables and uses it as a “distribution under the null” to test the inclusion of each variable. An outline of the BART variable selection is as follows:

1. Run the model with all variables on training data and compute inclusion proportions for all variables. Save this value as the observed inclusion proportion.
2. Approximate the distribution of the so-called null inclusion proportion.
3. Permute the response variable times. The permuted response variable has no relation with any of the predictor variables in training data.
4. With the permuted variable, compute a BART model and save the inclusion proportion of each variable.
5. A variable is selected if its observed inclusion proportion is larger than the $(1-\alpha)$ quantile of the corresponding null inclusion proportion distribution.

A5.3.5 Automated machine learning (AML)

AML is the process of setting an automatic workflow to construct a machine learning model. Different stages could be automatized, at least partially, such as data preprocessing, predictor construction and selection, model selection, and tuning. The open-source platform h2o contains an autoML (H2O.ai 2017) algorithm that performs an automatic model training and comparison across a fixed set of models to obtain the most appropriate for each problem.

The idea of AML is to simplify the model selection process by reducing the number of parameters defined by the user. However, there are some important drawbacks to these types of strategies. First, usually results in black-box type procedures, which are hard to interpret. Secondly, some stages in the modeling workflow are really hard to automatize (i.e., feature engineering). In this study, AML is not used as the main prediction method but to get a reference of predictive performance measures (such

as prediction error) to compare with other machine learning methods. This is important in order to end up with a machine learning model that is close to the best that can be done with the data available in terms of predictive performance and at the same time is possible to explain its results in terms of predictors variables.

Some of the computational implementation details are described next. AML is a wrapper function in the h2o environment that includes automatic training and tuning of many models in a specific time frame specified by the user or also specifying the number of total models trained. A simplified description of the model search steps is:

1. A hyperparameter grid search is set for each class of algorithms
2. According to performance measures, the best models are selected
3. Stacked ensembles are created with the best individual models.

The AML includes several families of machine learning algorithms. Including RF, GLM (generalized linear models with regularization penalty), XGBoost (a gradient boosting machine implementation), Extreme Randomized Tree (a variant of random forest with additional randomness), and Deep Learning. In total, 20 models were trained and two stacking meta-learners models were constructed. The meta-learners are constructed as combinations of the 20 machine learning methods into a new predictive model.

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Appendix 6

GIS data processing and variables construction

This appendix describes the GIS data processing conducted to produce data relevant for the analysis. The next section describes the process to create and clean a world grid that was later used for processing GIS data consistently and to predict values globally. Section A6.2 describes the GIS data processing of the variables of interest, data description, and sources. Section A6.3 describe the process to estimate the area of forest designed as accessible.

A6.1 WORLD GRID DATA

We processed GIS data to compute socioeconomic, biophysical and ecological, and climate features of the study areas. The information was later used to predict the global spatial explicit value of non-wood forest ecosystem service. We first constructed a $0.1^{\circ} \times 0.1^{\circ}$ world grid. The world grid consisted of 1,976,984 cells that totally or partially overlaps with terrestrial areas of the planet. In a second stage we masked out those grid cells that:

- Do not have the centroid located within a terrestrial area.
- Are located in Antarctica.
- Did not have any pixel of forest in any year between 1992 and 2020 in the ESA-CCI land cover map (ESA 2017b).
- Were classified as water bodies (100 percent of the grid cell) for every year between 1992 and 2020 by the ESA-CCI land cover map (ESA 2017b).

After removing cells following the criteria described above, we had 1,279,660 cells with at least one pixel classified as forest between 1992 and 2020 by the ESA-CCI land cover map (ESA 2017b).

A6.2 GIS DATA PROCESSING, DATA DESCRIPTION, AND SOURCES

We overlapped the world grid with different data sources to process socioeconomic, biophysical and ecological, and climate data relevant for the analysis. All the variables, data sources, and specific proceedings are described below. In general terms, we processed the following types of GIS data:

1. Point data that indicates the value of a shape file or a raster cell in a specific point of interest (cell centroid or study site location). For example, biome data is recorded in a shape file. We allocate to a cell the biome that intersects with the centroid of the cell, or a value estimate to the biome polygon that intersects with the study site point.
2. Average raster value within a cell. To compute the average value of raster data within a cell, we first re-scaled the raster data to have one cell of the same size as the cells in our $0.1^{\circ} \times 0.1^{\circ}$ world grid. The new re-scaled raster value is the average value of all the raster pixels whose centroid belong to the cell. Then, we impute to the cell the value of the intersection of the cell centroid and the re-scaled raster.
3. Area data from shape files. The area is computed as the intersection of each cell in the world grid and the shape file polygons.
4. Area from raster. To compute the area of each class value from the raster for each cell, we first re-scaled the raster data to have one cell of the same resolution as the raster. We used the tool

“Tabulate Area” to calculate the cross-tabulated area between the raster and the grid cells.

5. Length from line shapefiles. To compute the length of data coming from line shapefiles, we overlap the grid cell with the line shapefile. Then, we compute different variables, such as total roads length within a cell.
6. Raster data in round buffers at 25km, 50km, 75km, 100km, 200km, and 400km of each study

point and cell centroid. To construct the values of the round buffers at different distances, we first compute the distance from each study site point/cell centroid to the centroid of all the cells in the world grid. Second, we compute the average value of the variable of interest of the cells that are a shorter distance than the distance of interest to each study site/cell centroid.

VARIABLE	POPULATION DENSITY
Data source	Center for International Earth Science Information Network – CIESIN – Columbia University (2018)
URL	https://sedac.ciesin.columbia.edu/data/set/wacvm-gpw-v4-population-density-pre-release-1-2010
Data type	Raster
Resolution	30 arc-second adjusted count data were aggregated to 2.5 arc-minute
Time and frequency	Annual 2000, 2005, 2010, 2015, 2020
Type of processing	2. Average raster value within a cell 6. Raster data in round buffers at 25km, 50km, 75km, 100km, 200km, and 400km of each study point and cell centroid
Details on data processing	Input shape file: $0.1^{\circ} \times 0.1^{\circ}$ world grid cells Input raster: population density raster file in 2000, 2005, 2010, 2015 and 2020 GIS process: 1. Re-sample: rescale the population density file into the resolution at 0.1° to be the same as the world grid cells. 2. Zonal statistics as table: return the average value of population density for each year within each grid cell. Ignore no data pixels within each cell. Set the snap environment to match with the world grid cell data. 3. Export each dbf file to csv. <i>Post-processing</i> To compute cell specific annual values of population density, we follow two strategies. To interpolate values for years within the time span that we have data, we compute the annual average growth rate per cell as $\left[\left(\frac{Y_{t+x}}{Y_t} \right)^{1/x} - 1 \right] * 100$, where Y_t is the initial value, Y_{t+x} is the final value, t is the initial year and $t + x$ is the final year. We did this to interpolate the values within every sub period (t; $t+x$) (2000; 2005), (2005; 2010), (2010; 2015), and (2015; 2020). To extrapolate population density backwards for years previous to 2000, we first compute the annual average growth rate for the period (2000; 2020). Then, we used that growth rate to impute values to the cells for years before 2000.

VARIABLE	FOREST BIOME
Data source	Hansen, Stehman, and Potapov (2010)
URL	https://glad.geog.umd.edu/projects/gfm/
Data type	Shape file polygon
Resolution	n/a
Type of processing	1. Point data that indicates the value of a shape files or a raster cell in a specific point of our interest (cell centroid or study site location).
Details on data processing	Input shape file: 0.1° × 0.1° world grid cells Input shape file: world biome shapefile GIS process: 1. Spatial join: overlay the world biome file on top of the centroid of world grid cells to return the biome info at the centroid location for each world grid cell. a. Target feature: centroid. b. Join feature: Biome. c. Join: one to many to keep multiple biome info for each centroid if there are overlapping polygons. d. Output: joined shapefile. 2. Export attribute table for each shape file to csv.

VARIABLE	TEMPERATURE AND RAINFALL
Data source	Matsuura and Willmott (2018b, 2018a)
URL	http://climate.geog.udel.edu/~climate/html_pages/Global2017/README.GlobalTsT2017.html
Data type	Raster
Resolution	0.5°×0.5°
Time and frequency	Monthly average 1900–2017
Type of processing	2. Average raster value within a cell 6. Raster data in round buffers at 25km, 50km, 75km, 100km, 200km, and 400km of each study point and cell centroid
Details on data processing	Input shapefile: 0.1° × 0.1° world grid cells Input raster: monthly temperature and rainfall temperature from 1900 to 2017 GIS process: 1. Resample: rescale the climate raster data into the resolution at 0.1 deg to be the same as the world grid cells. 2. Zonal statistics as table: return the average temperature (deg) and rainfall (mm) for each month within each grid cell. Ignore nodata pixels within each cell. Set the snap environment to match with the world grid cell data. 3. Export each dbf file to csv. <i>Post-processing</i> Because of data resolution, many of the cells in the world grid end up not overlapping with the temperature and precipitation raster dataset. We imputed the value in the missing cells by imputing the average value of the four closer cells, measured as the distance of the centroid of each cell. Because many times there were more than two continuous cells having missing values, we repeated this process iteratively, until all the terrestrial cells were imputed with a value. We consider only cells in terrestrial continents for the imputation process. In the study we are interested in using weather variables as a proxy of climate conditions. To do this, we computed the average annual temperature and rainfall per cell for the period 1970–2017.

VARIABLE	URBAN AREA AND DISTANCE TO CLOSEST URBAN AREA
Data source	ESA (2017)
URL	https://www.esa-landcover-cci.org/
Data type	Raster
Resolution	300m × 300m
Time and frequency	Annual 1992 to 2020
Type of processing	- Area from raster - Distance - Raster data in round buffers at 25km, 50km, 75km, 100km, 200km, and 400km of each study point and cell centroid
Details on data processing	Input shapefile: 0.1° × 0.1° world grid cells Input raster: esacci land cover rasters from 1992 to 2020 GIS process: - Condition: create rasters representing urban only by using tool of "con". Reclassify classes for urban (value = 190) into value 1 and reclassify all other classes into nodata. - Conversion: convert rasters into polygon. option: non simplify polygon. - Reproject: reprojected all the input shapefiles and converted urban polygons from step 2 into the projection of "WGS_1984_Web_Mercator_Auxiliary_Sphere". - Intersect: overlay the world grid cells with the urban polygon generated from step 3 to calculate the area of urban within each cell. - Near: use the centroid shapefile from 0.1 deg * 0.1 deg world grid cells to calculate the distance from each point to the nearest urban polygon generated from step 3. - Export attribute table of shape file to csv. <i>Projection correction</i> Urban areas and distances were computed using Web Mercator Coordinate System (WGS 84).¹ The Web Mercator is a modification of the Mercator coordinate system, usually used for web maps and online services. The Web Mercator coordinate system is not conformal, and besides enormous area and distance distortions away from the equator, it also does not project rhumb lines as straight lines. The Web Mercator Coordinate System projection distorts data in the east-west direction, but the worst distortion is in the north-south direction.² To correct this issue, we re-projected the 0.1°×0.1° degrees world grid cell to Equal Earth projection system. Equal Earth is an equal-area pseudocylindrical projection for world maps. The projection was adopted by the NASA Goddard Institute for Space Studies. We compute the area of each cell in our world grid using both projections. We used that to construct a correction factor specific for each cell, allowing to recover the real area per cell, as well as the data processed at each cell. The correction factor ranges from 0.012 to 0.99. Total terrestrial surface after correction is 1.400e+10 ha., consistent with global statistics. Any straight line drawn on Mercator projection represents an actual compass bearing. These true direction lines are rhumb lines and generally do not describe the shortest distance between points. Distances are true along the equator or along the secant latitudes (standard parallels).

Distances were corrected multiplying the calculated distance with $\cos(\text{lat})$, since the scale of the Mercator projection is proportional to the secant of the latitude (secant is $1/\cos(\text{lat})$).⁴ The ratio between the Web Mercator adjustment and $\cos(\text{lat})$ is larger in the S-N direction, ranging from 0.9933 at the equator to 1.0034 at the poles. The W-E direction ratio starts with 1 at the equator and grows to 1.0034 at the poles. We correct the roads kms per cell using the Mercator distance correction using the latitude of the centroid of the cell. We also correct the distance to the closest urban area from the centroid of the cell or from the study site using the latitude of each of them, respectively.

¹ <https://desktop.arcgis.com/en/arcmap/latest/map/projections/mercator.htm>

² <https://support.esri.com/en/technical-article/000011356>

⁴ <https://gis.stackexchange.com/questions/14528/better-distance-measurements-in-web-mercator-projection>

Post-processing

We extrapolate urban extent at the cells and round buffers, as well as distance to the closer urban area for years previous to 1992 using the annual average growth rate per cell of each variable, defined as:

$$\left[\left(\frac{Y_{t+x}}{Y_t} \right)^{1/x} - 1 \right] * 100, \text{ where } Y_t \text{ is the initial value, } Y_{t+x} \text{ is the final value, } t \text{ is the initial year and}$$

$t + x$ is the final year. To extrapolate the variables for years previous to 1992, we first compute the annual average growth rate for the period (1992; 2018). Then, we used that growth rate to impute values to the cells for years before 1992.

VARIABLE	FOREST AREA
Data source	ESA (2017)
URL	https://www.esa-landcover-cci.org/
Data type	Raster
Resolution	300m × 300m
Time and frequency	Annual 1992 to 2020
Type of processing	4. Area from raster
Details on data processing	Input shape file: 0.1° × 0.1° world grid cells Input raster: ESACCI land cover rasters from 1992 to 2020 GIS process: 1. Resample: resample the rasters to the resolution of 0.1 to match input world grid cells. 2. Reproject: reproject the raster of land cover and world grid cells to the projection of "World_Cylindrical_Equal_Area" (WKID: 54034). 3. Tabulate area: use projected world grid cells from step 2 as zones and reprojected land cover rasters from step 2 to calculate area of each land cover class for each cell. 4. Export the dbf to csv. <i>Projection correction</i> Forest areas were computed using Web Mercator Coordinate System (WGS 84).¹ The Web Mercator is a modification of the Mercator coordinate system, usually used for web maps and online services. The Web Mercator coordinate system is not conformal, and besides enormous area and distance distortions away from the equator, it also does not project rhumb lines as straight lines. The Web Mercator Coordinate System projection distorts data in the east-west direction, but the worst distortion is in the north-south direction.² To correct this issue, we re-projected the 0.1°×0.1° degrees world grid cell to Equal Earth projection system. Equal Earth is an equal-area pseudocylindrical projection for world maps. The projection was adopted by the NASA Goddard Institute for Space Studies. We compute the area of each cell in our world grid using both projections. We used that to construct a correction factor specific for each cell, allowing to recover the real area per cell, as well as the data processed at each cell. The correction factor ranges from 0.012 to 0.99. Total terrestrial surface after correction is 1.400e+10 ha., consistent with global statistics. ¹ https://desktop.arcgis.com/en/arcmap/latest/map/projections/mercator.htm ² https://support.esri.com/en/technical-article/000011356 <i>Post-processing</i> We extrapolate forest area at the cells for years previous to 1992 using the annual average growth rate per cell of each variable, defined as: $\left[\left(\frac{Y_{t+x}}{Y_t} \right)^{1/x} - 1 \right] * 100$, where Y_t is the initial value, Y_{t+x} is the final value, t is the initial year and $t + x$ is the final year. To extrapolate the variables for years previous to 1992, we first compute the annual average growth rate for the period (1992;2018). Then, we used that growth rate to impute values to the cells for years before 1992.

VARIABLE	ROAD LENGTH
Data source	Meijer et al. (2018b)
URL	https://www.globio.info/download-grip-dataset
Data type	Shape file lines
Resolution	n/a
Time and frequency	1 layer. The GRIP dataset comprises more than 21.6millionkm of roads in total. This is a considerable improvement over the VMAPO and the gRoads datasets, which cover 7.4 and 9.1millionkm, respectively. Yet, the total global road length in GRIP is mostly smaller than suggested by the World Road Statistics (WRS) database, which contains non-spatial country-level road length estimates. Over 50% of the road length included in GRIP is from data sources published in 2010 or later. A further 23% is from data sources published between 2006 and 2010, and 14% was published between 2000 and 2005.
Type of processing	5. Distance
Details on data processing	Input shapefile: 0.1° × 0.1° world grid cells Input shapefile: world road shapefile GIS process: 1. Reproject: reprojected the two shapefiles into the projection of "WGS_1984_Web_Mercator_Auxiliary_Sphere". 2. Intersect: overlay the world grid cells with the world road shapefile to calculate the length of road within each cell. 3. Export the shape file to csv files. <i>Projection correction</i> Road lengths were computed using Web Mercator Coordinate System (WGS 84).¹ The Web Mercator is a modification of the Mercator coordinate system, usually used for web maps and online services. The Web Mercator coordinate system is not conformal, and besides enormous area and distance distortions away from the equator, it also does not project rhumb lines as straight lines. The Web Mercator Coordinate System projection distorts data in the east-west direction, but the worst distortion is in the north-south direction.² Any straight line drawn on Mercator projection represents an actual compass bearing. These true direction lines are rhumb lines and generally do not describe the shortest distance between points. Distances are true along the equator or along the secant latitudes (standard parallels). Distances were correcting multiplying the calculated distance with $\cos(\text{lat})$, since the scale of the Mercator projection is proportional to the secant of the latitude (secant is $1/\cos(\text{lat})$).⁴ The ratio between the Web Mercator adjustment and $\cos(\text{lat})$ is larger in the S-N direction, ranging from 0.9933 at the equator to 1.0034 at the poles. The W-E direction ratio starts with 1 at the equator and grows to 1.0034 at the poles. I correct the roads kms. per cell using the Mercator distance correction using the latitude of the centroid of the cell. I correct the distance to the closest urban area from the centroid of the cell or from the study site using the latitude of each of them, respectively. ¹https://desktop.arcgis.com/en/arcmap/latest/map/projections/mercator.htm ²https://support.esri.com/en/technical-article/000011356 ⁴https://gis.stackexchange.com/questions/14528/better-distance-measurements-in-web-mercator-projection

VARIABLE	SPECIES COUNT
Data source	BirdLife International and Handbook of the Birds of the World (2019) and IUCN, (2019)
URL	https://www.iucnredlist.org/ http://datazone.birdlife.org/species/requestdis
Data type	Shape file polygons
Resolution	n/a
Time and frequency	1 snapshot
Type of processing	1. Point data that indicates the value of a shape files or a raster cell in a specific point of our interest (cell centroid or study site location).
Details on data processing	Input shape file: 0.1° × 0.1° world grid cells Input shape file: species shape file from IUCN and BirdLife International GIS process: - Spatial join: overlay the species shapefile on top of the centroid of world grid cells to return the species info at the centroid location for each world grid cell. - Target feature: centroid. - Join feature: Species. - Join: one to many to keep multiple species info for each centroid. - Output: joined shape file. - Export attribute table for each shape file to csv. <i>Post-processing</i> The data exported from the GIS processing had one row per cell and per species of birds, mammals, amphibians, and reptiles present in the cell. The post-processing was done separately for each taxonomic group of species. Species richness was computed as the sum of all the species per taxonomic group present in the cell. For each taxonomic group, we: - Keep only those species that were still present in the area and were original from the area. - Sum all the species present in the cell. - Sum all the species that were classified as “endangered”, “critical”, or “vulnerable” by the IUCN Red List of Species (BirdLife International and Handbook of the Birds of the World 2019; IUCN 2019). - Keep one row per cell with the total number of species and total number of threatened species per taxonomic group.

VARIABLE	NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)
Data source	Vermote and NOAA CDR Program (2019)
URL	https://www.ncdc.noaa.gov/cdr/terrestrial/normalized-difference-vegetation-index
Data type	Raster
Resolution	0.05°×0.05°
Time and frequency	Daily from 1981 to present
Type of processing	2. Average raster value within a cell
Details on data processing	Input shapefile: 0.1° × 0.1° world grid cells Input raster: daily NDVI raster from 1981 to present GIS process: 1. Cell statistics: calculate monthly NDVI from daily input. 2. Zonal statistics as table: return the average NDVI for each month within each grid cell. Ignore nodata pixels within each cell. Set the snap environment to match with the world grid cell data. 3. Export each dbf file into a csv file to be imported into Stata. <i>Post-processing</i> We computed the average of the three higher month NDVI values per year for the period 1982–2018. We used the average of the three maximum month value per year, and not the annual average, because many cells show missing values for specific months. This is mostly the case of winter months in the northern cells, that are covered by snow. We consider that the average of the three maximum monthly values per year are a good indicator of ecological conditions.

VARIABLE	PROTECTED AREAS AND IUCN CATEGORY
Data source	UNEP-WCMC and IUCN (2016)
URL	https://www.iucn.org/theme/protected-areas/our-work/quality-and-effectiveness/world-database-protected-areas-wdpa
Data type	Shape file polygons and points
Resolution	n/a
Time and frequency	1 layer updated 2016
Type of processing	1. Point data that indicates the value of a shape files or a raster cell in a specific point of our interest (cell centroid or study site location) 3. Area from shape file
Details on data processing	Input shape file: WDPA shape file in polygons Input shape file: WDPA shape file in points Input shape file: terrestrial country boundaries Input shape file: 0.1° × 0.1° world grid cells Input shape file: centroid of 0.1 deg * 0.1 deg world grid cells GIS process: 1. Select: the field of marine in the WDPA polygons has value of either 0 or 1. Value "0" indicates the WDPA feature is non marine. Value "1" indicates the wdpa feature might be partially or completely ocean. Split the WDPA polygons into two files based on different value in the field of "marine". Output "wdpa_polygons_marine_0.shp" and "wdpa_polygons_marine_1.shp". 2. Clip: use the country boundary file to clip out the terrestrial portion from "wdpa_polygons_marine_1.shp". 3. Merge: combine "wdpa_polygons_marine_0.shp" and clipped "wdpa_polygon_marine_1_terrestrial.shp" from step 2 to create wdpa polygons terrestrial ready for future use. 4. Buffer: use the area field (unit: km²) in the WDPA point shape file to calculate appropriate radius distance for each point. Buffer each point using the calculated radius. This is called WDPA polygon file from points. This file is all terrestrial. The value in the field of "marine" is all equal to zero. 5. Erase: erase the new polygon file generated from step 4 from the WDPA polygon terrestrial file generated from step 3. This step is to make sure only keeping area from raw WDPA polygons when there is overlapping area between the two datasets. 6. Reproject: reproject the wdpa polygon terrestrial shapefile (from step 3) and wdpa polygon from point shapefile (from step 5) into the projection of "WGS_1984_Web_Mercator_Auxiliary_Sphere". 7. Conversion: convert the two reprojected shapefiles from step 6 to rasters in the resolution of 10km. Cell assignment is "MAXIMUM_COMBINED_AREA". Priority field is "IUCN category". This can make sure there is no overlapping areas between different categories.

	IUCN, priority a. Ia, 10 b. Ib, 9 c. II, 8 d. III, 7 e. IV, 6 f. V, 5 g. VI, 4 h. Not reported, 3 i. Not applicable, 2 j. Not assigned, 1 8. Conversion: convert rasters from step 7 back to polygons. Non simplify. -> wdpa_terrestrial_poly_rastertopoly.shp 9. Erase: the operation of converting polygons to rasters, and then convert back to polygons (step 7 and step 8) will recreate overlapping areas between WDPA polygons and WDPA polygons from points. Use erase to remove overlapping areas from WDPA polygons created from points. -> wdpa_terrestrial_point_rastertopoly.shp 10. Reproject: reproject the two shapefiles from step 8 and step 9 into the projection of "World_Cylindrical_Equal_Area" (WKID: 54034). a. Output 1: wdpa_terrestrial_poly_rastertopoly_equalarea.shp b. Output 2: wdpa_terrestrial_point_rastertopoly_equalarea.shp 11. Spatial join: overlay the reprojected shapefiles from step 10 on top of the centroid of world grid cells to return the WDPA info at the centroid location for each world grid cell. a. Target feature: centroid. b. Join feature: reprojected shapefile from step 10. c. Join: one to many. d. Output: joined shapefile. 12. Intersect: overlay the reprojected shapefiles from step 10 with 0.1 deg by 0.1 deg world grid cells shapefile to calculate the area of protected features within each cell. 13. Export attribute table of the shape files from step 11 and step 12 to csv.
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	<i>Post-processing</i> The GIS data processed contained one row per cell in the world grid per protected area intersected with the cell. In addition, protected areas from the shape file and the point file were processed separately. With these inputs, we did the following steps to produce the data finally used in the analysis: 1. We merged the data from shape file and point file into one file, having in total one row per grid cell and per protected area that intersect the cell. 2. Projection correction. The size of the protected areas was computed using Web Mercator Coordinate System (WGS 84).¹ The Web Mercator is a modification of the Mercator coordinate system, usually used for web maps and online services. The Web Mercator coordinate system is not conformal, and besides enormous area and distance distortions away from the equator, it also does not project rhumb lines as straight lines. The Web Mercator Coordinate System projection distorts data in the east-west direction, but the worst distortion is in the north-south direction.² To correct this issue, we re-projected the 0.1°×0.1° degrees world grid cell to Equal Earth projection system. Equal Earth is an equal-area pseudocylindrical projection for world maps. The projection was adopted by the NASA Goddard Institute for Space Studies. We compute the area of each cell in our world grid using both projections. We used that to construct a correction factor specific for each cell, allowing to recover the real area per cell, as well as the data processed at each cell. The correction factor ranges from 0.012 to 0.99. Total terrestrial surface after correction is 1.400e+10 ha., consistent with global statistics. ¹https://desktop.arcgis.com/en/arcmap/latest/map/projections/mercator.htm ²https://support.esri.com/en/technical-article/000011356 3. We create a variable that computes the sum of the total area that is protected per cell. 4. We compute the number of protected areas in a cell 5. We create a variable indicating the sum of the total area of the protected areas that are intersected with a cell. Usually, protected areas cover more than one cell. We consider it important to have a measure of the total protected area associated with a protected area that intersects a cell. 6. We compute an alternative measure to the one described in point 5., as the weight sum of the total area of the protected areas that are intersected with a cell. We use weights based in total area size. 7. We compute a variable for each cell indicating the total area size of the larger protected area that intersects with the cell. 8. We compute a variable for each cell indicating the sum of the total area of every protected area that intersect the cell. 9. We compute a variable indicating the protected area IUCN protection category per cell. For cells that are intersected by more than one protected area, we recorded the IUCN protection category of that protected area with stricter level of protection. 10. We compute a variable indicating the percentage of the area of a cell that is protected. 11. We end up with a dataset that the number of rows equals the number of cells that are intersect with at least one protected area.
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VARIABLE	SPECIES THREAT ABATEMENT METRIC (STAR-T)
Data source	STAR-t layer
URL	https://www.nature.com/articles/s41559-021-01432-0
Data type	Raster
Resolution	0.5° × 0.5°
Type of processing	2. Average raster value within a cell
Details on data processing	Input shapefile: 0.1° × 0.1° world grid cells Input raster: STAR-t layer GIS process: 1. Resample: rescale the STAR-t raster data into the resolution at 0.1 deg to be the same as the world grid cells. 2. Zonal statistics as table: return the average STAR-t scores within each grid cell. 3. Export each dbf file to csv.

A6.3 CONSTRUCTING DATA ON ACCESSIBLE FOREST

Data sources

1. Input shape file: $0.1^{\circ} \times 0.1^{\circ}$ world grid cells
2. Input shape file: world road shapefile
3. Input shape file: world river and lake centerlines from natural earth <https://www.naturalearthdata.com/downloads/10m-physical-vectors/10m-rivers-lake-centerlines/>
4. Input raster: ESACCI LULC from 1992 to 2018

GIS process

1. Merge: merge the shapefile of roads and rivers as one single combined shape file.
2. Conversion: convert polygons to rasters with resolution of 0.18 deg (approximately 20km wide).
3. Reproject: reproject the raster from step 2 into the projection of “WGS_1984_Web_Mercator_Auxiliary_Sphere”.
4. Reclassify: reclassify the reprojected raster from step 2 to value “1” indicating the accessible area from the road and rivers within the geodesic distance of 10km. Everywhere else would be nodata.
5. Reproject: reproject the input rasters (esacci and globecover) into the projection of “WGS_1984_Web_Mercator_Auxiliary_Sphere”.
6. Times: multiply the reprojected raster from step 4 with the reprojected input raster from step 5 to create accessible forest rasters within the geodesic distance of 10km from either roads or rivers.
7. Reproject: reproject the input $0.1 \text{ deg} \times 0.1 \text{ deg}$ world grid cells into the projection of “WGS_1984_Web_Mercator_Auxiliary_Sphere”.
8. Tabulate area: use the projected world grid cells from step 7 as zones and accessible forest raster from step 6 to calculate the area of accessible forest within each cell.

Appendix 7

Results—additional tables and figures

This section complements the regression results presented and discussed in Section 5.1 (Estimation results, sub-section 5.1.1 Meta-regression analysis). When choosing the models presented, we estimated several meta-regression models separately for each service considered. Model selection, the process of choosing empirical specification for predicting the dependent variable, was then conducted using R², Akaike Information Criteria (AIC), Bayesian

Information Criteria (BIC), and out-of-sample prediction power (root mean square error, RMSE). This appendix shows key models estimated by ecosystem service and used in model selection. In each table, the model highlighted in grey is the model selected as the primary regression model for a specific service. This appendix also includes scatter plots to illustrate the distribution of the underlying data and identification of observation with high leverage.

TABLE A7.1: REGRESSION ANALYSIS FOR RECREATIONAL SERVICES

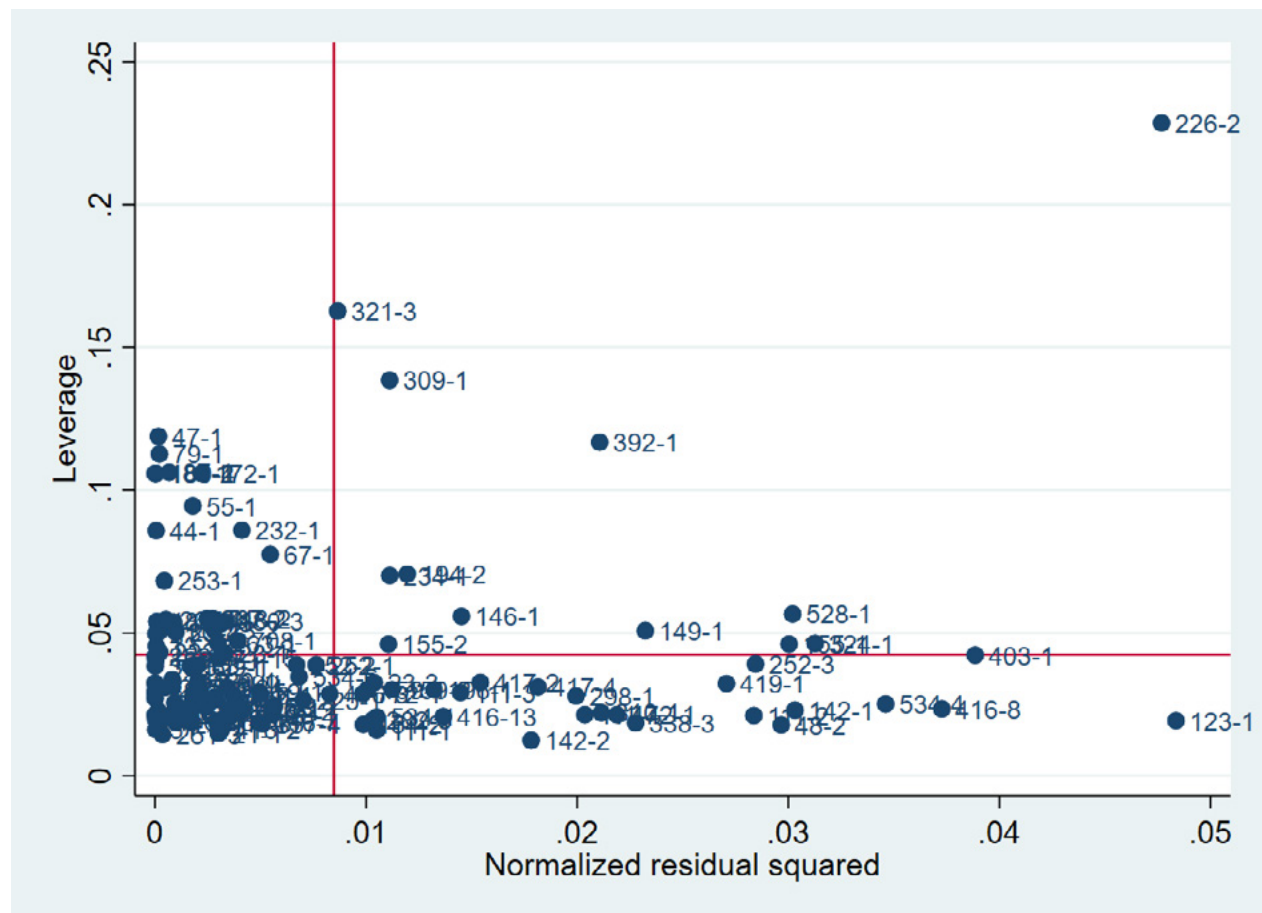
DEPENDENT VARIABLE: VALUE PER HA (LOG, USD PPP 2017)				
VARIABLE	(1)	(2)	(3)	(4)
GNI per capita (log, USD PPP 2017)	0.02 (0.19)	0.67** (0.25)	-0.17 (0.21)	0.49* (0.29)
Population density 75km buffer (log, People/ Km ²)	0.90*** (0.10)	0.72*** (0.10)	0.84*** (0.10)	0.69*** (0.09)
Temperature average 1970–2018 (log, K°)		33.28*** (9.67)		29.88*** (9.75)
Precipitation average 1970–2018 (log, annual mm)		0.28 (0.34)		0.28 (0.32)
Species threatened (fraction of all species)	-7.75 (4.96)	-12.48*** (3.82)	-11.18** (4.24)	-14.37*** (3.57)
Time trend			0.04** (0.02)	0.03 (0.02)
Forest area (fraction of grid cell)	1.90*** (0.63)	1.36** (0.63)	1.84*** (0.60)	1.36** (0.62)
Constant	0.40 (2.05)	-195.11*** (55.62)	-85.01** (39.39)	-232.90*** (59.84)
RMSE	1.86	1.74	1.81	1.73
Observations	110	110	110	110
R-squared	0.48	0.55	0.50	0.56
LL	-215.8	-207.8	-213	-206.4
Df	5	7	6	8

Robust standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Note: Model in gray is the model selected to be compared with alternative machine learning methods

FIGURE A7.1: LEVERAGE ANALYSIS REGRESSION ANALYSIS FOR RECREATIONAL SERVICES



Note: The lines on the chart show the average values of leverage and the (normalized) residuals squared. Leverage refers to the influence that individual observations can have on the estimation of the regression model. Points above the horizontal line have higher-than-average leverage; points to the right of the vertical line have larger-than-average residuals. Observations above both lines are considered influential and removed from final estimates. Models to identify influential observations were specified including GNI per capita, weather variables, and population density within a 75km buffer.

TABLE A7.2: REGRESSION ANALYSIS FOR HABITAT AND SPECIES PROTECTION

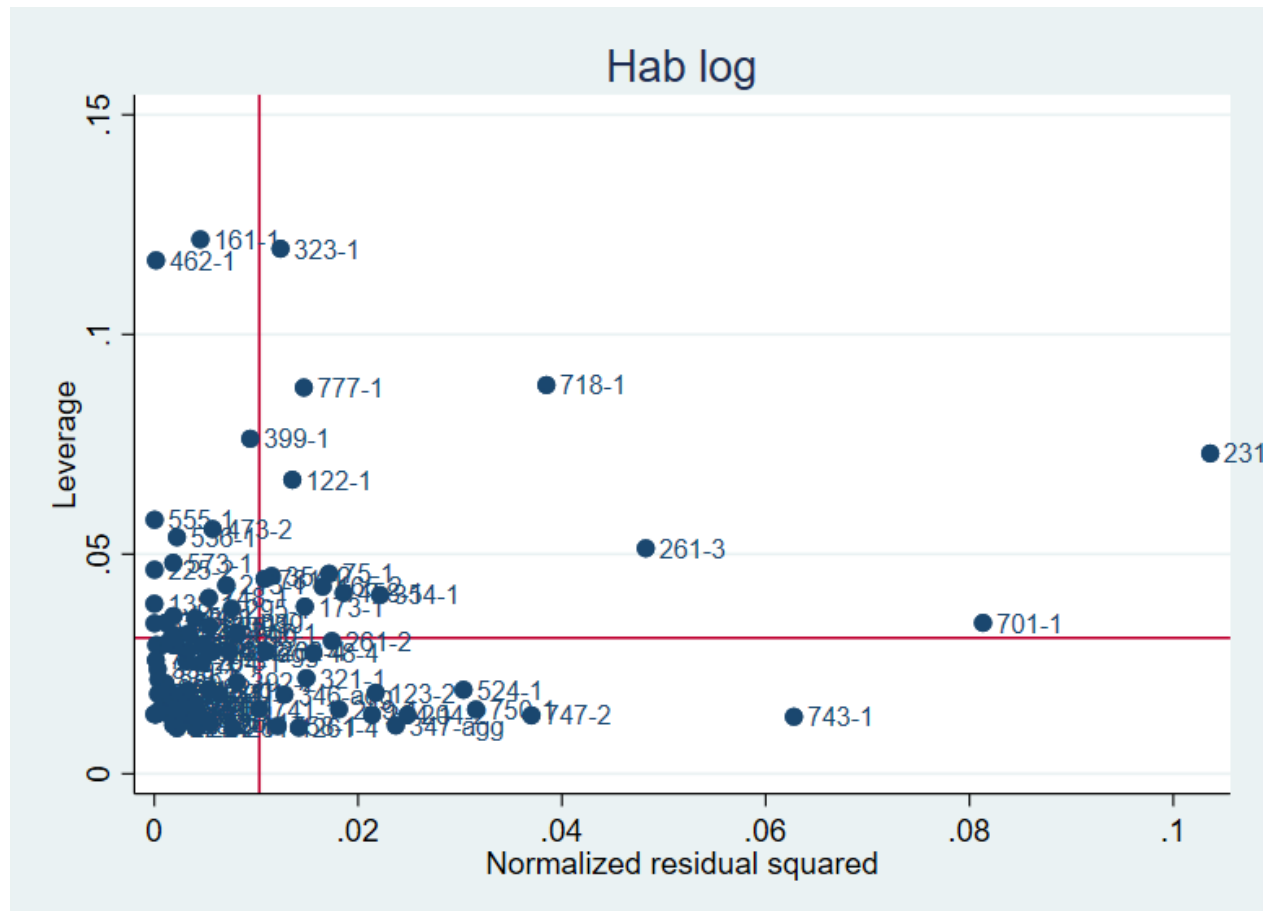
DEPENDENT VARIABLE: VALUE PER HA (LOG, USD PPP 2017)				
VARIABLE	(1)	(2)	(3)	(4)
GNI per capita (log, USD PPP 2017)	0.79** (0.33)	0.70** (0.34)	0.77** (0.34)	0.70** (0.34)
Population density 75km buffer (log, People/Km2)	0.85*** (0.20)	0.93*** (0.20)	0.87*** (0.22)	0.93*** (0.21)
Species threatened (fraction of all species)	-20.83*** (5.30)	-17.39** (5.35)*	-19.86*** (4.93)	-17.36*** (5.07)
Temperature average 1970–2018 (log, K°)		-10.78 (11.36)		-10.74 (11.43)
Precipitation average 1970–2018 (log, annual mm)		-0.40 (0.58)		-0.40 (0.58)
Time trend			-0.01 (0.03)	-0.00 (0.03)
Study site area (log, km ²)	-0.22*** (0.08)	-0.25*** (0.08)	-0.22*** (0.08)	-0.25*** (0.08)
Forest area (fraction of 400km buffer)	3.58*** (1.20)	3.98*** (1.24)	3.72*** (1.20)	3.99*** (1.21)
Road density 400km buffer (log, km roads/km ²)	-110.66 (78.46)	-136.39 (83.46)	-103.68 (77.63)	-136.03 (82.86)
Constant	-4.32 (3.66)	59.94 (62.04)	20.74 (55.15)	60.69 (79.14)
RMSE	2.00	2.01	2.03	2.05
Observations	88	88	88	88
R-squared	0.39	0.42	0.39	0.42
LL	-177.5	-175.4	-177.4	-175.4
Df	7	9	8	10

Robust standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Note: Model in gray is the model selected to be compared with alternative machine learning methods

FIGURE A7.2: LEVERAGE ANALYSIS REGRESSION ANALYSIS FOR HABITAT AND SPECIES PROTECTION



Note: The lines on the chart show the average values of leverage and the (normalized) residuals squared. Leverage refers to the influence that individual observations can have on the estimation of the regression model. Points above the horizontal line have higher-than-average leverage; points to the right of the vertical line have larger-than-average residuals. Observations above both lines are considered influential and removed from final estimates. Models to identify influential observations were specified including GNI per capita, weather variables, population density within a 75km buffer, and study site area.

TABLE A7.3: REGRESSION ANALYSIS FOR NON-WOOD FOREST PRODUCTS

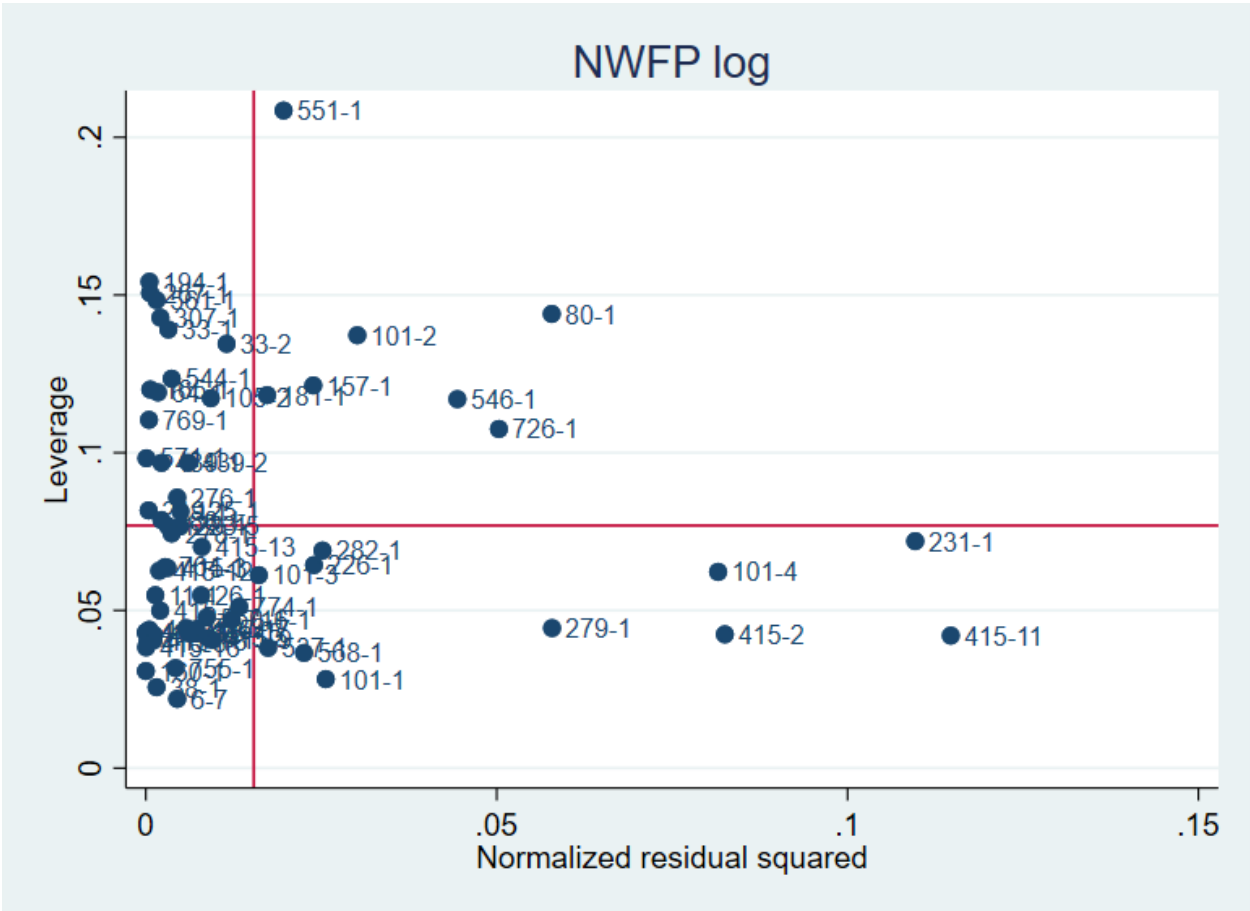
DEPENDENT VARIABLE: VALUE PER HA (LOG, USD PPP 2017)				
VARIABLE	(1)	(2)	(3)	(4)
GNI per capita (log, USD PPP 2017)	-1.11*** (0.20)	-1.11*** (0.17)	-1.14*** (0.21)	-1.13*** (0.17)
Road density 75km buffer (log, km roads/km ²)	135.42** (53.35)	196.97*** (51.23)	133.28** (55.83)	194.17*** (52.49)
Temperature average 1970–2018 (log, K°)		-33.24*** (10.50)		-32.95** (10.22)*
Precipitation average 1970–2018 (log, annual mm)		0.20 (0.38)		0.22 (0.38)
Forest area country (fraction)	6.79*** (0.85)	6.49*** (0.78)	6.93*** (0.91)	6.58*** (0.85)
Species richness (log)	-0.22 (0.42)	1.45* (0.75)	-0.26 (0.47)	1.38* (0.73)
Population density grid cell (log, People/km ²)	0.52*** (0.08)	0.57*** (0.08)	0.52*** (0.09)	0.57*** (0.08)
Time trend			0.01 (0.03)	0.01 (0.03)
Constant	9.61** (4.06)	186.31*** (55.77)	-6.46 (60.46)	172.49** (66.49)
RMSE	1.29	1.22	1.35	1.28
Observations	57	57	57	57
R-squared	0.65	0.71	0.65	0.71
LL	-89.37	-83.92	-89.27	-83.85
Df	6	8	7	9

Robust standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Note: Model in gray is the model selected to be compared with alternative machine learning methods

FIGURE A7.3: LEVERAGE ANALYSIS REGRESSION ANALYSIS FOR NON-WOOD FOREST PRODUCTS



Note: The lines on the chart show the average values of leverage and the (normalized) residuals squared. Leverage refers to the influence that individual observations can have on the estimation of the regression model. Points above the horizontal line have higher-than-average leverage; points to the right of the vertical line have larger-than-average residuals. Observations above both lines are considered influential and removed from final estimates. Models to identify influential observations were specified including GNI per capita, population density within a 75km buffer, fraction of the cell that is protected, and fraction of the country area covered by forest.

TABLE A7.4: REGRESSION ANALYSIS FOR WATER SERVICES

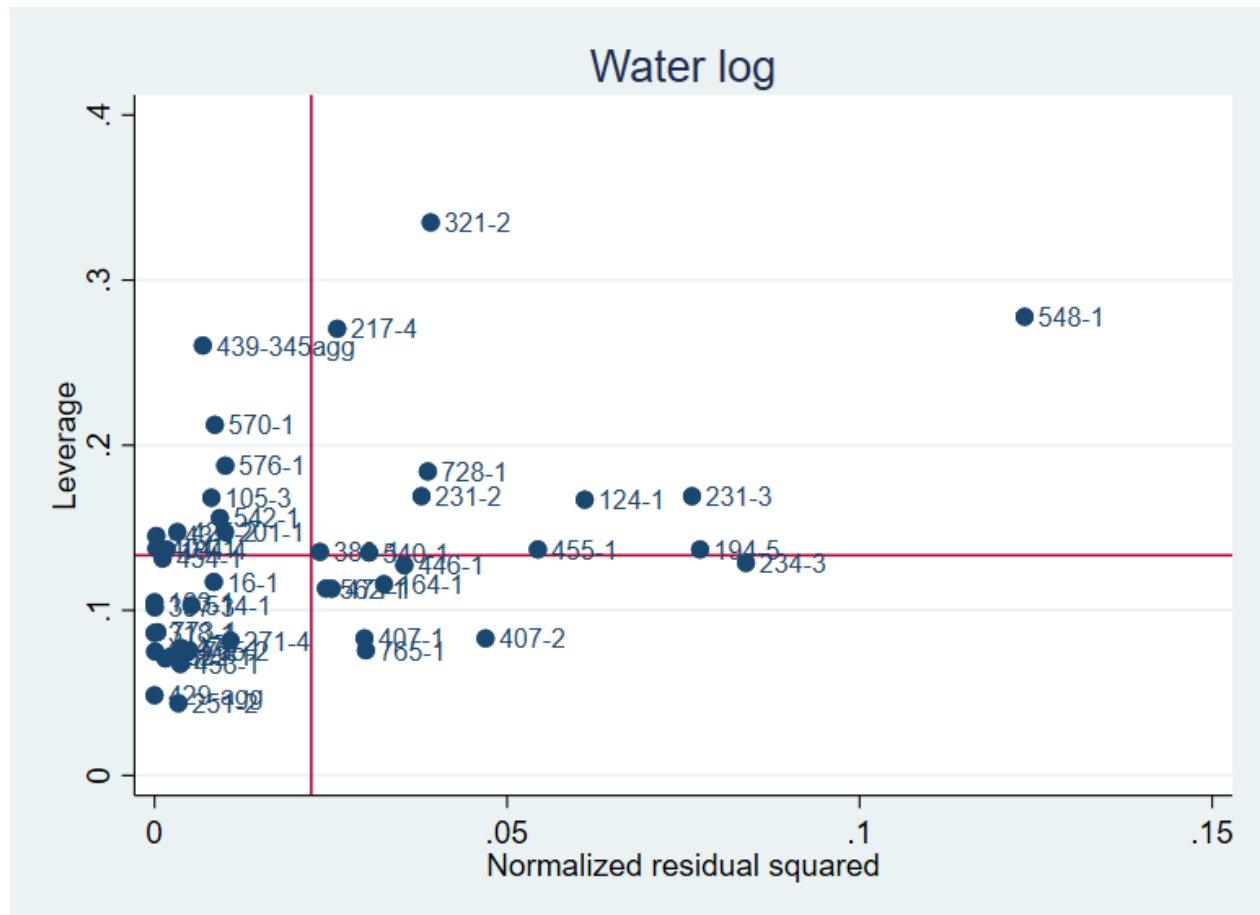
DEPENDENT VARIABLE: VALUE PER HA (LOG, USD PPP 2017)				
VARIABLE	(1)	(2)	(3)	(4)
GNI per capita (log, USD PPP 2017)	1.39** (0.65)	2.02*** (0.63)	1.46* (0.74)	2.18*** (0.70)
Road density 75km buffer (log, km roads/km ²)	166.99 (132.11)	254.19* (142.07)	166.06 (133.97)	256.84* (145.49)
Temperature average 1970–2018 (log, K°)		29.92 (24.26)		31.90 (25.54)
Precipitation average 1970–2018 (log, annual mm)		0.34 (0.87)		0.31 (0.88)
Time trend			-0.02 (0.06)	-0.03 (0.05)
Urban area (fraction 75km buffer)	-41.64** (19.57)	-50.29** (19.08)	-40.89** (19.78)	-49.15** (20.14)
Constant	-9.71 (6.25)	-188.36 (137.45)	21.15 (109.17)	-139.39 (155.09)
RMSE	2.390	2.428	2.453	2.480
Observations	39	39	39	39
R-squared	0.22	0.31	0.22	0.31
LL	-84	-81.81	-83.96	-81.64
Df	4	6	5	7

Robust standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Note: Model in gray is the model selected to be compared with alternative machine learning methods

FIGURE A7.4: LEVERAGE ANALYSIS REGRESSION ANALYSIS FOR WATER SERVICES



Note: The lines on the chart show the average values of leverage and the (normalized) residuals squared. Leverage refers to the influence that individual observations can have on the estimation of the regression model. Points above the horizontal line have higher-than-average leverage; points to the right of the vertical line have larger-than-average residuals. Observations above both lines are considered influential and removed from final estimates. Models to identify influential observations were specify including GNI per capita, weather variables, population density within a 75km buffer, and distance to nearest urban area.

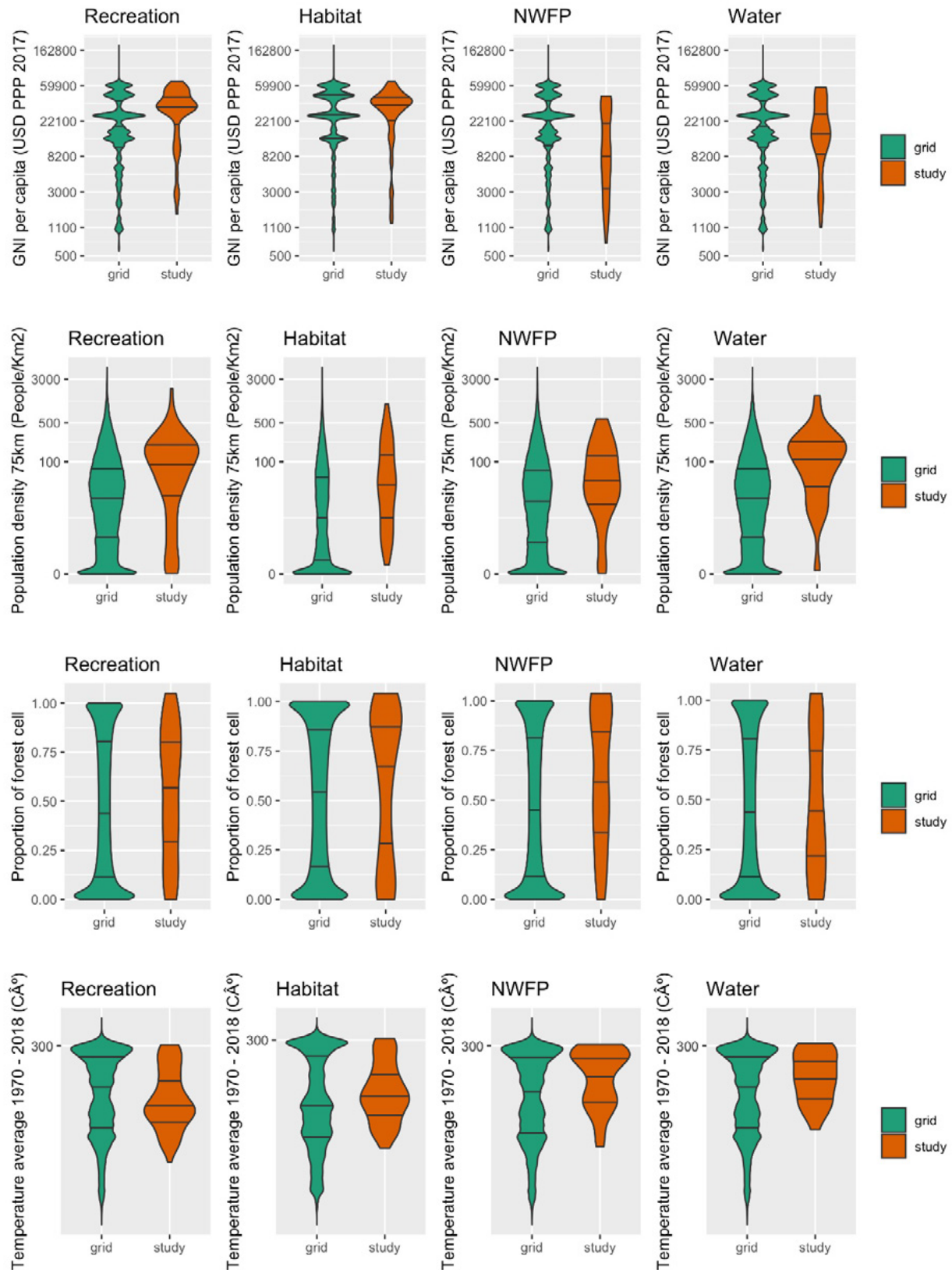
TABLE A7.5: DESCRIPTIVE STATISTICS WORLD GRID FOR 2020

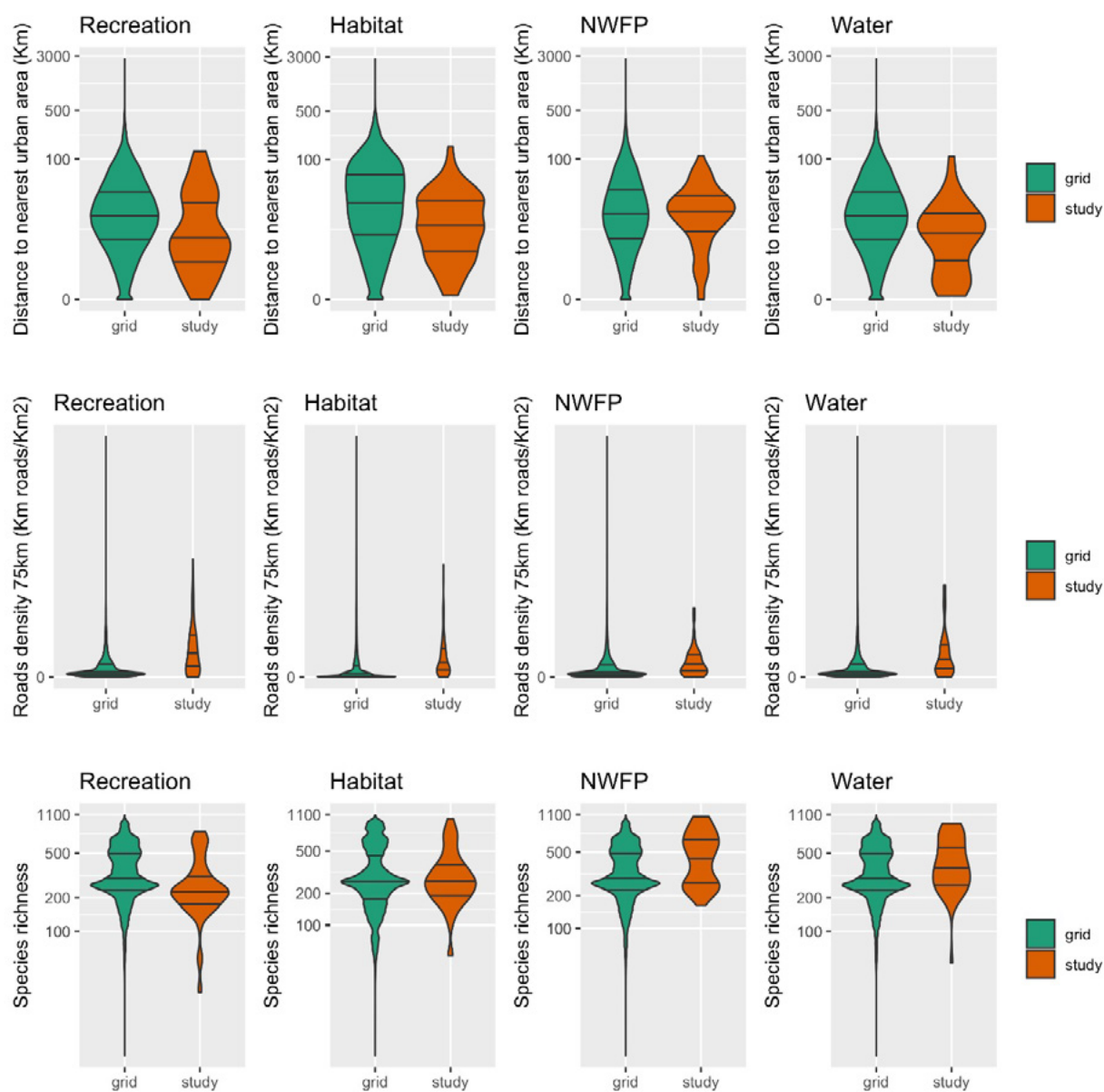
VARIABLE		# OF GRID CELLS	MEAN	STD. DEV.	DISTRIBUTION		
					MIN	MEDIAN	MAX
Socioeconomic	GNI per capita (USD PPP 2013)	1,279,660	26,898.16	18,012.66	0.00	25,953.35	188,915.50
	Continent	Africa (0/1)	1,279,660	0.13	0.34	0	1
		Americas (0/1)	1,279,660	0.36	0.48	0	1
		Asia (0/1)	1,279,660	0.13	0.34	0	1
		Europe (0/1)	1,279,660	0.33	0.47	0	1
		Oceania (0/1)	1,279,660	0.04	0.21	0	1
		Antarctica (0/1)	1,279,660	0.00	0.00	0	1
	Population density (people/km ²)	Cell	1,278,089	51.99277	357.6652	0	1.61754
		75km buffer around the centroid of the grid cell	1,279,466	52.73	153.34	0.00	4.46
		200km buffer around the centroid of the grid cell	1,279,614	53.04	119.62	0.00	7.41
		400km buffer around the centroid of the grid cell	1,279,615	52.87	105.54	0.00	10.80
	Road density (km roads/ha)	Cell	1,279,660	0.0017	0.0054	0	0.0000
		75km buffer around the centroid of the grid cell	1,279,660	0.00	0.00	0	0
		200km buffer around the centroid of the grid cell	1,279,660	0.00	0.00	0	0
		400km buffer around the centroid of the grid cell	1,279,660	0.00	0.00	0	0
	Urban area (fraction of grid cell/buffer)	Cell	1,279,660	0.04	0.04	0	0
		75km buffer around the centroid of the grid cell	1,279,660	0.02	0.02	0	0
		200km buffer around the centroid of the grid cell	1,279,660	0.01	0.01	0	0
		400km buffer around the centroid of the grid cell	1,279,660	0.01	0.01	0	0
	Distance to nearest urban area (km)		1,279,660	50.38	67.37	0.00	25.84

VARIABLE			# OF GRID CELLS	MEAN	STD. DEV.	DISTRIBUTION		
						MIN	MEDIAN	MAX
	IUCN protection category (0/1)	I	1,279,660	0.04	0.20	0		1
		II	1,279,660	0.06	0.23	0		1
		III	1,279,660	0.02	0.12	0		1
		IV	1,279,660	0.06	0.24	0		1
		V	1,279,660	0.03	0.18	0		1
		VI	1,279,660	0.04	0.20	0		1
		Not Reported/Not Applicable/Not Assigned	1,279,660	0.08	0.27	0		1
		Non-protected	1,279,660	0.67	0.47	0		1
	PA fraction of the grid cell		1,279,660	0.18	0.35	0	0	1
	PA area (ha)		1,279,660	13	28	0	0	100
Biophysical and ecological	Species richness		1,279,660	321.64	211.93	3	259.00	1,086.00
	N° mammal species		1,279,660	58.32	40.73	0	45.00	206.00
	N° bird species		1,279,660	217.54	122.02	2.00	194.00	654.00
	Biome	Boreal (0/1)	1,279,660	0.32	0.47	0		1
		Temperate (0/1)	1,279,660	0.16	0.37	0		1
		Tropical (0/1)	1,279,660	0.32	0.47	0		1
	Forest area (fraction of grid cell/ buffer)	Cell	1,279,660	0.46	0.32	0	0.45	1
		75km buffer around the centroid of the grid cell	1,279,660	0.48	0.38	0	0.48	1
		200km buffer around the centroid of the grid cell	1,279,660	0.44	0.29	0	0.41	1
		400km buffer around the centroid of the grid cell	1,279,660	0.40	0.27	0	0.36	1
	Forest area country (fraction)		1,279,287	0.40	0.16	0.00	0.39	0.97
	Latitude (absolute value)		1,279,660	39.47	22.34	0.03	44.25	79.62
Climate	Temperature (°C)		1,278,662	8.63	13.57	-22.65	7.73	35.00
	Rainfall (annual mm)		1,278,662	-0.64	4.78	-112.52	-0.68	67.03
Degra	NDVI trend 1982–2020		1,268,852	0.0014	0.00	-0.0100	0.0014	0.0131

VARIABLE	# OF GRID CELLS	MEAN	STD. DEV.	DISTRIBUTION		
				MIN	MEDIAN	MAX
Forest area change cell 1992–2020 (p.p.)	1,279,660	-0.0034	0.09	-1.00	0.00	0.93
N° species threatened	1,279,660	10.60	7.87	0.00	9.00	77
N° mammals threatened	1,279,660	3.01	3.59	0	2.00	34
N° birds threatened	1,279,660	6.76	4.42	0	6.00	35
Species threatened (fraction of all species)	1,279,660	0.04	0.02	0.00	0.04	0.39
Mammals threatened (fraction of all mammals)	1,279,660	0.05	0.07	0	0.04	1
Birds threatened (fraction of all birds)	1,279,660	0.04	0.02	0	0.03	0
STAR per ha	1,279,630	0.00	0.00	0	0.00	0.07

FIGURE A7.5: VIOLIN DENSITY PLOTS COMPARING VALUES FOR SELECTED VARIABLES BETWEEN THE WORLD GRID AND THE VALUE SITES 2020





Appendix 8

Global predictions by model

To select the model for estimating global predictions, we compared the performance of the different models in the global predictions. Table A8.1 shows the distribution of the global predictions by ecosystem service and model in 2020. Figure A8.1 shows the kernel distribution of the regression and random forest models by ecosystem service in 2020. In this section, we show predictions for the year 2020 as an illustrative year. Predictions are shown in constant 2017 US dollars PPP, because that is the currency used in the estimation dataset. In this section we analyze the predictions at both the grid-cell and country level.

Model prediction at grid-cell level

Table A8.1 shows the predictions distribution for the selected regression models, and for the three machine learning models per ecosystem services. Regression models and AML predictions are dispersed on a larger range of values, reaching very high and low values. Regression models estimate the predicted values using a structural relationship that allows predicting of values out of the range of values in the estimation dataset. Alternatively, RF models predict values by averaging the value of observations in the dataset, making sure their predictions are always bounded within the range of values of the estimation dataset. AML and BART are somewhere in between. The direct implication is that RF models avoid producing outliers, both upwards and downwards. While this can be seen as an advantage, it can also be a disadvantage, given that we know that there is a sub-representation of low value forest sites in the estimation dataset.

The number of observations (number of cells for which values are predicted) vary between services because of the differences in the area explained in Table 9. In addition, the number of cells predicted by the RF models is always larger than that predicted by the regression models. When a cell has a missing value for some of the explanatory variables, the RF models impute a value for that variable, or replace the variable with a highly correlated alternative variable. In contrast, the regression and BART models drop the cell, producing a missing value for every cell that has a missing value for at least one explanatory variable. While this is an advantage of the machine learning models, the number of cells dropped by the regression and BART models is very low, ranging from 0.05–0.2 percent of the total number of cells per service.

When looking at the distribution of the predictions, the selected regression models show a symmetric distribution, while the distribution of the RF models is multimodal (Figure A8.1). Again, this is a result of the nature of the models. The distribution of the prediction in the regression models is imposed by the structural relationship of the parameters. The distribution of the predictions in the RF models is purely empirical, clustering cells that are very similar, and assigning a value from one of the clusters produced in the estimation dataset. The valleys in the distribution are produced because the world grid has cells with different features than the observations in the estimation dataset. This obligates the model to shrink the cells in the world grid to the domain of the observations in the estimation dataset. The modes are highly explained by the distribution of the predictions by continent (see Table A8.1). A priori, this is an expectable result coherent with the method.

In addition, the distribution of the predictions excluding the climate variables shows a multimodal distribution, similar to the RF models. This is true for every service, except for habitat and species protection, for which climate variables were not significant. This highlights the importance of the climate variables in the structure of the prediction model, capturing the climate but also several additional non-observable determinants that are correlated with weather.

NWFPs show high outliers in the regression models, which are driven mostly by low-income countries. The NWFPs and GNI per capita show an inverse relationship in the regression models. When extrapolating this relationship to countries with income level lower than the minimum in the estimation dataset, predictions reach very high values. The high values are kept even after truncating the predictors and the predictions, because the cells have features that add up in the regression model.

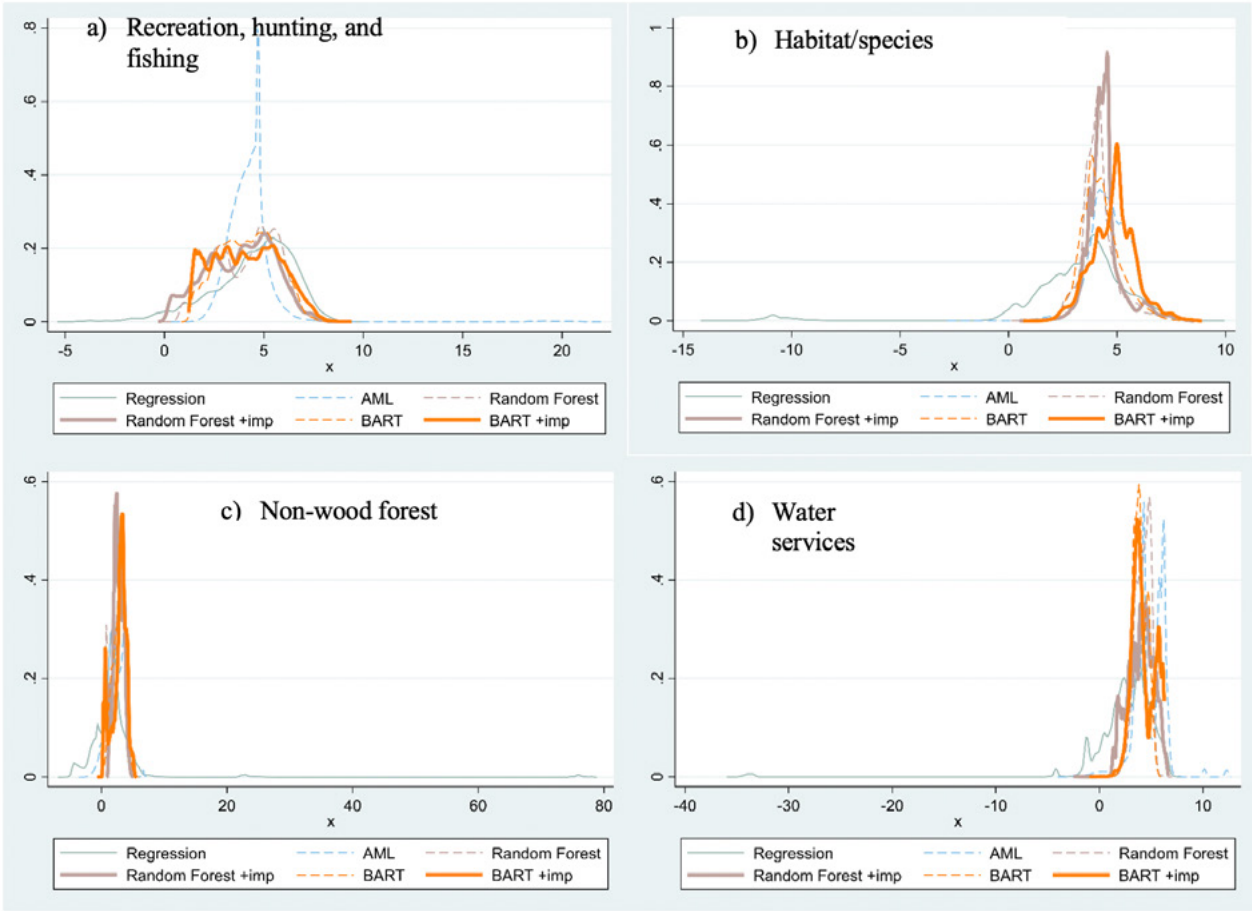
From the above, there is a clear trade-off between models. The regression models bring more robust estimates of the lower tail of the values' prediction by using a structural relationship that allows extrapolation to low forest values. These low values are under-represented in the estimation dataset. However, the same regression models tend to over-estimate the values in the high end of the distribution. Alternatively, the RF models bound the upper values to the values in the estimation dataset, but also bound the lower values.

TABLE A8.1: GLOBAL PREDICTIONS DISTRIBUTION BY MODEL AND ECOSYSTEM SERVICE 2020 (CONSTANT USD 2017 PPP)

MODELS	PERCENTILES														SD	KURTOSIS		SKEWNESS	OBS	RMSE
	1%	5%	10%	25%	50%	75%	90%	95%	99%											
Recreation	Estimation dataset	1.1	2.1	4.5	22.2	148.9	830.5	4,078.8	8,492.3	25,913.1	0.22	28,436	1,531.33	4,240.55	24.97	4.51	139			
	Regression – model (1)	1.5	2.5	4.6	12.4	49.1	153.8	362.8	568.8	1,255.6	0.47	12,392	140.65	275.42	117.80	7.30	764,088	1.86		
	Regression – model (2)	0.1	0.7	2.1	13.8	59.9	201.0	491.1	769.5	1,752.1	0.00	18,799	186.10	367.20	93.63	6.33	763,685	1.74		
	Regression – model (3)	4.5	7.7	14.3	39.7	150.8	458.8	1,028.7	1,586.6	3,739.3	0.96	219,773	459.40	2,015.37	2,785.05	42.42	764,088	1.81		
	Regression – model (4)	0.2	1.7	4.9	28.7	126.3	392.9	881.8	1,349.2	2,984.1	0.00	22,534	340.55	618.89	56.27	5.38	763,685	1.73		
	AML	9.2	16.0	21.8	37.2	70.2	112.3	178.6	284.6	1,341.3	1.40	3,49E+09	2.28E+06	4.27E+07	1,201.03	29.62	764,223	1.83		
	RF	2.5	4.6	6.9	16.0	75.6	216.9	408.4	585.3	1,109.1	0.89	5,339	160.11	233.79	27.58	3.65	764,223	2.12		
	RF most important variables	1.3	2.3	4.2	12.0	54.9	172.6	375.1	592.1	1,510.8	0.72	6,537	152.06	287.84	47.62	5.33	764,223	2.00		
	BART	4.2	6.5	10.0	21.8	68.8	198.8	431.5	631.6	1,157.3	2.36	4,254	162.82	247.33	24.86	3.72	757,668	2.28		
	BART most important variables	4.0	4.9	6.3	16.0	62.6	238.5	583.5	931.7	1,917.2	3.38	12,145	217.26	415.13	59.96	5.47	757,668	2.09		
Habitat/species protection	Estimation dataset	0.0	1.2	5.2	20.5	207.2	789.3	4,407.8	9,365.9	29,695.6	0.01	29,696	1,487.24	3,884.84	31.49	4.83	97			
	Regression – model (1)	0.0	0.7	1.7	6.3	21.1	66.2	168.7	274.6	655.5	0.00	5,995	68.40	170.09	213.43	11.12	467,770	2.00		
	Regression – model (2)	0.0	0.8	1.6	5.7	22.2	68.0	172.2	289.1	772.4	0.00	12,095	75.01	241.96	509.60	18.28	467,215	2.01		
	Regression – model (3)	0.0	0.5	1.3	4.9	16.9	54.4	141.1	232.1	562.3	0.00	5,391	57.45	149.41	236.85	11.81	467,770	2.03		
	Regression – model (4)	0.0	0.8	1.6	5.6	22.0	67.4	170.9	287.0	767.2	0.00	12,025	74.44	240.45	510.56	18.30	467,215	2.05		
	AML	6.3	21.1	33.5	57.4	101.7	203.9	345.0	491.3	1,095.1	0.06	4.2E+03	1.7E+02	2.1E+02	37.36	4.60	212,295	2.43		
	RF	11.2	18.6	27.3	39.8	58.9	86.8	172.8	344.5	1,245.2	1.14	2,916	107.68	203.83	46.44	6.01	212,295	2.97		
	RF most important variables	14.6	28.5	36.2	53.4	75.6	101.8	202.5	497.5	1,548.7	1.66	5,221	136.51	268.13	57.07	6.55	212,295	2.64		
	BART	12.6	19.8	25.4	38.9	63.1	114.8	230.5	369.0	851.4	3.49	3,358	112.19	167.15	52.19	5.67	209,458	2.88		
	BART most important variables	11.7	23.9	33.3	64.8	133.9	233.5	407.9	689.7	1,823.4	1.96	7,392	217.27	343.25	60.03	6.18	209,458	2.75		

	MODELS	PERCENTILES															SD	KURTOSIS		SKEWNESS	OBS	RMSE
		1%	5%	10%	25%	50%	75%	90%	95%	99%	MIN	MAX	MEAN									
NWFPs	Estimation dataset	0.0	0.3	0.4	2.1	11.3	91.6	300.0	322.7	1,665.0	0.01	1,665	110.70	272.36	22.94	4.34	65					
	Regression – model (1)	0.1	0.2	0.4	1.9	5.3	21.0	85.2	239.9	9.3E+09	0.04	5.7E+35	6.4E+32	1.0E+34	536.30	20.43	806,457	1.29				
	Regression – model (2)	0.0	0.1	0.2	1.3	5.2	14.7	67.8	167.8	6.5E+09	0.00	1.8E+34	7.5E+30	1.6E+32	2,311.82	41.78	806,013	1.22				
	Regression – model (3)	0.1	0.3	0.4	2.2	6.0	24.3	100.2	292.0	1.9E+10	0.05	3.3E+36	3.8E+33	6.0E+34	528.15	20.30	806,457	1.35				
	Regression – model (4)	0.0	0.1	0.3	1.4	5.7	16.2	75.9	192.1	1.1E+10	0.00	5.9E+34	2.5E+31	5.4E+32	2,260.04	41.23	806,013	1.28				
	AML	0.4	1.0	1.8	4.0	8.9	26.6	46.0	59.8	113.5	0.03	1,788	21.76	58.73	157.97	11.61	795,571	1.83				
	RF	1.3	1.9	2.3	7.4	16.5	28.8	47.0	56.9	75.4	0.81	178	20.98	17.68	4.45	1.23	795,571	2.36				
	RF most important variables	3.3	4.3	5.8	8.9	14.3	26.7	41.2	50.0	75.8	2.26	160	19.88	15.71	7.38	1.79	795,571	2.07				
Water services	BART	1.9	3.2	4.3	8.3	18.2	34.4	54.7	70.9	111.2	0.61	400	25.21	23.94	13.45	2.39	760,265	2.41				
	BART most important variables	1.3	1.7	2.2	10.3	22.7	37.9	62.3	77.5	143.9	0.51	284	28.99	27.58	9.68	2.15	760,265	2.22				
	Estimation dataset	0.0	0.1	1.2	8.7	63.5	443.1	1,494.9	2,672.5	6,048.2	0.01	6,048	494.05	1,091.31	16.83	3.53	45					
	Regression – model (1)	0.1	1.2	3.1	18.3	58.5	133.8	243.7	294.2	369.6	0.00	1,699	90.88	96.11	4.50	1.38	764,223	2.39				
	Regression – model (2)	0.0	0.3	0.9	4.7	19.1	69.9	206.4	361.3	692.4	0.00	2,940	73.26	137.19	22.27	3.64	763,820	2.43				
	Regression – model (3)	0.1	0.8	2.2	14.3	48.3	116.0	215.5	261.5	328.4	0.00	1,664	78.30	85.67	4.67	1.43	764,223	2.45				
	Regression – model (4)	0.0	0.1	0.5	2.8	12.4	49.0	160.5	290.8	569.9	0.00	2,472	56.19	111.79	22.25	3.72	763,820	2.48				
	AML	0.8	12.0	26.8	54.5	121.7	424.6	558.8	695.5	23,517.0	0.02	3.3E+05	1.5E+03	1.5E+04	193.03	13.65	764,223	2.15				
	RF	10.0	18.7	25.2	38.6	71.3	117.7	155.9	178.0	226.6	0.08	1,140	82.48	53.24	6.19	1.13	764,223	2.79				
	RF most important variables	3.9	6.0	8.9	22.3	59.3	133.0	259.5	356.7	536.4	0.08	775.9	101.76	115.40	7.34	1.99	764,223	2.57				
	BART	7.4	14.6	20.1	31.3	51.6	177.5	331.3	433.6	491.5	0.36	504	117.98	130.63	3.83	1.42	167,330	2.80				
	BART most important variables	8.8	15.0	19.8	29.0	45.9	82.2	125.9	152.2	211.7	1.04	378	61.07	45.12	5.41	1.51	167,330	2.56				

FIGURE A8.1: KERNEL DENSITY DISTRIBUTION OF GLOBAL PREDICTIONS BY MODEL AND ECOSYSTEM SERVICE 2020 (NATURAL LOGARITHM)



Appendix 9

Regional and country-level average predictions per hectare 2020 and total wealth

TABLE A9.1: AVERAGE VALUE PER HECTARE PER SERVICE, TOTAL NON-WOOD FOREST ECOSYSTEM SERVICES, AND PERCENTAGE OF TOTAL AVERAGE VALUE BY PROTECTED AREAS; AND TOTAL WEALTH PER SERVICE AND TOTAL NON-WOOD FOREST ECOSYSTEM SERVICE (CONSTANT USD 2020)

COUNTRY/REGION	AVERAGE VALUE PER HECTARE PER ECOSYSTEM SERVICE (US\$ 2020)				PROTECTED FOREST				WEALTH PER ECOSYSTEM SERVICE (US\$ 2020)					
	TOTAL FOREST													
	Recreation		NWFPs		Water services		Total average value per ha 2020	Recreation		NWFPs		Water services		Total wealth Non-wood forest services
AFRICA	24.3	9.6	36.8	70.7	14.4	8.3	34.9	57.7	2.51E+11	9.95E+10	3.80E+11	7.30E+11	21.6%	
DZA	171.1	9.5	38.5	219.1	224.3	11.2	53.4	288.9	5.42E+09	2.99E+08	1.22E+09	6.94E+09	8.1%	
AGO	11.3	10.3	33.2	54.8	9.4	11.0	43.2	63.6	1.23E+10	1.11E+10	3.59E+10	5.93E+10	3.2%	
BEN	45.3	13.5	42.7	101.5	34.1	12.6	40.7	87.3	2.31E+09	6.86E+08	2.17E+09	5.17E+09	69.2%	
BWA	19.5	7.9	74.5	101.9	7.2	8.5	74.2	89.9	4.83E+09	1.95E+09	1.85E+10	2.52E+10	9.9%	
BFA	24.1	11.0	49.1	84.2	19.9	11.8	58.7	90.4	2.43E+09	1.11E+09	4.96E+09	8.50E+09	16.8%	
BBDI	114.1	16.1	69.9	200.1	157.2	10.7	52.1	220.0	5.18E+08	7.31E+07	3.17E+08	9.09E+08	45.2%	
CMR	70.6	13.2	40.2	123.9	37.3	12.7	33.8	83.9	2.33E+10	4.35E+09	1.33E+10	4.09E+10	13.1%	
CPV	16.3	18.2	69.7	104.3	0.0	0.0	0.0	0.0	1.21E+07	1.35E+07	5.18E+07	7.74E+07	0.0%	
Central African Republic	3.3	6.3	30.1	39.8	1.4	3.7	30.6	35.7	1.21E+09	2.28E+09	1.09E+10	1.44E+10	0.7%	
TCD	14.6	10.3	35.4	60.3	8.4	8.2	45.8	62.4	1.02E+09	7.23E+08	2.48E+09	4.23E+09	41.5%	
COM	16.1	17.2	19.6	52.8	21.1	26.0	15.2	62.3	8.61E+06	9.19E+06	1.05E+07	2.83E+07	0.0%	
Côte d'Ivoire	47.6	6.7	46.2	100.5	38.3	5.4	42.6	86.3	2.19E+09	3.09E+08	2.13E+09	4.63E+09	39.4%	
Democratic Republic of Congo	24.1	9.7	33.9	67.7	8.8	6.6	26.9	42.3	4.95E+10	1.98E+10	6.94E+10	1.39E+11	12.0%	
Djibouti	53.6	21.2	14.2	89.0	0.0	0.0	0.0	0.0	5.05E+06	2.00E+06	1.34E+06	8.39E+06	0.0%	
Egypt	40.2	4.1	2.8	47.1	0.0	0.0	0.0	0.0	2.94E+07	3.02E+06	2.06E+06	3.44E+07	..	
Equatorial Guinea	19.5	11.8	37.1	68.3	22.8	14.6	25.5	62.9	7.74E+08	4.71E+08	1.47E+09	2.72E+09	10.3%	
Eritrea	64.0	12.3	61.2	137.6	38.0	9.3	40.2	87.5	1.10E+09	2.11E+08	1.05E+09	2.36E+09	6.4%	
Ethiopia	13.7	10.7	38.2	62.6	9.9	9.2	37.9	57.0	3.79E+09	2.96E+09	1.06E+10	1.74E+10	..	
GAB	4.5	9.7	22.1	36.3	3.5	10.1	18.5	32.0	1.72E+09	3.69E+09	8.46E+09	1.39E+10	12.7%	
GMB	43.3	12.6	54.7	110.6	44.0	11.3	33.9	89.2	1.71E+08	4.96E+07	2.16E+08	4.36E+08	7.4%	
Ghana	44.2	7.8	49.7	101.7	47.2	8.0	47.5	102.7	5.73E+09	1.01E+09	6.44E+09	1.32E+10	18.0%	

COUNTRY/REGION	AVERAGE VALUE PER HECTARE PER ECOSYSTEM SERVICE (US\$ 2020)				WEALTH PER ECOSYSTEM SERVICE (US\$ 2020)								
	TOTAL FOREST				PROTECTED FOREST								
	Recreation	NWFPs	Water services	Total average value per ha 2020	Recreation	NWFPs	Water services	Total average value per ha 2020					
GIN	21.3	11.4	46.6	79.3	12.4	11.2	45.9	69.5	2.15E+09	1.14E+09	4.69E+09	7.98E+09	42.5%
GNB	42.3	12.7	42.2	97.2	41.1	12.2	38.3	91.6	1.36E+09	4.09E+08	1.36E+09	3.13E+09	1.2%
KEN	32.2	11.4	55.4	99.1	35.6	11.2	44.0	90.8	1.89E+09	6.72E+08	3.25E+09	5.81E+09	29.9%
LSO	67.3	4.9	81.0	153.1	45.5	4.8	107.9	158.2	3.77E+07	2.74E+06	4.54E+07	8.59E+07	15.0%
LBR	39.7	11.1	65.4	116.1	36.4	11.0	50.4	97.9	4.91E+09	1.37E+09	8.10E+09	1.44E+10	..
LBY	77.4	11.2	43.2	131.7	72.0	9.3	11.0	92.3	2.73E+08	3.94E+07	1.52E+08	4.64E+08	..
MDG	12.0	9.1	41.8	62.9	11.0	7.7	25.5	44.2	2.42E+09	1.83E+09	8.45E+09	1.27E+10	28.1%
MWI	21.7	11.9	40.6	74.2	18.6	8.5	35.3	62.4	7.92E+08	4.33E+08	1.48E+09	2.70E+09	28.4%
MLI	16.9	11.3	39.6	67.8	16.9	10.7	37.7	65.3	3.65E+09	2.44E+09	8.56E+09	1.46E+10	21.4%
MRT	19.9	6.0	20.6	46.6	31.4	9.6	100.7	141.7	1.01E+08	3.07E+07	1.05E+08	2.37E+08	48.6%
MUS	493.7	33.4	19.1	546.2	0.0	0.0	0.0	0.0	3.11E+08	2.10E+07	1.20E+07	3.44E+08	0.0%
MYT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..
MAR	118.7	7.8	69.0	195.5	112.9	8.1	69.2	190.2	1.11E+10	7.25E+08	6.44E+09	1.82E+10	4.4%
MOZ	12.7	10.5	33.4	56.6	7.1	10.0	32.6	49.7	7.55E+09	6.29E+09	2.00E+10	3.38E+10	36.4%
NAM	18.6	6.6	60.3	85.6	10.8	6.0	53.3	70.1	2.01E+09	7.17E+08	6.50E+09	9.23E+09	20.8%
NER	29.4	11.6	18.5	59.5	7.4	5.9	4.2	17.5	5.16E+08	2.04E+08	3.24E+08	1.04E+09	6.0%
NGA	73.4	14.4	39.1	126.9	40.1	11.4	31.3	82.8	2.58E+10	5.08E+09	1.37E+10	4.46E+10	8.7%
COG	16.4	7.8	31.7	56.0	2.7	6.9	29.5	39.0	5.86E+09	2.80E+09	1.13E+10	2.00E+10	12.4%
REU	193.4	59.5	91.7	344.6	200.2	64.7	95.8	360.7	3.09E+08	9.51E+07	1.47E+08	5.51E+08	64.0%
RWA	181.8	19.8	53.0	254.5	176.6	10.8	43.8	231.2	8.15E+08	8.86E+07	2.38E+08	1.14E+09	69.4%
SHN	49.4	5.7	91.8	146.8	0.0	0.0	0.0	0.0	1.60E+06	1.84E+05	2.98E+06	4.77E+06	..
STP	15.5	17.1	0.6	33.2	17.5	12.5	0.6	30.6	1.31E+07	1.44E+07	5.27E+05	2.80E+07	52.3%
SEN	40.3	13.7	57.6	111.6	35.1	13.8	59.6	108.5	5.29E+09	1.79E+09	7.55E+09	1.46E+10	90.4%
SYC	8.9	17.9	0.7	27.5	0.0	0.0	0.0	0.0	4.87E+06	9.78E+06	3.89E+05	1.50E+07	..

COUNTRY/REGION	AVERAGE VALUE PER HECTARE PER ECOSYSTEM SERVICE (US\$ 2020)						WEALTH PER ECOSYSTEM SERVICE (US\$ 2020)						
	TOTAL FOREST			PROTECTED FOREST			Recreation			NWFPs			
	Recreation	NWFPs	Water services	Total average value per ha 2020	Recreation	NWFPs	Water services	Total average value per ha 2020	Recreation	NWFPs	Water services	Total wealth Non-wood forest services	% Protected areas
SLE	41.6	10.5	44.9	97.0	48.6	10.0	45.6	104.3	1.71E+09	4.33E+08	1.85E+09	4.00E+09	10.1%
SOM	18.8	8.6	63.8	91.2	0.0	0.0	0.0	0.0	1.83E+09	8.33E+08	6.20E+09	8.86E+09	..
ZAF	134.7	7.0	86.4	228.1	119.0	6.5	95.0	220.5	3.73E+10	1.94E+09	2.39E+10	6.32E+10	1.3%
SSD	0.5	0.7	2.9	4.1	0.4	0.6	3.9	4.9	6.12E+07	8.05E+07	3.33E+08	4.74E+08	..
SDN	25.2	11.5	60.3	97.0	19.6	17.3	113.4	150.3	7.52E+09	3.44E+09	1.80E+10	2.89E+10	39.8%
SWZ	130.1	6.9	53.5	190.5	171.9	5.9	43.8	221.6	1.05E+09	5.54E+07	4.33E+08	1.54E+09	5.4%
TZA	7.5	6.9	31.3	45.7	4.1	5.6	26.2	35.9	5.55E+09	5.13E+09	2.33E+10	3.39E+10	49.0%
TGO	40.9	14.6	56.6	112.1	38.4	15.1	33.8	87.3	8.04E+08	2.87E+08	1.11E+09	2.20E+09	12.6%
TUN	78.6	6.9	40.8	126.3	78.3	6.9	43.3	128.6	8.97E+08	7.90E+07	4.66E+08	1.44E+09	10.9%
UGA	22.8	14.8	30.0	67.5	29.6	14.2	36.3	80.1	8.65E+08	5.61E+08	1.14E+09	2.56E+09	..
ZMB	16.4	10.2	33.5	60.1	13.2	10.0	34.0	57.1	1.19E+10	7.42E+09	2.44E+10	4.37E+10	67.6%
ZWE	53.9	20.3	79.4	153.5	18.7	18.0	90.7	127.4	1.53E+10	5.74E+09	2.25E+10	4.35E+10	14.6%
ASIA	100.2	13.9	56.8	170.9	70.0	11.3	42.1	123.4	1.01E+12	1.41E+11	5.75E+11	1.73E+12	18.1%
AFG	36.9	14.5	27.3	78.7	33.0	17.1	45.2	95.3	7.24E+08	2.85E+08	5.36E+08	1.55E+09	..
ARM	98.5	3.6	39.8	141.8	94.9	3.6	39.4	138.0	5.25E+08	1.93E+07	2.12E+08	7.57E+08	..
AZE	72.1	3.9	34.8	110.8	78.0	4.1	29.3	111.4	1.33E+09	7.25E+07	6.39E+08	2.04E+09	33.0%
BHR	369.5	15.6	9.5	394.5	0.0	0.0	0.0	0.0	4.20E+06	1.77E+05	1.08E+05	4.49E+06	..
BGD	168.2	15.3	57.7	241.2	76.0	10.4	92.1	178.5	5.15E+09	4.67E+08	1.76E+09	7.38E+09	24.3%
BTN	13.2	13.6	37.2	63.9	10.5	11.7	23.3	45.4	5.85E+08	6.00E+08	1.65E+09	2.83E+09	28.8%
BRN	29.1	9.1	49.0	87.1	20.8	7.1	19.9	47.8	1.79E+08	5.59E+07	3.02E+08	5.38E+08	2.7%
KHM	24.6	15.6	63.1	103.4	22.8	14.7	59.6	97.0	3.23E+09	2.04E+09	8.27E+09	1.35E+10	36.5%
CHN	145.6	17.3	75.0	237.9	108.8	16.7	92.5	218.0	5.20E+11	6.19E+10	2.68E+11	8.50E+11	12.6%
CXR	76.4	49.6	15.2	141.2	76.2	62.2	2.4	140.8	..	..	..	..	..
CYP	154.3	27.0	65.0	246.2	151.7	25.1	54.8	231.6	4.32E+08	7.57E+07	1.82E+08	6.90E+08	9.5%

COUNTRY/REGION	AVERAGE VALUE PER HECTARE PER ECOSYSTEM SERVICE (US\$ 2020)								WEALTH PER ECOSYSTEM SERVICE (US\$ 2020)							
	TOTAL FOREST				PROTECTED FOREST											
	Recreation	NWFPS	Water services	Total average value per ha 2020	Recreation	NWFPS	Water services	Total average value per ha 2020	Recreation	NWFPS	Water services	Recreation	NWFPS	Water services	Total wealth Non-wood forest	% Protected areas
TLS	72.9	16.6	50.0	139.5	63.5	16.5	45.2	125.3	1.09E+09	2.49E+08	7.48E+08	2.09E+09	2.49E+08	7.48E+08	2.09E+09	..
GEO	65.6	3.7	45.3	114.6	74.4	3.8	44.4	122.7	3.01E+09	1.71E+08	2.08E+09	5.25E+09	1.71E+08	2.08E+09	5.25E+09	12.0%
HKG	1695.7	29.7	85.5	1811.0	1837.5	21.7	69.4	1928.6	..	..	..	..	..	..	..	..
IND	74.0	13.9	49.1	136.9	83.1	12.9	38.1	134.0	8.68E+10	1.62E+10	5.75E+10	1.61E+11	1.62E+10	5.75E+10	1.61E+11	19.0%
IDN	30.7	8.2	34.1	73.1	20.9	5.9	18.0	44.8	4.60E+10	1.23E+10	5.10E+10	1.09E+11	1.23E+10	5.10E+10	1.09E+11	34.4%
IRN	172.2	7.1	67.0	246.2	248.9	7.8	60.8	317.5	3.01E+10	1.24E+09	1.17E+10	4.30E+10	1.24E+09	1.17E+10	4.30E+10	18.1%
IRQ	50.4	8.3	61.2	120.0	50.3	7.1	54.3	111.7	6.76E+08	1.12E+08	8.21E+08	1.61E+09	1.12E+08	8.21E+08	1.61E+09	0.0%
ISR	1669.4	51.9	154.1	1875.4	1624.3	56.1	228.7	1909.1	3.80E+09	1.18E+08	3.50E+08	4.27E+09	1.18E+08	3.50E+08	4.27E+09	21.8%
JPN	279.1	29.2	122.1	430.3	339.8	31.2	111.4	482.3	1.13E+11	1.18E+10	4.95E+10	1.74E+11	1.18E+10	4.95E+10	1.74E+11	..
JOR	381.2	21.4	11.8	414.4	0.0	0.0	0.0	0.0	6.04E+08	3.39E+07	1.86E+07	6.56E+08	6.04E+08	3.39E+07	1.86E+07	..
KAZ	20.5	4.5	20.8	45.7	27.3	5.0	20.8	53.1	1.15E+09	2.51E+08	1.17E+09	2.57E+09	1.15E+09	2.51E+08	1.17E+09	37.7%
KGZ	48.1	2.2	13.5	63.7	33.2	2.4	14.5	50.1	1.03E+09	4.67E+07	2.88E+08	1.36E+09	1.03E+09	4.67E+07	2.88E+08	6.2%
LAO	17.3	6.0	49.5	72.9	21.1	6.3	50.6	78.0	4.67E+09	1.62E+09	1.34E+10	1.96E+10	4.67E+09	1.62E+09	1.34E+10	..
LBN	504.1	23.8	57.5	585.4	556.2	23.2	52.9	632.3	1.17E+09	5.55E+07	1.34E+08	1.36E+09	1.17E+09	5.55E+07	1.34E+08	..
MAC	816.9	40.4	37.6	895.0	0.0	0.0	0.0	0.0	..	..	..	..	..	..	..	..
MYS	53.7	8.5	37.1	99.3	56.7	9.0	25.6	91.4	1.67E+10	2.64E+09	1.15E+10	3.08E+10	1.67E+10	2.64E+09	1.15E+10	16.6%
MNG	1.9	2.0	10.6	14.6	1.0	1.2	6.0	8.1	4.43E+08	4.61E+08	2.45E+09	3.35E+09	4.43E+08	4.61E+08	2.45E+09	11.7%
MMR	31.0	8.6	28.9	68.5	6.3	5.8	24.7	36.7	1.44E+10	3.98E+09	1.34E+10	3.17E+10	1.44E+10	3.98E+09	1.34E+10	9.8%
NPL	64.3	13.6	65.3	143.2	69.2	13.9	55.8	138.9	6.23E+09	1.32E+09	6.33E+09	1.39E+10	6.23E+09	1.32E+09	6.33E+09	56.0%
PRK	195.0	32.5	130.0	357.4	192.9	34.2	116.4	343.4	1.91E+10	3.18E+09	1.27E+10	3.50E+10	1.91E+10	3.18E+09	1.27E+10	..
OMN	94.5	11.2	81.2	186.9	85.0	12.3	109.1	206.4	3.84E+06	4.53E+05	3.30E+06	7.59E+06	3.84E+06	4.53E+05	3.30E+06	..
PAK	94.4	18.0	37.1	149.6	65.6	23.3	47.4	136.3	5.72E+09	1.09E+09	2.25E+09	9.06E+09	5.72E+09	1.09E+09	2.25E+09	..
PSE	1276.2	26.8	133.5	1436.5	1208.3	24.0	19.3	1251.5	2.10E+08	4.42E+06	2.20E+07	2.37E+08	2.10E+08	4.42E+06	2.20E+07	..

COUNTRY/REGION	AVERAGE VALUE PER HECTARE PER ECOSYSTEM SERVICE (US\$ 2020)								WEALTH PER ECOSYSTEM SERVICE (US\$ 2020)				
	TOTAL FOREST				PROTECTED FOREST								
	Recreation	NWFPs	Water services	Total average value per ha 2020	Recreation	NWFPs	Water services	Total average value per ha 2020	Recreation	NWFPs	Water services	Total wealth Non-wood forest services	% Protected areas
PHL	58.0	23.0	36.9	117.9	66.7	21.3	29.4	117.4	6.77E+09	2.69E+09	4.31E+09	1.38E+10	28.1%
QAT	492.9	13.4	20.7	527.0	507.5	12.0	19.0	538.6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..
SAU	71.2	15.1	66.2	152.5	91.7	12.2	43.1	147.0	1.13E+09	2.40E+08	1.05E+09	2.42E+09	0.3%
SGP	1203.4	60.5	174.6	1438.5	0.0	0.0	0.0	0.0	3.04E+08	1.53E+07	4.42E+07	3.64E+08	0.0%
KOR	313.0	26.7	103.8	443.4	294.0	27.3	119.9	441.3	3.20E+10	2.72E+09	1.06E+10	4.53E+10	6.9%
LKA	162.2	21.5	41.7	225.4	82.4	16.7	52.2	151.4	5.57E+09	7.37E+08	1.43E+09	7.74E+09	40.0%
SYR	350.2	35.0	129.3	514.6	0.0	0.0	0.0	0.0	2.97E+09	2.97E+08	1.10E+09	4.36E+09	..
TWN	1178.6	31.0	100.7	1310.3	931.4	32.0	61.8	1025.2	..	..	..	..	..
TJK	52.9	3.3	9.0	65.1	69.2	3.4	17.5	90.1	3.64E+08	2.24E+07	6.17E+07	4.48E+08	..
THA	67.9	12.7	53.8	134.4	57.4	12.2	52.0	121.6	2.19E+10	4.10E+09	1.74E+10	4.34E+10	..
TUR	111.8	8.4	43.9	164.1	74.1	8.8	53.7	136.7	4.04E+10	3.04E+09	1.59E+10	5.93E+10	27.8%
TKM	53.6	8.8	8.1	70.5	32.6	10.5	6.6	49.7	3.60E+09	5.89E+08	5.44E+08	4.73E+09	..
ARE	349.2	9.4	78.0	436.6	92.2	11.1	9.2	112.5	1.80E+09	4.84E+07	4.02E+08	2.25E+09	..
UZB	91.8	3.1	26.2	121.1	96.2	3.2	31.0	130.4	5.50E+09	1.85E+08	1.57E+09	7.26E+09	100%
VNM	81.8	15.8	51.8	149.4	74.5	14.8	45.0	134.2	1.95E+10	3.76E+09	1.23E+10	3.56E+10	13.4%
YEM	233.3	59.1	177.2	469.6	34.2	5.6	20.9	60.7	2.08E+09	5.27E+08	1.58E+09	4.19E+09	0.7%
AMERICAS	58.9	6.3	46.9	112.1	45.3	5.6	32.2	83.0	1.53E+12	1.63E+11	1.22E+12	2.91E+12	16.1%
AIA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..
ATG	6.9	8.9	32.7	48.5	0.0	0.0	0.0	0.0	9.11E+05	1.18E+06	4.31E+06	6.40E+06	..
ARG	38.5	11.1	94.3	143.9	43.7	12.0	79.4	135.1	1.79E+10	5.14E+09	4.38E+10	6.68E+10	6.3%
ABW	79.5	31.3	17.9	128.8	0.0	0.0	0.0	0.0	5.43E+05	2.14E+05	1.22E+05	8.79E+05	..
BHS	41.6	14.4	83.7	139.8	16.8	2.4	28.7	48.0	3.45E+08	1.20E+08	6.93E+08	1.16E+09	..
BRB	237.5	103.4	165.0	505.9	0.0	0.0	0.0	0.0	2.43E+07	1.06E+07	1.69E+07	5.18E+07	0.0%

COUNTRY/REGION	AVERAGE VALUE PER HECTARE PER ECOSYSTEM SERVICE (US\$ 2020)						WEALTH PER ECOSYSTEM SERVICE (US\$ 2020)								
	TOTAL FOREST			PROTECTED FOREST			Recreation			Water services			Total wealth		% Protected areas
	Recreation	NWFPs	Water services	Total average value per ha 2020	Recreation	NWFPs	Water services	Total average value per ha 2020	Recreation	NWFPs	Water services	Non-wood forest			
BLZ	37.6	13.1	75.9	126.5	42.9	11.6	54.1	108.5	7.79E+08	2.71E+08	1.57E+09	2.62E+09	50.9%		
BMU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	.		
BOL	5.0	5.8	38.8	49.6	3.5	5.3	32.2	40.9	4.11E+09	4.77E+09	3.21E+10	4.09E+10	20.2%		
BES	98.0	11.5	99.6	209.2	0.0	0.0	0.0	0.0	3.04E+06	3.58E+05	3.09E+06	6.49E+06	0.0%		
BRA	27.4	6.5	45.0	78.9	14.3	5.0	26.7	46.0	2.21E+11	5.27E+10	3.63E+11	6.37E+11	17.6%		
VGB	276.3	80.0	104.9	461.1	0.0	0.0	0.0	0.0	1.62E+07	4.71E+06	6.17E+06	2.71E+07	..		
CAN	17.1	2.3	19.9	39.4	6.6	1.4	14.7	22.7	9.66E+10	1.32E+10	1.12E+11	2.22E+11	4.9%		
CYM	45.7	47.5	118.3	211.5	0.0	0.0	0.0	0.0	9.44E+06	9.82E+06	2.44E+07	4.37E+07	0.0%		
CHL	43.8	7.3	54.1	105.2	13.5	4.4	37.1	55.0	1.30E+10	2.16E+09	1.60E+10	3.11E+10	10.9%		
COL	58.6	5.8	32.0	96.4	57.7	4.6	21.2	83.6	5.63E+10	5.57E+09	3.08E+10	9.26E+10	18.2%		
CRI	170.4	15.0	63.3	248.8	186.4	13.4	51.8	251.6	8.40E+09	7.40E+08	3.12E+09	1.23E+10	43.4%		
CUB	196.4	43.3	121.2	360.8	165.9	38.9	82.8	287.5	1.03E+10	2.28E+09	6.38E+09	1.90E+10	15.9%		
CUW	106.3	14.0	182.1	302.4	0.0	0.0	0.0	0.0	1.21E+05	1.60E+04	2.07E+05	3.44E+05	..		
DMA	55.2	50.3	17.7	123.2	0.0	0.0	0.0	0.0	4.29E+07	3.91E+07	1.37E+07	9.58E+07	0.0%		
DOM	134.4	29.7	39.3	203.4	103.0	28.4	26.3	157.8	4.68E+09	1.03E+09	1.37E+09	7.09E+09	..		
ECU	97.8	8.7	36.5	143.0	123.2	6.2	23.1	152.4	1.99E+10	1.76E+09	7.40E+09	2.90E+10	27.8%		
SLV	116.8	21.3	64.6	202.7	118.7	20.7	76.0	215.4	1.11E+09	2.02E+08	6.13E+08	1.92E+09	3.1%		
FLK	10.2	3.0	73.3	86.4	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..		
GUF	7.1	10.3	47.7	65.1	3.8	9.1	36.0	49.0	9.22E+08	1.34E+09	6.20E+09	8.46E+09	23.2%		
GRL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..		
GRD	8.2	4.2	19.3	31.6	0.0	0.0	0.0	0.0	2.36E+06	1.20E+06	5.54E+06	9.10E+06	0.0%		
GLP	230.3	56.0	56.8	343.1	223.2	50.0	35.7	308.8	2.69E+08	6.54E+07	6.64E+07	4.01E+08	28.9%		

COUNTRY/REGION	AVERAGE VALUE PER HECTARE PER ECOSYSTEM SERVICE (US\$ 2020)						WEALTH PER ECOSYSTEM SERVICE (US\$ 2020)							
	TOTAL FOREST			PROTECTED FOREST			Recreation			NWFPs				
	Recreation	NWFPs	Water services	Total average value per ha 2020	Recreation	NWFPs	Water services	Total average value per ha 2020	Recreation	NWFPs	Water services	Total wealth Non-wood forest	% Protected areas	
GTM	Guatemala	88.2	12.3	65.4	165.9	41.3	8.4	48.4	98.1	5.06E+09	7.04E+08	3.75E+09	9.51E+09	31.0%
GUY	Guyana	2.2	4.1	23.0	29.2	0.4	7.3	13.5	21.3	6.46E+08	1.22E+09	6.87E+09	8.73E+09	4.0%
HTI	Haiti	159.5	43.0	45.0	247.6	151.8	36.3	36.2	224.3	9.00E+08	2.43E+08	2.54E+08	1.40E+09	8.3%
HND	Honduras	52.6	10.8	49.7	113.1	25.0	10.0	27.0	62.0	5.43E+09	1.12E+09	5.14E+09	1.17E+10	17.7%
JAM	Jamaica	175.3	29.7	39.2	244.2	170.6	29.3	17.8	217.6	1.70E+09	2.88E+08	3.80E+08	2.37E+09	19.7%
MTQ	Martinique	213.0	75.4	115.6	403.9	214.3	69.9	104.4	388.5	1.81E+08	6.40E+07	9.82E+07	3.43E+08	24.2%
MEX	Mexico	78.1	9.9	56.0	144.0	94.6	7.6	50.4	152.6	8.33E+10	1.06E+10	5.98E+10	1.54E+11	..
NIC	Nicaragua	35.1	8.8	34.9	78.8	13.0	7.0	27.8	47.8	1.94E+09	4.86E+08	1.93E+09	4.36E+09	23.8%
PAN	Panama	34.5	9.4	27.0	70.9	25.1	7.7	15.8	48.6	2.36E+09	6.43E+08	1.85E+09	4.86E+09	32.9%
PRY	Paraguay	15.7	4.8	54.5	75.0	4.2	3.0	44.1	51.4	4.12E+09	1.24E+09	1.43E+10	1.96E+10	..
PER	Peru	8.5	6.2	22.7	37.4	3.3	5.8	10.7	19.8	9.93E+09	7.34E+09	2.67E+10	4.39E+10	16.8%
PRI	Puerto Rico	695.9	60.2	62.8	818.8	1386.8	60.4	1.4	1448.5	5.61E+09	4.85E+08	5.06E+08	6.60E+09	..
KNA	Saint Kitts and Nevis	46.8	68.0	47.0	161.9	0.0	0.0	0.0	0.0	8.36E+06	1.22E+07	8.41E+06	2.89E+07	..
LCA	Saint Lucia	102.0	74.0	25.0	201.1	0.0	0.0	0.0	0.0	3.44E+07	2.50E+07	8.45E+06	6.78E+07	0.0%
SPM	Saint Pierre and Miquelon	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..
VCV	Saint Vincent and the Grenadines	54.4	48.8	17.3	120.5	56.9	37.3	2.1	96.3	2.52E+07	2.26E+07	8.03E+06	5.59E+07	36.8%
SXM	Sint Maarten	51.8	79.8	154.3	285.9	0.0	0.0	0.0	0.0	3.11E+05	4.80E+05	9.28E+05	1.72E+06	0.0%
SUR	Suriname	2.0	1.5	12.5	16.1	1.6	0.9	6.3	8.9	5.03E+08	3.77E+08	3.09E+09	3.97E+09	6.9%
TTO	Trinidad and Tobago	126.2	21.8	47.0	195.0	97.3	13.8	25.7	136.7	4.68E+08	8.07E+07	1.74E+08	7.23E+08	6.0%
TCA	Turks and Caicos Islands	19.6	36.7	45.2	101.5	0.0	0.0	0.0	0.0	3.35E+06	6.28E+06	7.72E+06	1.74E+07	..
USA	United States	199.3	8.7	97.0	305.0	243.3	5.8	70.4	319.4	1.00E+12	4.36E+10	4.88E+11	1.54E+12	10.7%

COUNTRY/REGION	AVERAGE VALUE PER HECTARE PER ECOSYSTEM SERVICE (US\$ 2020)					WEALTH PER ECOSYSTEM SERVICE (US\$ 2020)								
	TOTAL FOREST			PROTECTED FOREST		Recreation	NWFPs	Water services	Total average value per ha 2020	Recreation	NWFPs	Water services	Total wealth Non-wood forest	% Protected areas
	Recreation	NWFPs	Water services	Total average value per ha 2020										
UMI	United States Minor Outlying Islands	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	..	..	..	..	..
URY	Uruguay	76.1	7.3	131.6	215.0	68.2	8.9	153.1	230.1	2.51E+09	2.42E+08	4.34E+09	7.10E+09	2.0%
VEN	Venezuela	64.6	10.7	51.7	127.0	65.0	10.6	44.1	119.7	4.85E+10	8.05E+09	3.88E+10	9.54E+10	93.0%
VIR	Virgin Islands, US	241.1	93.1	117.2	451.3	0.0	0.0	0.0	0.0	7.80E+07	3.01E+07	3.79E+07	1.46E+08	..
EUROPE		39.2	4.8	22.7	66.7	79.2	7.1	29.7	116.0	6.48E+11	7.91E+10	3.76E+11	1.10E+12	8.7%
ALB	Albania	95.5	4.0	28.5	127.9	97.8	4.3	30.3	132.4	1.22E+09	5.15E+07	3.65E+08	1.64E+09	..
AND	Andorra	182.2	14.8	123.1	320.1	187.5	13.8	238.3	439.6	4.74E+07	3.84E+06	3.20E+07	8.32E+07	..
AUT	Austria	353.3	25.3	76.6	455.2	372.7	22.2	74.7	469.6	2.24E+10	1.60E+09	4.85E+09	2.88E+10	23.2%
BLR	Belarus	38.6	3.4	25.8	67.8	39.4	3.4	28.4	71.1	5.49E+09	4.87E+08	3.68E+09	9.66E+09	16.3%
BEL	Belgium	475.5	44.8	80.1	600.4	425.1	44.0	49.5	518.6	5.33E+09	5.02E+08	8.97E+08	6.72E+09	..
BIH	Bosnia and Herzegovina	83.5	4.9	37.5	125.9	89.6	5.2	45.1	139.8	2.97E+09	1.75E+08	1.33E+09	4.48E+09	..
BGR	Bulgaria	87.3	10.7	39.2	137.2	89.4	10.1	38.2	137.7	5.52E+09	6.77E+08	2.48E+09	8.68E+09	18.2%
HRV	Croatia	142.0	7.3	66.0	215.3	133.4	6.9	65.7	206.0	4.47E+09	2.31E+08	2.08E+09	6.78E+09	2.7%
CZE	Czech Republic	300.6	18.1	51.6	370.2	311.8	17.4	43.0	372.2	1.31E+10	7.86E+08	2.24E+09	1.61E+10	5.5%
DNK	Denmark	239.5	16.4	152.5	408.4	185.4	13.8	131.5	330.8	2.45E+09	1.67E+08	1.56E+09	4.17E+09	6.8%
EST	Estonia	68.0	5.9	36.1	110.0	53.4	5.5	37.0	96.0	2.69E+09	2.35E+08	1.43E+09	4.36E+09	19.1%
FRO	Faroe Islands	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..
FIN	Finland	56.8	17.1	56.5	130.5	12.4	9.3	36.2	57.9	2.07E+10	6.23E+09	2.06E+10	4.75E+10	5.6%
FRA	France	426.0	24.6	107.9	558.5	412.0	22.3	102.8	537.1	1.19E+11	6.91E+09	3.03E+10	1.57E+11	21.9%
DEU	Germany	538.3	41.0	80.9	660.2	553.6	40.6	60.7	654.9	9.99E+10	7.61E+09	1.50E+10	1.22E+11	28.7%
GIB	Gibraltar	184.8	15.4	17.3	217.5	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..
GRC	Greece	139.3	9.5	87.6	236.4	136.7	9.7	79.3	225.7	8.83E+09	6.02E+08	5.55E+09	1.50E+10	..

GLOBAL ASSESSMENT OF THE ECONOMIC VALUE OF NON-WOOD FOREST ECOSYSTEM SERVICES

COUNTRY/REGION	AVERAGE VALUE PER HECTARE PER ECOSYSTEM SERVICE (US\$ 2020)								WEALTH PER ECOSYSTEM SERVICE (US\$ 2020)					
	TOTAL FOREST				PROTECTED FOREST									
	Recreation		NWFPs		Water services		Total average value per ha 2020	Recreation		NWFPs		Water services		Total average value per ha 2020
SVK	Slovakia	287.7	10.2	76.5	374.3	271.1	9.7	78.5	359.3	9.00E+09	3.18E+08	2.39E+09	1.17E+10	28.5%
SVN	Slovenia	228.1	12.0	82.4	322.6	223.4	11.8	90.2	325.4	4.59E+09	2.42E+08	1.66E+09	6.49E+09	19.9%
ESP	Spain	199.3	9.0	100.9	309.2	190.4	8.8	97.4	296.5	6.01E+10	2.71E+09	3.05E+10	9.33E+10	..
SJM	Svalbard and Jan Mayen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..
SWE	Sweden	49.3	14.1	67.9	131.3	23.0	10.4	55.0	88.4	2.24E+10	6.39E+09	3.09E+10	5.97E+10	5.2%
CHE	Switzerland	651.2	60.2	107.3	818.8	457.2	60.8	134.1	652.1	1.34E+10	1.24E+09	2.21E+09	1.69E+10	13.9%
UKR	Ukraine	78.7	3.0	23.3	105.0	74.3	2.9	19.5	96.7	1.24E+10	4.65E+08	3.67E+09	1.65E+10	13.4%
GBR	United Kingdom	189.8	27.4	103.7	321.0	201.8	27.6	115.3	344.7	9.84E+09	1.42E+09	5.38E+09	1.66E+10	9.8%
ALA	Áland	46.4	15.5	38.7	100.7	0.0	0.0	0.0	0.0	..	..	..	..	..
OCEANIA		50.8	7.6	114.1	172.5	70.1	6.8	105.7	182.6	1.53E+11	2.29E+10	3.43E+11	5.19E+11	17.0%
ASM	American Samoa	29.8	39.8	190.3	259.9	0.0	0.0	0.0	0.0	8.28E+06	1.11E+07	5.30E+07	7.23E+07	0.0%
AUS	Australia	59.2	7.6	147.0	213.7	61.0	6.4	103.4	170.9	1.29E+11	1.66E+10	3.20E+11	4.65E+11	14.4%
COK	Cook Islands	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..
FJI	Fiji	20.0	8.1	41.4	69.5	17.9	8.5	33.0	59.4	3.70E+08	1.50E+08	7.67E+08	1.29E+09	..
PYF	French Polynesia	11.5	11.4	30.7	53.6	0.0	0.0	0.0	0.0	2.80E+07	2.77E+07	7.44E+07	1.30E+08	0.0%
GUM	Guam	35.2	70.3	23.0	128.5	0.0	0.0	0.0	0.0	1.60E+07	3.20E+07	1.05E+07	5.84E+07	..
KIR	Kiribati	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..
FSM	Micronesia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	..
NCL	New Caledonia	48.7	13.0	93.4	155.1	57.0	15.4	82.4	154.8	6.63E+08	1.77E+08	1.27E+09	2.11E+09	10.8%
NZL	New Zealand	193.3	10.3	158.1	361.7	137.1	8.2	138.1	283.3	3.11E+10	1.66E+09	2.54E+10	5.81E+10	28.2%
NIU	Niue	45.3	12.3	300.2	357.8	0.0	0.0	0.0	0.0	1.39E+07	3.77E+06	9.20E+07	1.10E+08	..

AVERAGE VALUE PER HECTARE PER ECOSYSTEM SERVICE (US\$ 2020)				WEALTH PER ECOSYSTEM SERVICE (US\$ 2020)			
TOTAL FOREST				PROTECTED FOREST			
COUNTRY/REGION	Total average value per ha 2020			Total average value per ha 2020			
	Recreation			Recreation			
	NWFPs			NWFPs			
	Water services			Water services			
	55.4	33.3	2.8	91.5	0.0	0.0	0.0
	15.4	39.7	2.3	57.4	0.0	0.0	0.0
	17.4	9.6	37.1	64.0	0.0	0.0	0.0
	5.0	6.7	36.0	47.7	3.3	7.0	37.8
	19.6	18.7	57.7	96.0	0.0	0.0	0.0
	13.9	9.0	26.2	49.1	0.0	0.0	0.0
15.5	16.7	57.1	89.3	0.0	0.0	0.0	
18.0	7.9	56.7	82.7	26.9	17.6	91.4	
27.1	25.1	32.6	84.8	0.0	0.0	0.0	
ANTARCTICA				0.2	0.3	0.2	0.7
South Georgia and the South Sand				0.0	0.0	0.0	0.0
French Southern Territories				0.1	0.2	0.1	0.3
WLD	52.5	7.5	42.0	102.0	48.3	6.8	35.4
				90.5	346E+12	4.94E+11	2.77E+12
				6.73E+12	16.3%		

*Percentage of the contribution of protected areas to total wealth was truncated to 100% for Uzbekistan.

