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The economic values of global forest ecosystem services: A meta-analysis

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ABSTRACT

This study presents a meta-analysis of the economic values of global forest ecosystem services. The meta-analysis is conducted based on data from primary studies published between 1990 and 2018. The value-estimates from those studies are standardized into international currency units i.e. US dollar/ha/year using the purchasing power parity of countries at 2017 price levels. This standardization results in a database of 261 eligible primary studies and 758 value-estimates or observations. The study reveals large variations in the reported economic values of forests and the ecosystem services that they provide. Results from the meta-regression indicate a range of drivers that influence these economic values, including GDP per-capita, proportion of forest cover, continental location, type of forest, ecological zone, forest area, ecosystem services being valued and the valuation method employed. The meta-regression results also indicate the importance of valuing multiple ecosystem services together, rather than valuing specific services separately. The danger with the latter approach is that valuation studies can inadvertently suggest industrial plantation forests, with harvesting for timber or bio-mass energy, have the greatest economic value. However, such studies do not properly consider trade-offs inherent in the management of these types of forests; namely the loss of multiple ecosystem services that are provided by more natural forests. These findings contribute to the literature evaluating the economic values of global forest ecosystem services by conveying relevant information regarding the divergence of the economic values associated with different forest features, thus helping to inform forest management.

1. Introduction

The world's forests provide myriad ecosystem services that are essential to humans' continued existence and wellbeing. These services encompass the full spectrum of provisioning, regulating and cultural services, that range from tangible direct uses such as the provision of timber and fibre products, to indirect tangible uses such as coastal and erosion protection, and intangible services, such as cultural and spiritual wellbeing (Canadell and Raupach, 2008; Gibson et al., 2011; Glük, 2000; Ojea et al., 2012). While some of these services are rival and excludable and so are exchanged through markets as private goods with observable market prices, most are non-excludable and provided 'free of charge', as common pool resources or public goods. In other words, due to market failure, many ecosystems services provided by forests are not reflected in market prices, hampering societally optimal forest management (Froger et al., 2015; Glük, 2000; Krieger, 2001; Lant et al., 2008).

Economic valuation of environmental goods and services is a way of demonstrating the relative importance of ecosystem services to human welfare and environmental sustainability (Daily and Matson, 2008; Daily et al., 2009; Schild et al., 2018b). Through economic valuation we are able to ascertain the utilitarian concept of value, incorporating ethical and social dimensions (Daily, 1997) and accounting for both use and non-use values. Accurately valuing both marketed and non-marketed ecosystem services is an important part of informing decision-making for socially optimal use and management of natural resources and externalities. Fundamentally, the inclusion of both marketed and non-marketed ecosystem services helps to inform trade-offs inherent in resource allocation problems, where there is a tension between utilisation or experience of competing ecosystem services. In cases where allocation decisions are made between marketed and non-marketed goods/services, the value of the former tends to take

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precedence as the benefits are captured privately and often immediately. Explicitly seeking to include the value of non-marketed environmental goods and services in decision making, helps to redress this imbalance (Smith, 1997). That is, economic valuation assigns a readily comparable 'importance value' to specific ecosystem services (or ecosystems in the aggregate) by revealing monetary estimates similar to those ascribed to more familiar private goods and services (Armatas et al., 2018). Therefore, economic valuation can play an important role in guiding optimal decision-making and correcting the imbalances between environmental management and economic development (Pearce, 1993). Recently, the leaders' pledge for nature at the UN summit on biodiversity warns of a "planetary emergency" that demands nature and its services are appropriately valued for decision-making (Cox, 2020).

The body of peer-reviewed articles on the economic valuation of forests has increased substantially in the last few decades. Valuation estimates reported in these studies can best assist policy- and decision-making if they are synthesized and statistically analysed. A synthesis of the literature on the economic value of forests can help to evaluate gaps in our knowledge and identify the determinants of value estimates. Further, a statistical analysis of previous findings enables us to better understand variations in economic value estimates and make inherent trade-offs in forest and natural area management more easily visible. Such an analysis can also help to promote or design financial incentives, through for example, payments for ecosystem services (PES) schemes that target the conservation of forests to preserve the otherwise non-marketed ecosystem services that they provide.

Meta-analysis is an established method of quantitatively analysing a large amount of existing information, in order to provide clear guidance and insights for decision-making and policy formulation. In this context, as noted by Chiabai et al. (2011), a meta-analysis can play a significant role in building a more comprehensive body of knowledge by integrating data from a range of valuation methods, including those based on market data and those derived by other (non-market and shadow market) valuation techniques (Nelson and Kennedy, 2009).

A comprehensive assessment of the first global economic value of ecosystem services was provided by Costanza et al. (1997) and followed by many others (Costanza et al., 2014; de Groot et al., 2012; Zhongxin and Xinshi, 2000). There is also a body of literature focussed specifically on forests, (cf. Acharya et al., 2019; Krieger, 2001; Ninan and Inoue, 2013a, 2013b) and another body of literature focusing on specific aspects, i.e. one type of ecosystem service or a specific valuation approaches. For instance, Chiabai et al. (2011) conducted a meta-analysis on cultural services, specifically recreation and passive use values, in the assessment of forests ecosystem losses over time. Zandersen and Tol (2009) undertook a meta-analysis of the recreational value of forests in Europe estimated via the travel cost method. Ojea and Martin-Ortega (2015) analysed the economic value of water ecosystem services from tropical forests, with a focus on Latin America. Salem and Mercer (2012) investigated the economic value of mangrove forests. van Kooten et al. (2004) explored the costs of creating carbon offsets through forest sinks. Similarly, Lindhjem (2007) conducted a meta-analysis on historic stated preference valuation studies of non-timber benefits from Fennoscandian forests. Barrio and Loureiro (2010) undertook a meta-analysis of contingent valuation studies on forest values and estimated the marginal value of different management programs. Chaudhary et al. (2016) analysed the economic trade-offs and profitability of different management approaches and their effects on species richness. In an analysis of the causes of tropical deforestation, Atmadja and Sills (2016) explored the relationship between income and forest cover and outlined the trade-offs between development and forest conservation.

Most of the literature cited above has focused on evaluating the economic value of specific forest ecosystem services, without considering the aggregated values of these services. Nonetheless there is also a body of work reporting values for multiple ecosystem services, providing a contrast to values associated with extractive uses such as the provision of timber (cf. Dupras et al., 2016; Mutoko et al., 2015; Preece et al., 2016; Sambu et al., 2014). Such assessments can illustrate the importance of conservation management and the optimal provision of ecosystem services from forests (Daily and Matson, 2008). The meta-analysis in this study incorporates the aggerated ecosystem service values, allowing comparison against the values of timber and biomass-based energy services. In this respect, the study takes an innovative approach by providing average value estimates for specific ecosystem types for various forest features (e.g. ecological zones) and, more importantly, by comparing the value estimates for multiples of ecosystem services against single-use extractive activities; hence contributing to the literature highlighting the conservation values of forests.

The main objective of this study is to identify and further examine the drivers of the economic values of forest ecosystem services, globally, through a meta-analysis: specifically, to: (i) identify and explore determinants of the economic values of forests; (ii) elaborate variations in value estimates with respect to different forest types, ecological zones or biomes, ecosystem services, and valuation methods; (iii) compare the value estimates of forests under an extractive single-use management regime with forests being managed for multiple uses; and (iv) provide insights for forest management decisions and policy-making.

2. Data and methods

The meta-analysis is undertaken following a systematic review of primary studies. A systematic literature review is a qualitative research method that attempts to collate all empirical evidence that fits pre-specified eligibility criteria in order to answer specific research questions (Higgins and Green, 2019). The review typically follows a three-step process: (i) identification of literature via a systematic search of online databases; (ii) screening for relevance; and (iii) eligibility and exclusion assessment against a pre-defined set of inclusion and exclusion criteria (Folkersen et al., 2018). The systematic literature review for this meta-analysis was conducted between July 2018 and June 2019 and encompassed all terrestrial forest ecological zones. The literature search was undertaken using the query terms consisting of: *"((forest* OR woodland OR mangrove OR taiga) AND (value OR economic OR monetary OR benefit OR cost))"*. The search process was conducted considering the *title, abstract and keywords* of the primary studies and using three literature-databases (SCOPUS, Web of Science and Science Direct) and the Google Scholar search engine.

In our initial search process, we identified 1377 primary studies. Then the screening for relevance i.e. whether the study is about forest ecosystem services and reports estimates of economic values (through reading the title, abstract and keywords) led to the exclusion of 362 studies. In addition to that, 648 studies were excluded following a

Table 1
Procedures of the literature data organization.

Stages of data organization	Description	Number of studies	Number of observations
Literature search	Studies obtained through browsing on search terms and identified as relevant, after avoiding duplicates	1377	NA
Screening	Identifying studies that could be potentially relevant through reading the title, abstract, and keywords	1015	NA
Eligibility	Thorough reading of the studies and selecting based on pre-defined set of criteria for inclusion	367	1068
Value standardization	Studies that are eligible for conducting the meta-analysis i.e. with standardized value estimates	261	758

thorough eligibility and exclusion assessment – and hence 367 primary studies were deemed eligible for the systematic review (see Table 1). A comprehensive description of the eligibility and exclusion criteria is presented in Appendix A (Table A.1).

The primary studies included in the systematic review report monetary values of ecosystem services at different spatial aggregations (e.g. local, regional, national, sub-continental, continental or global) using different currencies and valuation methods. In addition, the year of study ranged from 1990 to 2018, demanding that value estimates required adjustment for inflation. Therefore, the value estimates were transformed into a common monetary unit (USD/ha/year) following a standardization procedure (see Appendix B for details). Due to missing information, the standardization procedure led to a further reduction in the number of eligible primary studies. For instance, in some cases values were reported for the total forest area rather than on a per-hectare basis and the forest area was not provided. This study, therefore, is based on 261 eligible primary studies (and 758 unique observations). The 758 observations are identified since several primary studies reported value estimates for more than one type of ecosystem services or in more than one forest area.

3. Results

3.1. Descriptive summary statistics

3.1.1. Geographical location and publication trend of the primary studies

As noted above, our process of identification, screening, eligibility assessment and value standardization resulted in a database of 261 primary studies, together providing 758 value estimates or observations. Most primary studies included within the meta-analysis were conducted in Asia ($n = 108$) accounting for 41% of the total. Studies from Europe, Africa, and North America accounted for 21, 15, and 11% of the total number of studies respectively. The remainder were from South America and the Australia/Pacific region, with a small number of studies covering several countries or taking a global perspective. China, India, USA, Brazil and Indonesia were the five most represented countries, each with more than ten studies. The economic values were reported in 39 different currencies, with values reported in USD accounting for just over half of all studies. About 93% of the studies are obtained from peer-reviewed journals, with the remaining from conference proceedings, working papers, governmental and non-governmental reports.

As shown in Fig. 1, the annual number of publications increases moderately between 1990 and 2009, and more rapidly from 2010 onwards. On average, approximately five studies were published each year

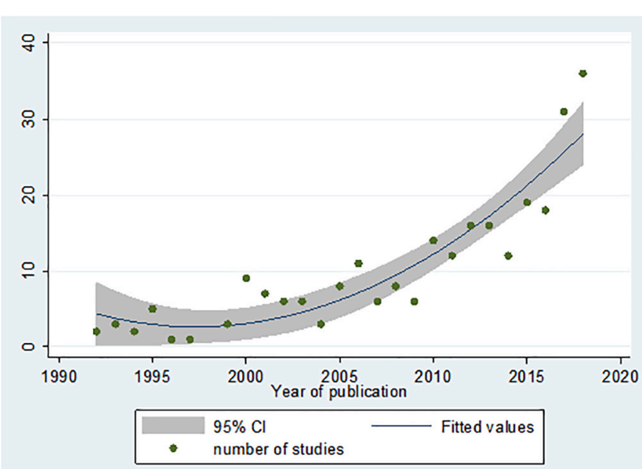

Fig. 1. The number of primary studies on the valuation of forest ecosystem services.

between 1990 and 2009, increasing to 19 per year from 2010 to 2018. In 2018 alone, 36 studies were published. These figures could be considered as a manifestation of the growing attention to the economic valuation of forest ecosystem services.

3.1.2. Number of observations per forest ecological zones, forest types, protection status and types of ecosystem services

Following the Food and Agricultural Organization (FAO) classification (FAO, 2020), forests were allocated into different ecological zones, with the addition of a separate class for mangroves (see Table 2). While mangroves are not classified as separate forest biomes by the FAO, given the importance of the ecosystem services that they provide, as evidenced by the body of literature (Barbier, 2016; Brander et al., 2012; Das and Crépin, 2013; Salem and Mercer, 2012) it was decided to include them separately. In fact, mangroves represent the largest share of observations with standardized value estimates ($n = 183$) followed by tropical rainforests ($n = 90$), temperate mountain systems ($n = 64$) and temperate oceanic forests ($n = 52$). Tropical deserts, temperate deserts and temperate steppes are the least represented forest ecological zones.

Global forests are further classified into primary natural, secondary natural, plantation, (or unspecified).[1] Primary natural forests account for the highest number of observations ($n = 408$), followed by secondary natural forests ($n = 196$). Plantation forests are the least represented, with only 65 observations. The remaining are classified as '*unspecified*',

Table 2
Summary statistics of values by forest ecological zone, type and protection status ($n = 758$).

Variables	Value estimates (USD/ha/year)			Obs.
	Median	Mean	Std. Dev.	
Forest ecological zones				
Tropical rainforest	113	1747	8588	90
Tropical moist forest	125	407	607	18
Tropical mountain system	97	$1.6E^{5}$	$1.1E^{6}$	49
Tropical desert	102	102	–	1
Tropical dry forest	19	561	1543	41
Tropical shrubland	52	80	85	3
Tropical unspecified	118	109	59	5
Subtropical humid forest	248	1054	2556	45
Subtropical mountain system	44	$1.1E^{4}$	$6.7E^{4}$	47
Subtropical dry forest	177	$3.4E^{4}$	$1.2E^{5}$	51
Subtropical steppe	$3.0E^{5}$	$9.1E^{5}$	$1.4E^{6}$	4
Temperate continental forest	90	5039	$1.7E^{4}$	41
Temperate mountain system	242	$1.3E^{6}$	$5.8E^{6}$	64
Temperate oceanic forest	187	8632	$5.5E^{4}$	52
Temperate desert	38	38	33	2
Temperate steppe	38	38	50	2
Temperate unspecified	196	$1.6E^{4}$	$5.6E^{4}$	19
Boreal coniferous forest	57	1112	2782	14
Boreal mountain system	255	255	46	4
Mangrove	454	4919	$1.7E^{4}$	183
Unidentified biome	70	256	330	23
Forest types				
Primary natural forest	139	3034	$1.3E^{4}$	408
Secondary natural forest	128	$4.1E^{4}$	$5.4E^{5}$	196
Plantation forest	193	1914	5058	65
Forest type unspecified	595	$1.0E^{6}$	$5.0E^{6}$	89
Protection status				
Protected forest	97	991	2570	134
Unprotected forest	188	$1.6E^{5}$	$1.9E^{6}$	624

[1] This is consistent with FAO (2015) definitions, where primary forests are defined as a naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed. Secondary natural equates with forests that have been logged or are regenerating following agricultural land use. Plantation forests are forests predominantly composed of trees established through planting and/or deliberate seeding.

because the '*type*' of forests was not specifically mentioned in the original study. We also categorised forests by their protection status as either '*protected*' or '*unprotected*'. The forests that are identified as protected i.e. in areas especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means (FAO, 2015; UNEP-WCMC and IUCN, 2016) account for 18% of the observations. Unprotected forests represent 56% of observations, with remaining 26% of '*unspecified*' protection status.

The types of ecosystem services are identified following the *Common International Classification of Ecosystem Services (CICES) Version 5* (Haines-Young and Potschin-Young, 2018). Twenty five separate ecosystem services are identified within the commonly recognised groups of provisioning, regulating and cultural services (Haines-Young and Potschin-Young, 2018; MEA, 2005; Ojea et al., 2012; TEEB, 2010). This study also incorporates primary studies that report the economic value of multiple ecosystem services (and which were unable to be disaggregated), as a separate category of "*aggregated ecosystem services*". Note that the term 'aggregated ecosystem services' is not considered as an additional type of ecosystem service, rather, it represents the values of different ecosystem services estimated together and not individually identified in the primary studies. As shown in Fig. 2, this category accounts for the largest share of observations, making up 17% of the total. The ecosystem services '*atmospheric regulation (carbon)*' and '*timber and fibre products*' are the next most represented, each accounting for approximately 14% of all observations. A detailed description of ecosystem service categories is provided in Appendix C (Table C.1).

3.1.3. Value estimates across ecological zones, forest types and protection status

As shown in Table 2, value estimates for ecosystem services have higher standard deviations, implying substantial variations in the values reported in primary studies. These variations are substantial with respect to the different ecological zones, forest types, and protection status and persist even after the standardization of the value estimates – the process that serves to minimize variations by accounting for inflation, and adjusting for exchange rates and differences in living standards among countries over time (de Groot et al., 2012). For this reason, we consider the median estimates, rather than the mean, as a better representation of the 'average' values.

Within forest ecological zones (and a consideration of large number of observations), the ecosystem services from *mangroves*, *subtropical humid forests,* and *temperate mountain systems* are indicated to have the highest monetary value estimates. The lowest values are associated with *tropical dry forest*, *temperate desert,* and *temperate steppe forests*. These differences in value estimates for the various forest ecological zones are also illustrated graphically in Fig. 3. The tropical and boreal forests have lower median (and 3rd quartile) value estimates.

Regarding forest type, the highest median value is reported for *plantation forests* with an estimate of 193 USD/ha/year. This can be attributed to a range of provisioning services, such as timber, as well as non-timber forest products like fibres, palms, medicinal products and other extractive forest resources, and differences in valuation approaches. These services are harvested from plantation forests in greater quantities than from natural forests; and coupled with higher market prices, have led to higher exchange values.

In terms of protection status, *protected* forests provide ecosystem services with an estimated median value of 97 USD/ha/year while *unprotected* forests provide services with an estimated median value of 188 USD/ha/year. The larger median for unprotected forests can be attributed to higher level of harvested consumption products. Notwithstanding, these value estimates should be treated with caution, given the enormous variances.

3.1.4. Value estimate across countries and regions

As shown in Fig. 4, the values of ecosystem services also have considerable variations across countries and regions. The economic values for provisioning services (panel a), are estimated to be between 100 and 1000 USD/ha/year in most counties, including Russia, the South East Asian counties, USA, and Brazil; while the highest values i.e. above 5000 USD/ha/year are reported from countries in Central America. For regulating services (panel b) the values range between 100 and 1000 USD/ha/year for many counties, while the highest values are reported from China and small pockets of Europe, with value estimates above 1000 USD/ha/year. For cultural services (panel c) the values are estimated at less than 100 USD/ha/year for most countries. The highest values for cultural services are found in France and a few South-East Asian countries, with estimates ranging from 1000 to 5000 USD/ha/year. For aggregated ecosystem services (panel d), many countries report values above 1000 USD/ha/year, with the highest values reported from North and East Africa, Southern Europe, and Japan, with estimates above 5000 USD/ha/year.

3.1.5. Value estimates of different types of ecosystem services

There is also a wide disparity in reported values across the different types of ecosystem services, as shown in Table 3. The highest value is reported for *aggregated ecosystem services*, with a median of 1837 USD/ha/year. This is not surprising as this category represents the value of multiple ecosystem services estimated together. In terms of specific ecosystem services, the highest reported values are for *air flow regulation, food from freshwater plants & animals* and *water cycle regulation*, with median values of 847, 580 and 527 USD/ha/year, respectively. *Timber and fibre products (n = 103)* are estimated at a median value of 146 USD/ha/year, while the *atmospheric regulation* services (n = 107) are estimated at a median value of 75 USD/ha/year. Note also that large standard deviations in those ecosystem service categories suggest that the estimated average values should be used with caution. As shown in Fig. 5, ecosystem services can be re-grouped into 1) *timber and biomass-based energy services*; 2) *other provisioning*; 3) *atmospheric regulation (carbon)*; 4) *other regulating services*; 5) *cultural services*; and 6) *aggregated ecosystem services*. The *aggregated ecosystem services* category is reported at the highest median (and 3rd quartile) value followed by the *other regulating services*. The lowest median values are associated with *atmospheric regulation.*

We also estimate median values of ecosystem service types across different ecological zones (Appendix C, Table C.2). Again the *Aggregated ecosystem services* category is reported at higher median values across all ecological zones. Higher median values of *timber and fibre products* are estimated for the boreal, temperate and mangrove forests. It is notable that higher estimates for *food – from freshwater plants & animals* are reported for mangroves, whereas higher median values for *atmospheric regulation* are reported for tropical and mangrove forests. Higher values of *non-extractive recreational services* are reported for subtropical and mangrove forests, while the maximum median values for *non-use values* are from tropical forests.

3.1.6. Summary statistics of value estimates from different valuation methods

The value of ecosystem services reported in primary studies are estimated using a wide range of different valuation techniques[2] including market princes, revealed or stated preference methods, cost-based methods and benefit transfer (see Table 4). Direct market pricing is the most common method, accounting for 57% of all value estimates. In contrast, very few values were obtained via revealed preference methods, with travel cost and hedonic pricing accounting for only nine out of the 758 observations. It is important to note that different methods are often applied to value different types of ecosystem

[2] A comprehensive review of the theory and methods underpinning the various valuation methods is beyond the scope of this paper; an excellent reference for this is Freeman et al. (2014).

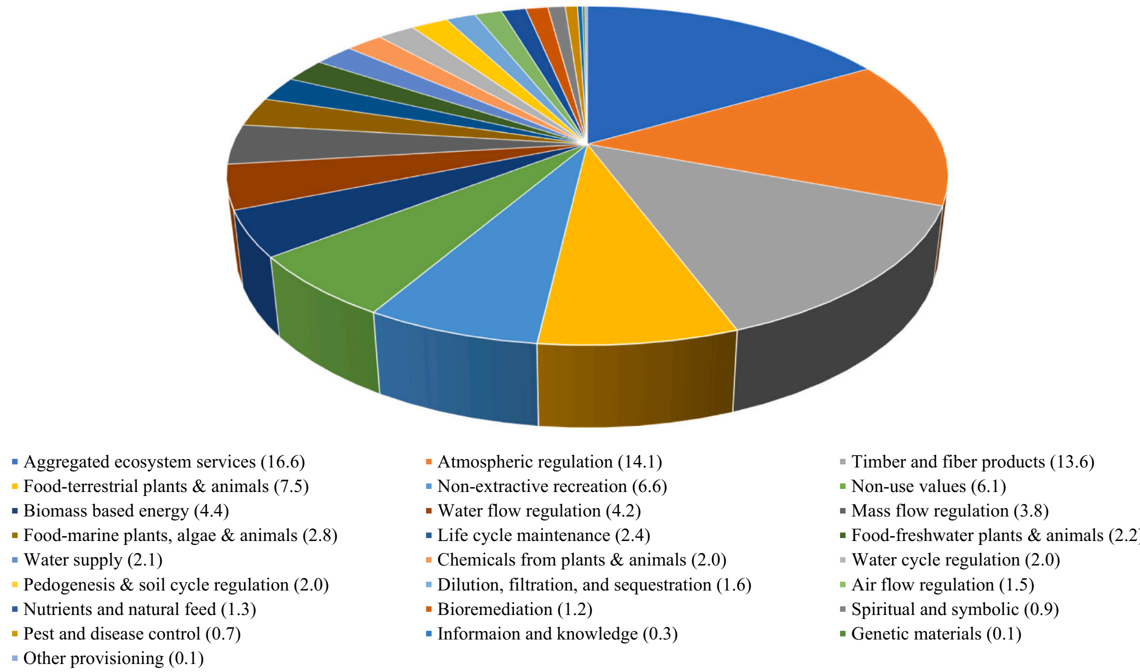

Fig. 2. Share of the types of ecosystem services in the database (percentage shown in brackets).

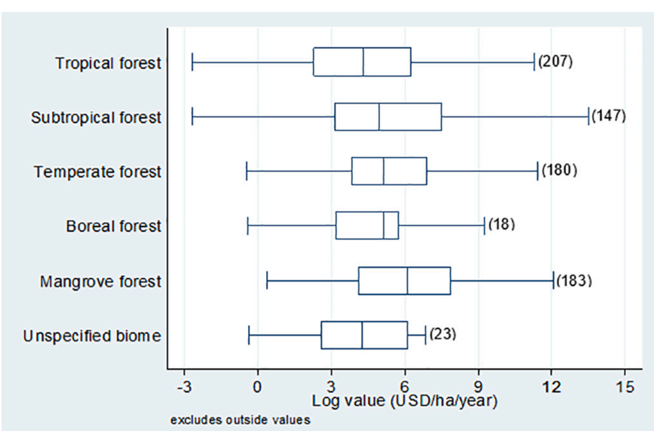

Fig. 3. Distribution of value estimates by forest ecological zones (number of observations in brackets). Note that the outlier values above the upper adjacent lines are excluded as defined by Turkey (1977).

services and different aspects of total economic value. Keeping this in mind, benefit transfer, contingent valuation and the travel cost method provide the highest value estimates, while the replacement cost method provides the lowest. Looking further into the distribution of value estimates across valuation methods (Fig. 6), the highest estimates are reported in benefit transfer, stated preference methods, and direct market pricing and the lowest values in cost-based methods.

3.2. Meta-analysis

3.2.1. Econometric modelling

The economic values of forest ecosystem services have a number of drivers. First, the economic values are measured in monetary units at national levels and are likely to be influenced by macroeconomic factors such as GDP per capita or population density. Second, the values of different types of ecosystem services could be associated with several aspects of forest characteristics (including e.g. ecological zone, forest type, or level of protection). Further, the size of value estimates could be determined by the valuation approaches employed.

Previous meta-analysis studies have considered many of these factors as explanatory variables in different contexts. For example, Carrasco et al. (2014) examined the valuation of ecosystem services of tropical forests through a meta-analysis considering variables such as, the type of ecosystem service being delivered, valuation method employed, forest area, protection status, level of biodiversity, carbon content, country of study area, continental location, GDP, and population density. Similarly, Quintas-Soriano et al. (2016), explained the value of ecosystem services from forests in Spain by GDP, ecological biome (e.g. forests, insular, mountains), category of ecosystem service delivered (provisioning, regulating or cultural), and valuation method (stated preference, revealed preference or cost methods). Zandersen and Tol (2009) outlined the determinants of the recreational values of European countries' landscapes by incorporating variables including the country of study, site characteristics (i.e. area, forest density, age diversity index), study characteristics (publication date, study type, sample size), methodological issues, and authorship. Likewise, Salem and Mercer (2012) explored the economic value of mangroves by considering the mangrove area, scale of valuation (local versus global), continental location, protection status, ecosystem service type, and GDP per capita. Schild et al. (2018a, 2018b) conducted a meta-regression analysis on the monetary values of dryland ecosystem services using explanatory variables such as the type of ecosystem services delivered, valuation method, study area extent, land use systems, GDP per capita, and population density.

This study provides a comprehensive analysis of the determinants of the economic values of forest ecosystem services. The explanatory variables (Table 5) are selected based on literature reviews from similar meta-analysis studies and underlying theory (de Groot et al., 2012; Lara-Pulido et al., 2018; Schild et al., 2018a, 2018b). Hence, the regression equation (Eq. 1) consists of three groups of moderator variables: 1) country specific indicators (GDP per capita, population density, forest cover, and continental location); 2) forest features (forest ecological zones, forest types, protection status, forest area, and the type of ecosystem service); and 3) valuation approaches, including the year of study. In addition, interaction terms between the types of ecosystem services and ecological zones are included in the regression analysis to demonstrate their combined effects.

The meta-analysis is conducted using the following simple linear

a. Provisioning services **b.** Regulating services

c. Cultural services **d.** Aggregated ecosystem services

Fig. 4. Distribution of value estimates of ecosystem service categories by country.

regression specification.

$$LogValue\ (USD/ha/year) = \beta_0 + \beta_c' C + \beta_f' F + \beta_v' V + \varepsilon \tag{1}$$

where β_0 is the constant term and the other βs represent the coefficients of variables in each group; ε is the random error term assumed to be independent and normally distributed. '*C*', '*F*', and '*V*' represents the three groups of moderator variables.

3.2.2. Estimation results

The dependent variable is transformed into a natural logarithmic form following the Shapiro-Wilk test of normality (Shapiro and Wilk, 1965), which rejects the null hypothesis for normality of the value estimates. Further, the meta-regression analysis is conducted based on Huber-White robust standard errors, since White's test rejects the null hypothesis of a homoscedastic error term. This is a commonly followed procedure in many meta-analysis studies (Barrio and Loureiro, 2010; Brander et al., 2006; Lindhjem, 2007; Loomis and White, 1996). Also note that the country-specific variables, *GDP per-capita*, *population density,* and *forest area* are transformed into natural logarithmic forms to improve model fit. The *proportion of forest cover* and *year of study* are incorporated as continuous numeric variables. The *continental location*, *type of forest* being 'natural', and the *forest protection status* as 'protected' are both treated as dummy-coded variables. The forest ecological zone, main ecosystem services being valued, and the valuation methods employed are all considered as categorical variables.

The meta-regression analysis is conducted based on the simple linear regression and a semi-log ordinary least squares (OLS) estimation. As shown in Table 6, many of the variables are found to be significant at the 5% level. The model estimation is performed using 624[3] observations and with an R-square of 30%.

Turning first to country-specific indicators, *GDP* per capita significantly increases the economic value of forest ecosystem services. As this variable is expressed in logarithmic form, the coefficient can be interpreted as an elasticity; and in this case, GDP per capita has an inelastic effect; as GDP per-capita increases by 1%, the value of forest ecosystem services increases by 0.3%, all other factors being constant. The percentage of *forest cover* also has a positive effect on forest ecosystem service values – i.e. the value of ecosystem services increases by 2% for a 1% increase in the proportion of a country's land mass that is covered by forest. Regarding *continental location*, the estimated coefficient for the Asian dummy is significant and positive, implying higher value estimates of ecosystem services reported by primary studies of forests in Asian countries. Other factors remaining constant, the value of forest ecosystem services from forests in Asia are estimated to be 79% higher than values from other continents.

In terms of the features of the forest being valued, *protected* forests

[3] Number of observations has reduced to 624 because of the missing values in some of the variables (e.g. GDP per capita in studies conducted on several countries or at a global scale)

Table 3
Summary statistics on the values of forest ecosystem services ($n = 758$).

Ecosystem services	Value estimates (USD/ha/year)			
	Median	Mean	Std. Dev.	Obs.
Provisioning services				
Water supply	171	255	295	16
Food-terrestrial plants & animals	31	1062	5553	57
Food-freshwater plants & animals	580	3053	5463	17
Food-marine plants, algae & animals	229	5023	1.1E^4	21
Nutrients and natural feed	52	653	1893	10
Timber and fibre products	146	1386	3924	103
Chemicals from plants & animals	73	637	1671	15
Genetic materials	167	167	–	1
Biomass based energy	52	2527	1.4E^4	33
Other provisioning services	13	13	–	1
Regulating services				
Bioremediation	83	1449	3610	9
Dilution, filtration, and sequestration	78	496	808	12
Air flow regulation	847	1441	2244	11
Water flow regulation	160	8385	4.3E^4	32
Mass flow regulation	430	3740	7701	29
Atmospheric regulation	75	808	3060	107
Water cycle regulation	527	1585	2568	15
Pedogenesis & soil cycle regulation	149	488	734	15
Life cycle maintenance	411	4411	1.7E^4	18
Pest and disease control	46	395	802	5
Cultural services				
Non-extractive recreation	156	1053	2824	50
Information and knowledge	528	528	559	2
Spiritual and symbolic	28	1.9E^4	3.4E^4	7
Non-use values	114	1438	4229	46
Aggregated ecosystem services	1837	7.7E^5	4.2E^6	126

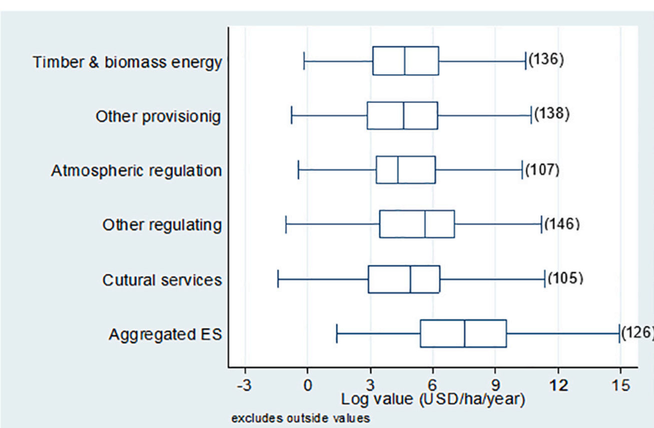

Fig. 5. Distribution of value estimates by groups of ecosystem services (number of observations in brackets).

yield lower values compared to *unprotected* forests. The value of ecosystem services delivered by *protected* forests is estimated to be approximately 61% lower than for *unprotected forests*, all else being constant. Larger forests are associated with lower (per hectare) values, with an inelastic effect - the economic value of ecosystem services delivered by a forest decreases by 18% for every 1% increase in its area, again, all else being equal. In addition, our regression result shows that the *type of ecosystem service* determines the value estimates. Specifically, it is estimated that *other regulating* services, and *aggregated ecosystem services* yield higher values than *timber* or *biomass-based energy* services (the reference case). *Other regulating* services are estimated at approximately 3.2 times higher values than *timber* or *biomass energy*, *aggregated ecosystem services* 14.4 times higher. The economic values of forest ecosystem services do not appear to be significantly determined by the different ecological zones.

Finally, the economic value of forests is also influenced by the

Table 4
Summary statistics on the value estimates across different valuation methods ($n = 758$).

Valuation method	Value estimates (USD/ha/year)			
	Median	Mean	Std. Dev.	Obs.
Direct market pricing	180	1.9E^4	1.6E^5	433
Stated preferences				
Contingent valuation	241	9.6E^5	5.0E^6	86
Choice experiment	170	702	1123	18
Revealed preferences				
Travel cost method	297	745	1068	5
Hedonic pricing	106	115	106	4
Benefit transfer	489	1.2E^5	9.6E^5	63
Cost-based				
Replacement cost	58	604	1986	73
Avoided cost	166	1728	3128	12
Others	75	991	2668	64

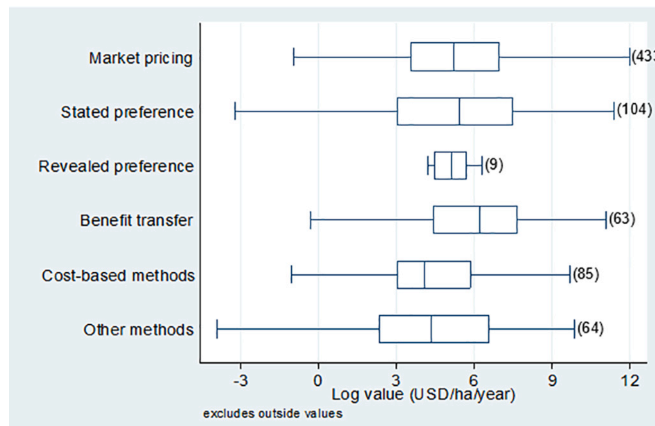

Fig. 6. Distribution of value estimates across valuation approaches (number of observations in brackets).

valuation approaches employed. Values reported with marginal units, that is *value estimated per ha*, yield higher estimates than values estimated in gross terms. The values estimated using *cost-based methods* or *other valuation methods* are also reported to be significantly lower in contrast to the values reported using direct market pricing (the reference case).

The regression result reveals some significant interaction effects. For example, the *food provisioning* services of *mangroves* are estimated at higher economic values in contrast to all other services within the same ecological zones. The *aggregated ecosystem services* and *atmospheric regulation* of tropical forests are also indicated to be significant (at 10% level).

4. Discussion

This study employs a meta-analysis to provide a comprehensive assessment of the economic value of global forest ecosystem services. The meta-analysis was conducted on 624 observations, covering a wide range of forest biomes and ecosystem services. The findings provide useful insights into the multiple and synergistic, or conflicting, economic values of forest ecosystem services and the influential factors attributed to variations in such estimates, as currently reported in the valuation literature. We believe that the econometric modelling provides a rigorous assessment of the determinants of the values of ecosystem services, and represents a substantial advance on earlier studies that relied on smaller databases or site-specific cases (cf. Carrasco et al., 2014; de Groot et al., 2012).

To date, the most comprehensive assessment of ecosystem service

Table 5
Variables included in the meta-regression.

Variables	Measurement
Country specific indicators (C)	
Population density	Average population density (population per km^2) of a country
GDP per-capita	GDP per capita of a country in USD (at the 2017 price level)
Forest cover	The percentage of total forest cover in a country
Asian studies	Dummy (1 if the primary studies are from Asian countries; 0 otherwise)
Forest features (F)	
Natural forest	Dummy (1 = primary or secondary natural, 0 = plantation or unspecified)
Protected forest	Dummy (1 = protected, 0 = unprotected)
Forest ecological zones	Categorical
	1 = all tropical forests (i.e. tropical rainforest, tropical moist, tropical dry forest, or tropical unspecified)
	2 = all subtropical forests (subtropical humid, subtropical dry forest, and subtropical steppe)
	3 = all temperate forests (temperate oceanic, temperate continental, temperate mountain systems, temperate steppe, or temperate unspecified)
	4 = boreal forests (boreal coniferous or boreal mountain systems)
	5 = mangrove forests
	6 = unidentified biome
Forest area	Forest area in hectares
Ecosystem services	Categorical
	1 = timber and biomass energy
	2 = other provisioning services
	3 = atmospheric regulation
	4 = other regulating services
	5 = cultural services
	6 = aggregated ecosystem services
Valuation methods and year of study (V)	
Value per hectare	Dummy (1 = value estimated on per-ha basis, 0 otherwise)
Value at local level	Dummy (1 = value indicated at local scale, 0 otherwise)
Valuation methods	Categorical
	1 = direct market pricing
	2 = stated preferences (contingent valuation and choice experiment)
	3 = revealed preference (travel cost and hedonic pricing method)
	4 = benefit transfer
	5 = replacement/avoided cost,
	6 = others
Year of study	The date (year) when the study has been conducted

values has been provided by de Groot et al. (2012), which stands as a useful comparison to our study. As indicated in Table 7, our study incorporates substantially more primary studies per individual ecosystem services than were available to de Groot et al. in 2012. The average value estimates are substantially different between the two studies. For instance, in de Groot et al. (2012), the value estimates for *water supply*, *timber and fibre products*, *pedogenesis & soil cycle regulation* and *life cycle maintenance* in the *tropical* forests are noticeably lower while the *chemicals from plants and animals*, *water flow regulation*, *atmospheric regulation* and *non-extractive recreation* in the same forest biome are higher in contrast to our results.

This study also supports the empirical evidence on the significance of country-specific factors, such as GDP per-capita, in determining the value of forest ecosystem services, which has been demonstrated in similar studies (Barrio and Loureiro, 2010; Brander et al., 2012). This significance can be attributed to direct use extractive products, such as timber; and non-extractive activities, such as recreation value, being exchanged at both higher prices and quantities in higher-income countries (e.g. Grammatikopoulou and Vačkářová, 2021; Mills Busa, 2013).

With respect to types of forests, we found *protected* forests to yield lower values than *unprotected* forests. The lower valuation of *protected* forests could potentially be attributed to its ecosystem services being less accessible, therefore facing increasing marginal costs of exploitation (supply), reducing demand and consumer surpluses from its products.

Table 6
Results based on the OLS estimation.

Variables	Coefficient	Std. E.	*P*-Value
Population density (log)	0.16	0.12	0.183
GDP per-capita (log)	0.30**	0.13	0.019
Forest cover	0.02***	0.01	0.008
Asian studies	0.79**	0.30	0.038
Natural forest	−0.36	0.34	0.255
Protected forest	−0.61***	0.30	0.002
Forest area (log)	−0.18***	0.04	0.000
Forest biomes (Ref. = Tropical forest)			
Subtropical forest	−0.002	0.55	0.787
Temperate forest	0.18	0.54	0.564
Boreal forest	−0.55	0.83	0.576
Mangroves	0.22	0.54	0.521
Ecosystem services (ref. = timber or biomass energy)			
Other provisioning services	−0.29	0.57	0.764
Atmospheric regulation	0.08	0.70	0.647
Other regulating services	3.17***	0.55	0.004
Cultural services	−0.30	0.80	0.964
Aggregated ES (TEV)	14.44***	0.66	0.000
Value estimated per ha	1.04***	0.25	0.003
Value at local level	−0.50*	0.34	0.059
Valuation methods (Ref. = direct market pricing)			
Stated preference	−0.11	0.35	0.874
Revealed preference	0.72	0.66	0.251
Benefit transfer	0.08	0.37	0.694
Replacement/avoided cost	−0.59**	0.39	0.038
Other methods	−0.80**	0.62	0.025
Year of study	−0.004	0.02	0.810
Interaction terms			
Timber in tropical forest	0.28	0.80	0.476
Carbon in tropical forest	2.25*	0.97	0.090
Cultural services in tropical forest	1.14	1.01	0.209
Aggregated ES in tropical forest	2.32*	0.82	0.061
Timber in subtropical forest	0.61	0.79	0.320
Carbon in subtropical forest	−0.26	0.84	0.952
Cultural services in subtropical forest	0.44	1.02	0.388
Aggregated ES in subtropical forest	−0.25	0.82	0.955
Timber in temperate forest	0.89	0.76	0.226
Cultural services in temperate forest	1.54	0.80	0.118
Aggregated ES in temperate forest	0.33	0.99	0.433
Timber in mangrove forest	−0.05	1.02	0.647
Food in mangrove forest	3.13**	0.64	0.012
Carbon in mangrove forest	0.69	0.70	0.272
Constant	10.11	33.40	0.762
R-squared	0.31		
No of observations	624		

***, **, * significant at 1%, 5%, and 10% levels of significance.
Note that the coefficients of all dummy variables are adjusted for 'exact' interpretations following the semi-logarithmic specification (Giles, 2011; Jan van Garderen and Shah, 2002).

For example, Carrasco et al. (2014) describe the relationship between accessibility (distance from the ecosystem and the ecosystem service beneficiary) and economic value as an 'n' shape – the closer the service, the more degraded it is and the lower its value, while more distant the service, i.e. the less accessible, the lower its value, whilst the most highly valued were those that were optimised for both integrity and accessibility. Further, our descriptive analysis shows that *mangrove* forests are valued relatively higher than other ecological zones, in nearly all individual ecosystem services. Mangroves are well-studied, typically provide diverse ecosystem services with multiple provisioning and regulating services, including fishery, climate stability, and coastal protection, which could result in higher value-estimates (Brander et al., 2012; Getzner and Islam, 2020; Salem and Mercer, 2012). Note that the value estimates reported in the recent study by Getzner and Islam (2020) are much higher than reported for these biomes here due to the aggregation they followed, and perhaps also linked to the different contexts of included primary studies. The values of mangrove forests are commonly assessed as part of complex and dense ecological systems in proximity to ecosystem service beneficiaries, in high population density areas (Failler et al., 2015; Koch et al., 2009) and thus benefits are not eroded due to

Table 7
Comparison of the mean monetary values of selected ecosystem services evaluated in the present study and in de-Groot et al. (2012) – with the number of observations indicated in brackets.

Ecosystem services	This study		de Groot et al. (2012)	
	Tropical	Temperate	Tropical	Temperate
Water supply	67 [4]	169 [5]	27 [3]	191 [1]
Terrestrial, marine and freshwater food	217 [35]	30 [8]	200 [18]	299 [2]
Timber and fibre products	1401 [35]	1920 [24]	84 [15]	181 [4]
Chemicals from plants & animals	212 [11]	442 [1]	1504 [1]	–
Water flow regulation	124 [7]	1791 [5]	342 [2]	–
Atmospheric regulation	952 [23]	1083 [36]	2044 [7]	152 [6]
Pedogenesis & soil cycle regulation	87 [2]	222 [4]	3 [3]	93 [1]
Life cycle maintenance	340 [3]	251 [4]	11 [1]	235 [2]
Non-extractive recreation	41 [7]	517 [14]	867 [20]	989 [25]

Note: There is slight difference in the terminologies used in de Groot et al. (2012). For instance, according to de Groot et al. (2012), timber and fibre products are stated as 'raw materials', chemicals from plants and animals are referred as 'medicinal plants', and atmospheric regulation is noted as 'climate regulation'.

distance effects (Carrasco et al., 2014).

Our study also reveals the positive effect of *aggregated ecosystem services*. Studies assessing multiple ecosystem services together (cf. Christie et al., 2012), show higher values than any category of specific individual ecosystem services. This illustrates how the different streams of value of multifunctional forests could be individually reported at significantly lower values, therefore distorting decision making if valuation is undertaken for only a specific individual ecosystem service (e.g. timber or biomass energy) Similar meta-analysis studies have demonstrated the monetary value of ecosystem services being determined by the types of ecosystem service being valued (Carrasco et al., 2014; Schild et al., 2018b; Teoh et al., 2019). The *aggregated ecosystem services* are reported at much higher values in contrast to *timber and biomass-based energy*. Aggregating ecosystem service values is the premise of PES schemes, where the managers of the (often primary) forests and indigenous land stewards are compensated for optimising the ecosystem service value spill overs, in contrast to pursuing extractive development pathways (Bishop and Hill, 2014). Hence, valuation of multiples of ecosystem services could help to justify the importance of conservation mechanisms such as PES schemes, especially in developing countries where forests significantly contribute to sustaining community livelihoods (Arnold et al., 2011; Pimentel, 1997; Rasmussen et al., 2017; Wunder et al., 2014). The PES approach recognises that the benefits of many forest ecosystem services accrue at spatial and temporal scales beyond the forest itself and its users, and aim to transfer these benefits back to forest stewards (CIFOR, 2005; Pagiola, 2008).

Prior studies have documented the importance of narrow suites of (predominantly) provisioning ecosystem services where the economic value is captured privately, is heavily discounted (value is weighted towards short term benefits) and the *social* opportunity cost (Quiggin, 2019) is not fully considered. It is commonly understood that an increase in the use of some ecosystem services (e.g. timber) will lead to a reduction in other services (e.g. carbon sequestration) (see Martín-López et al., 2014; Seidl et al., 2007; Wang and Fu, 2013). In addition, due to market failure, many ecosystem services remain underestimated or underrepresented in policy making (Christie et al., 2012; Froger et al., 2015; Krieger, 2001). Therefore, the trade-off and synergies of forest ecosystem services should be taken into account for better management and socially optimal decision making (Cord et al., 2017; Ferreira et al., 2018; Lin et al., 2018; Locatelli et al., 2014).

In regard to the influence of valuation techniques, unlike previous studies that found significantly higher value estimates associated with the use of stated and revealed preference methods (Jacobs et al., 2016; Quintas-Soriano et al., 2016; Salem and Mercer, 2012; Schild et al., 2018b); we find no significant difference between non-market valuation and direct market pricing methods.

As a proxy for geographical factors, we include a continental dummy, finding that studies of Asian forests yield higher estimates than studies elsewhere. This, however, is a rather coarse geographical coding. Previous studies, e.g. Zandersen and Tol (2009) elaborate the significance of site-specific characteristics in determining the value of ecosystem services. The present study, covering a wider range of ecosystem services and lack of proper indicators of 'site specific' information in primary studies, could not effectively examine the role of such variables.

Finally, the interaction terms included in our regression analysis highlight the relevance of considering specific types of ecosystem services within different ecological zones. There could also be interaction effects; e.g. as shown in Salem and Mercer (2012) that might have indicated potential intermediation of some contributing variables. However, we are restricted to limit the interaction terms due to a severe multicollinearity problem in our estimation.

While this study provided a comprehensive assessment of the economic values of forest ecosystem services, there are limitations specifically associated with the value standardization process i.e. the value estimates being transformed into a common monetary unit and expressed in marginal terms, i.e. USD/ha/year. In general, the limitations of this study can be explained as follows. First, the primary studies report monetary estimates of forests at different spatial aggregation from part of a forest area to all forests at a national level, and the conversion of the value estimates at marginal units through similar formulation might not account for all relevant spatially attributed factors. Second, the temporal aggregation could also be a concern in this regard as the primary studies could provide value estimates with aggregation over different time periods with various factors (e.g. different exchange rates) affecting the valuation. Third, comparing economic values based on different valuation approaches is challenging, as the valuation methods follow different assumptions and value orientation. Fourth, the meta-analysis only provides a general assessment of the determinants of economic values of ecosystem services including national level variables, without properly accounting for local contexts at a more micro or site-specific scale. It should be acknowledged that primary valuation studies are often conducted on specific policy objectives and in consideration of local contexts; for instance, forest income from provisioning services i.e. timber or non-timber products depends on the economic status and other income sources of households (Abdullah et al., 2016; Rueff et al., 2008; Schaafsma et al., 2012; Van Gevelt, 2013); recreational services can be influenced by the forest landscape, species composition, silvicultural management, or recreational facilities (Dhakal et al., 2012; Holgén et al., 2000; Juutinen et al., 2014; Nielsen et al., 2007). Further, as argued by Teoh et al. (2019), the economic value of multifunctional forests can be determined by several factors, including the geographical and ecological location of the forests, species richness, and other forest features that are not contained in this meta-analysis.

5. Conclusion

Research into the valuation of forest ecosystem services has been growing over the last three decades, with emphasis on informing conservation efforts. Collectively, the individual studies provide estimates of economic values for a wide range of ecosystem services and functions of forests through different valuation techniques. This study attempts to systematically analyse the outcomes of these studies via a meta-analysis performed on a large-scale database of 261 primary studies, together providing 758 value estimates or observations.

The meta-analysis provides an overview of the role of country-specific factors and various forest features (ecological zones, forest types, and ecosystem services) and demonstrates the significance of the value of multifunctional forests. Such an understanding of the determinants of the value of ecosystem services can help to identify policy interventions in global forest conservation efforts by providing evidence through exploring the determining factors. Moreover, this understanding can help to design better livelihood strategies for forest dwelling communities by emphasising the monetary values of multifunctional natural forests and integrating conservation efforts using market-based mechanisms, for instance, involving PES schemes.

The most important message from this study is the significance of valuing ecosystem services in the aggregate, rather than valuing marginal changes in specific individual ecosystem services, which has been the primary focus of the valuation literature. This is an important illustration of the trade-offs between industrial and multifunctional forest management and in how, when and who captures the monetary and non-monetary values of forests. It should be noted that conservation efforts and alternative land use planning decisions require consideration of the public goods value of ecosystem services and the trade-offs between these services and those captured privately.

For instance, plantation forests managed for industrial production have been purported to have higher values (without carefully considering the social opportunity costs of externalities) from extractive uses (e.g. timber production), potentially leading to conversion of multifunctional natural forests. Capturing the value of timber, however, could lead to a reduction in value estimates of other ecosystem services influenced by market-oriented forest management practices. Our meta-regression result demonstrates the importance of considering the value of multiples of ecosystem services and, hence, supports public policy against the management of forest for single-use, extractive industrial production, or clearing for mineral extraction and agriculture. In this regard, our results support local, regional and global efforts to protect indigenous access and use rights of forests, reduce biodiversity loss, and minimize atmospheric greenhouse gas concentrations, as articulated in the UN Declaration on the Rights of Indigenous Peoples, which supports the survival, dignity and well-being of the Indigenous peoples, and cuts across the majority of the UN Sustainable Development Goals.[4] At the local level, our data supports the evolution of institutions that can support value exchange between customary land stewards and purchasers of public goods ecosystem services beyond the carbon focus inherent in REDD+ schemes.

The results from the meta-analysis, however, must be treated with caution, particularly when making inferences for decision making over forest resource management and policy making. First, as shown in the descriptive summary statistics, mean values can be misleading, as there are significant variations across value estimates. Second, the econometric model does not incorporate all potentially explanatory variables excluding, for example, species composition, biodiversity richness, forest density or vegetation cover, and more refined location-specific attributes. All of these could significantly impact the value of ecosystem services derived from individual forests. Capturing this level of data was beyond the scope of the database from which the meta-analysis was conducted and was often not reported in primary studies. Third, it should be noted that the database is organized by taking the monetary value of forest ecosystem services without proper distinction between 'net' and 'gross' values. The 'value' of ecosystem services is considered without disentangling the 'value-added' component i.e. for inclusion (or exclusion) of factors inputs. Again, primary studies have often not provided sufficient detail of these aspects for us to incorporate in this analysis.

In general, it is hoped that this study provides useful insights into the drivers of the economic values of forest ecosystem services. Compared to the extant literature, it is a comprehensive study drawn from a larger database, encompassing a wider range of ecological zones and ecosystem service categories. The study also provides an opportunity to identify research gaps. For instance, some globally important forests, specifically the tropical rainforest in the Democratic Republic of Congo (the second largest rainforest, after the Brazilian Amazon), are not adequately represented in the underlying literature. We, therefore, suggest more research on evaluating the economic value of globally important forests for socially optimal management practices and land use planning. Moreover, we would suggest further research on establishing a standard framework for reporting and transforming value estimates into common measurements for ease of comparison and further analysis. Finally, this study reveals the role of non-market valuation methods in providing monetary values of important ecosystem services and proposes more applications of such methods to account for non-use ecosystem services, for the fact that relying on market-based methods alone is likely to systematically underestimate the values of ecosystem services derived from the world's forests.

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Declaration of Competing Interest

The authors confirm that there were no known competing interests that influenced the findings of the study.

Appendix A

Table A.1
Eligibility and exclusion criteria used for the systematic literature review.

Criterion	Eligibility criteria	Remarks
Timeline	1990–2018	
Language	English	
Literature type	Peer reviewed in academic journals, "grey literature", working papers, government reports, conference proceedings, unpublished MSc and PhD theses	Documents accessible on internet, any news outlets, power point presentations etc. without credible sources are not considered
Publication status	Published and/or available on-line	
Ecosystem Services	At least **one** type of forest ecosystem services	
Sector	Forest ecosystems, e.g. tropical, temperate, boreal, taiga, mangroves, woodland etc.	Terrestrial non-forest biomes such as tundra, cropland, lakes, rivers; and marine ecosystems are not included
Types of monetary or carbon estimates		Value reported based on secondary monetary estimates (e.g. literature reviews) from other papers are not considered

(*continued on next page*)

[4] Our data supports institutions, policies and projects that work towards achievement of the targets in Sustainable Development Goals 1, 2, 3, 5, 6, 8, 10, 13, 15, 16 and 17.

Table A.1 (*continued*)

Criterion	Eligibility criteria	Remarks
	Primary "new" monetary estimates of forest values or primary studies with own equations and calculations of monetary estimates. Or estimates of carbon sequestration/emission in tons	
Methodologies	Contingent valuation, cost-benefit analysis, net value, economic impact assessment e.g. any economic method	Other non-economic methodologies related to geophysics, biology, geography, chemistry, topography, etc. are not included

Appendix B. Value standardization procedure

The first step in our standardization process required the conversion of values into marginal spatial units, in this case per hectare, per year, thus controlling for discrepancies in spatial and temporal aggregations (de Groot et al., 2012; Schild et al., 2018a, 2018b). Therefore, values that reported over a number of years (for example, as a Net Present Value, or NPV) were converted into per annum values using the standard annuity[5] formula (with the same discount rate provided in the primary studies). Values reported for a whole forest area were converted to a per hectare basis based on the reported size of the study area, or in some cases were based on the area data obtained from an external source (e.g. national forest service website).

The second step was to make inflation adjustments to convert all values to a 2017 base year via World Bank Gross Domestic Product (GDP) deflation factors (The World Bank: Data, 2019). Values were then converted into international currency units using the PPP index for 2017 (Barrio and Loureiro, 2010; de Groot et al., 2012). For studies that provided values of carbon sequestration or emissions reduction in physical, rather than monetary units, we derived monetary values by using an international carbon price of $10 per ton (Parry, 2017; Yaron, 2001).[6]

We undertook additional standardization for studies that reported values at a per individual or per household level.[7] These values were aggregated into a per hectare per year monetary unit by summing individual or household values across the population assumed to benefit from the ecosystem services, provided that this information was given in the primary study. This approach is consistent with previous meta-analysis studies; see for example, Chiabai et al. (2011) and was particularly useful for dealing with non-market valuation studies that reported marginal willingness-to-pay (WTP) or consumer surplus estimates.

Appendix C

Table C.1
List of ecosystem services and benefits (according to CICES version 5.1).

Section	Ecosystem Service	Examples of ecosystem services and benefits
Provisioning	Water	Drinking water, for crop production, or livestock
	Food-terrestrial	Game animals, non-timber forest products
	Food-freshwater	Seabass, salmon, trout
	Food-marine	Seaweed, crayfish, prawns
	Nutrients and natural feed	Nutrient resources for crops, fodder for livestock
	Timber and fibre products	Logged timber, skin for manufacturing, straw, flax
	Chemicals from plants & animals	Substances such as rubber, enzymes, herbs for medicinal use for further processing
	Genetic materials	Genetic materials from crop plants, animals, etc.
	Biomass based energy	Wood for fuel, heating, light; algae or oil for biomass energy
	Other provisioning	Other provisioning ecosystem services that are not classified elsewhere in this section
Regulating	Bioremediation	Chemical detoxification and breakdown of pollutants by plants and microorganisms
	Dilution, filtration, and sequestration	Dilution of wastewater, removal of organic material and nutrients from water, filtration of particulates
	Air flow regulation	Dust storm mitigation, shelter from wind, heat mitigation in urban areas
	Water flow regulation	Prevention of flood damage by regulating timing and magnitude of water run-off
	Mass flow regulation	Stabilization of soil and mudflows, prevention of soil erosion
	Atmospheric regulation (carbon)	Carbon dioxide (CO_2) absorption, climate regulation, temperature and humidity regulation
	Water cycle regulation	Oxygenation of water, retention of nutrients in water, improvement of water quality
	Pedogenesis & soil cycle regulation	Maintenance of soil fertility, productivity and structure in the cultivated system
	Noise, visual or fire regulation	Natural buffering and screening against noise and fire
	Life cycle maintenance	Habitat and gene pool protection, pollination, maintenance of nursery habitats
	Pest and disease control	Control of pathogens, reduced hazard level to crops, human health and the environment
Cultural	Non-extractive recreation	Enjoyment from hiking, bird watching, whale-watching
	Information and knowledge	Scientific progress, increased knowledge, education
	Spiritual and symbolic	Cultural heritage value, landscape character, sense of place identity
	Non-use values	Availability of biodiversity and ecosystems for future generations or future uses i.e. the bequest values, existence values, and option values.
Aggregated ecosystem services		The value of a bundle of the above listed, ecosystem services, but not necessarily all ecosystem services

[5] The annuity is an annualized present value, calculated using the formula: $V = A\left(\frac{r}{1-(1+r)^{-T}}\right)$, where V is the annual value, A is the total value, r is the discount rate and T is the time period.

[6] This is a conservative estimate, perhaps leading to an undervaluation of atmospheric regulation as an ecosystem service. Other studies in the literature have employed higher values, including Kremen et al. (2000) who employ a value of $20 per ton.

[7] For example, willingness-to-pay per individual, or per household.

Table C.2
The average (median) values of forest ecosystem services by ecological zones (USD/ha/year). Notice the number of observations indicated in brackets.

Ecosystem services	Tropical forest	Subtropical forest	Temperate forest	Boreal forest	Mangrove forest	Unspecified biome
Water supply	8 [4]	365 [5]	171 [6]		1197 [1]	
Food-terrestrial plants & animals	20 [34]	941 [6]	27 [8]		55 [7]	54 [2]
Food-freshwater plants & animals	54 [1]		19 [2]		1254 [14]	
Food-marine plants, algae & animals	64 [2]				409 [19]	
Nutrients and natural feed	75 [4]	51 [2]			3034 [2]	27 [2]
Timber and fibre products	76 [36]	40 [16]	432 [30]	538 [4]	432 [15]	368 [2]
Chemicals from plants & animals	22 [11]		442 [1]		163 [3]	
Genetic materials					167 [1]	
Biomass based energy	35 [15]	89 [4]	62 [5]		32 [9]	
Other provisioning		13 [1]				
Bioremediation	516 [2]	83 [3]	47 [1]		271 [3]	
Dilution, filtration, and sequestration	26 [4]	94 [3]	489 [1]		490 [3]	364 [1]
Air flow regulation	72 [1]		1098 [5]		341 [3]	458 [2]
Water flow regulation	37 [7]	28 [6]	584 [7]		448 [9]	68 [3]
Mass flow regulation	228 [2]	2081 [9]	32 [7]		1286 [10]	3.3 [1]
Atmospheric regulation	218 [25]	49 [22]	59 [39]	20 [2]	280 [16]	33 [3]
Water cycle regulation		922 [5]	492 [7]	0.7 [1]	5342 [2]	
Pedogenesis & soil cycle regulation	87 [2]	216 [7]	84 [4]		149 [1]	850 [1]
Life cycle maintenance	484 [3]	10 [3]	203 [4]	311 [1]	1063 [6]	8.1 [1]
Pest and disease control		46 [3]	49 [1]		43 [1]	
Non-extractive recreation	0.9 [7]	272 [12]	199 [17]	29 [3]	346 [9]	307 [2]
Information and knowledge					528 [2]	
Spiritual and symbolic	1.3 [1]	0.1 [1]	1.4 [1]		22,933 [4]	
Non-use values	256 [18]	245 [7]	90 [7]	24 [3]	15 [11]	
Value of aggregated ecosystem services	1656 [28]	4631 [32]	2513 [27]	294 [4]	1920 [32]	184 [3]

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