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Full Length Article

Considering the land-cover elasticity of ecosystem service value coefficients improves assessments of large land-use changes

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ABSTRACT

Economic development often impacts on ecosystem services. Previous studies have raised public and political awareness of the costs associated with such impacts and the benefits of ecosystem services. In cases where empirical information on the value of ecosystem services is lacking, benefit transfer (BT) approaches that use value estimates from a previously studied site to estimate the economic values of a new target area have been established. One of the most popular BT approaches is unit value transfer, where constant ecosystem service value coefficients are used to assess a given land-use/land-cover (LULC) change. In several case studies assessing LULC changes, such unit value transfers with constant value coefficients are biased when nonmarginal changes are involved. Theoretical considerations suggest that large changes in land allocation should alter the opportunity costs of gaining or losing natural capital because the marginal costs of additional losses increase as some LULC types become scarcer (e.g. natural ecosystems). In contrast, marginal benefits shrink as other LULC types become more abundant (e.g. agricultural replacement systems).

Here, we propose an improved method for assessing larger scale (i.e., at national levels and beyond) LULC changes using endogenous value coefficients that account for the size of the land cover allocated to each LULC type and derive an equation for calculating these coefficients. The extent to which the value coefficient changes with variations in the land cover area depends on the land-cover elasticity of the value coefficient. Using a hypothetical numerical example of an area of tropical forest converted into grassland, we show that the bias caused by neglecting this land-cover elasticity can be considerable. We also demonstrate how the elasticity needed to correct the value coefficient can be estimated empirically. Finally, we suggest some modifications for future studies assessing large LULC changes.

1. Introduction

Ongoing environmental degradation in many countries underpins growing concern about the sustainable provision of ecosystem services (e.g., Alfonso et al., 2017). Because ecosystem services are commonly considered to be all ecosystem aspects that benefit people (Fisher et al., 2009), a substantial proportion of the ever-increasing number of ecosystem services studies mention economic elements (Fig. 1). Some authors seek to determine monetary ecosystem service values (*ESV*) by applying, and possibly adapting, published valuation results (e.g., Kreuter et al., 2001; Troy and Wilson, 2006; TEEB, 2010; van der Ploeg et al., 2010; Frélichová et al., 2014; Kindu et al., 2018; Sannigrahi et al., 2018; Arowolo et al., 2018; Li et al., 2019; Ouyang et al., 2020; Assefa et al., 2021; Gong and Chang, 2022). A landmark study by Costanza et al. (1997) arguably provides the most prominent starting point in valuing ecosystem services based on existing valuation results, a method called "unit value benefit transfer" (Rolfe et al., 2015). That study was polarising from the outset: its publication was heralded by some as an "… audacious bid to value the planet …" (Nature Editorial, 1998) and criticised by others as a "… serious underestimate of infinity …" (Toman, 1998). After some debate (e.g. Pearce, 1998; Heal, 2000; Johnston and Rosenberger, 2009; Spangenberg and Settele, 2010), however, the scientific community has broadly come to agree that such valuation work has yielded some astonishing successes in terms of raising public and political awareness about the potential economic dimensions of environmental changes (Daily and Ruckelshaus, 2022).

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Among other achievements, the effort to economically value nature's services generated several comprehensive collections of valuation results for various biomes and land-use/land-cover types (LULC) (e.g., van der Ploeg et al., 2010; de Groot et al., 2012; Müller et al., 2019; Foundation for Sustainable Development, 2021).

These collections provide ecosystem service value coefficients per hectare, which are now frequently used to assess the economic consequences of LULC changes (e.g., Turner et al., 2016; Kindu et al., 2016; Sannigrahi et al., 2018; Li et al., 2019; Wang et al., 2022; Gong and Chang, 2022; Biedemariam et al., 2022). Standard assessments of the change of *ESV* associated with LULC changes consider value coefficients as exogenous and constant information (Costanza et al., 2014; Sannigrahi et al., 2018). However, we argue that value coefficients are likely endogenous and negatively correlated with the land size covered by a specific LULC type.

We see great potential for ecosystem services to be incorporated into accounts of national well-being and income (Ouyang et al., 2020) and for using value coefficients to assess the contribution of natural capital to our well-being (Costanza et al., 2014). In addition, we second that economic studies should go beyond considering only marginal changes (Braat and de Groot, 2012) simply because nonmarginal changes occur in the real world.

However, major land reallocation processes comprising several thousand or even millions of hectares will alter the value coefficients. For example, significant reductions in ecosystem services supply would increase their marginal values (Addicott and Fenichel, 2019; Farley, 2008) and, with this, the shadow prices of all types of natural capital (Troy and Wilson, 2006).

Endogenous value coefficients are intuitive. If one accepts the principle of diminishing marginal utility, a principle associated with standard social welfare functions (e.g., Gollier, 2010; Weitzman, 2012; Dietz and Hepburn, 2013), then people would be willing to pay less for an additional unit of an abundant ecosystem service than a scarce one (Knoke et al., 2021) (Fig. 2). Under this assumption, changes in value coefficients could likely be interpreted as signals of increasing or decreasing scarcity of ecosystem services, much like prices in a market economy (Batabyal et al., 2003).

In our study, we use a theoretical analysis to show how applying constant value coefficients would over- or underestimate the losses of *ESV* associated with LULC changes. We then present a stylised numerical example using hypothetical value coefficient functions (where value coefficients depend on the land currently covered by a specific LULC type) to quantify a possible order of magnitude of the resulting bias when using constant value coefficients and suggest how it can be corrected.

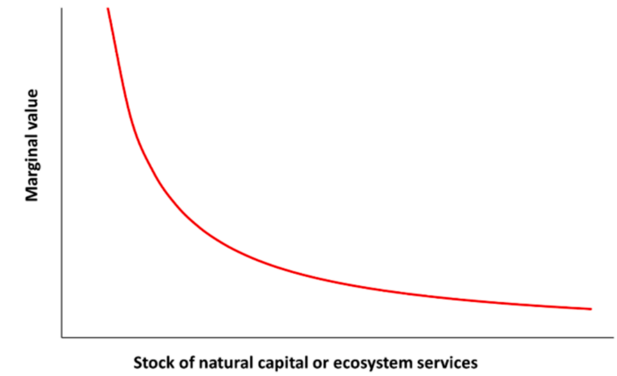

Fig. 2. Theoretical relationship between marginal value and the stock of natural capital (concept adopted from Farley, 2008).

2. Theoretical consideration of land reallocation processes

In most studies analysing the impact of LULC changes on ecosystem services, the changes of *ESV* flows (ΔESV) result from multiplying the area affected by land-cover changes of a specific LULC type (ΔA) with previously published value coefficients *VC* (e.g., Li et al., 2019; Kindu et al., 2016; Troy and Wilson, 2006).

$$\Delta ESV = \Delta A \cdot VC \tag{1}$$

However, using constant value coefficients is a poor approximation to estimate ΔESV, when large land reallocation processes cause changes. Instead of using Eq. 1, we suggest that changes of ecosystem service value flows should consider endogenous value coefficients $VC(A)$ to represent marginal ecosystem service values, which depend on the land A covered by the corresponding LULC type (Eq. 2). A_1 and A_2 are the areas of land covered at the beginning and end of the change.

$$\Delta ESV^* = \int_{A_1}^{A_2} VC(A)dA \tag{2}$$

In our schematic Fig. 3, we contrast the application of Eq. 1 with an application of Eq. 2 concerning the gains/losses of *ESV*, using the conversion of tropical forest into grasslands. We assume that ecosystem

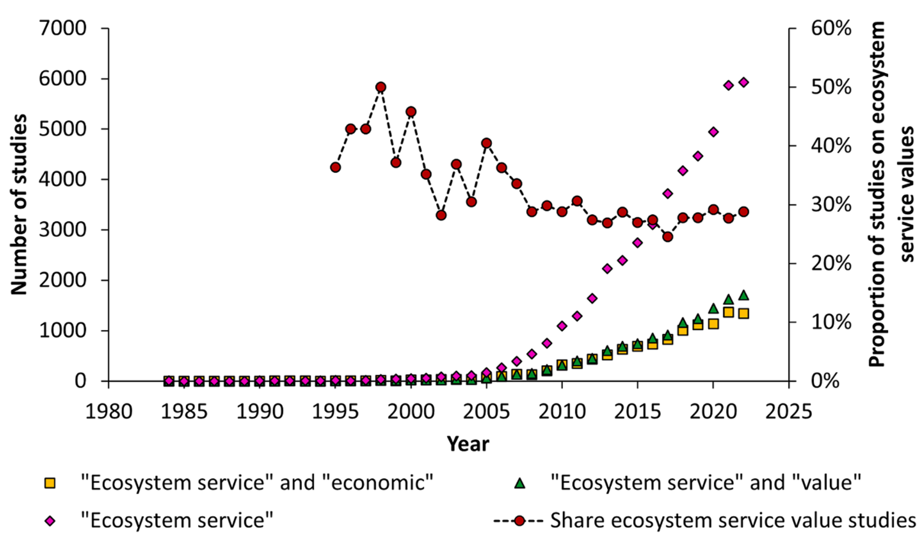

Fig. 1. Number of studies on ecosystem services searching for "ecosystem service" and "economic", "ecosystem" and "value", and "ecosystem service", searching in in title, abstract or keywords. Data was retrieved from the SCOPUS database on 23.12.2022.

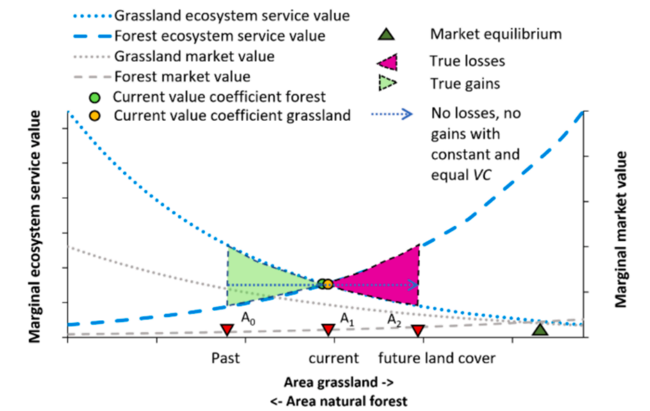

Fig. 3. Ecosystem service value coefficient functions for grassland and tropical forests depending on the land area allocated to both land-use/land-cover (LULC) types. The value coefficients and area proportions covered by tropical forest (green circle) and grassland (orange circle) are equal in this example. The curves are inspired by theoretical considerations in Fisher et al. (2008) and Pearce (2007).

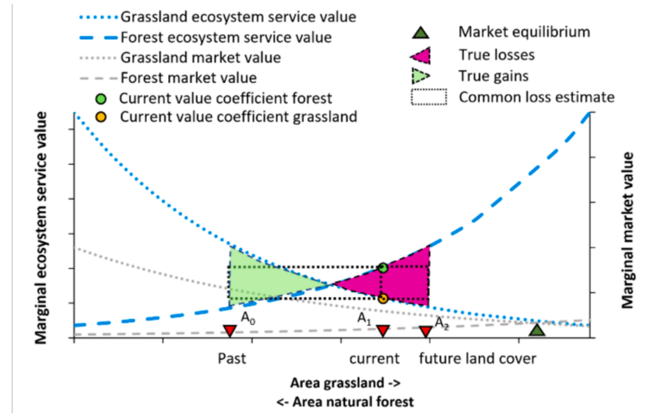

Fig. 4. Comparison of ecosystem service value coefficient functions for grassland and tropical forest depending on the land area allocated to both LULC types with common ecosystem service value loss estimates. The value coefficients and area proportions covered by tropical forest (green circle) and grassland (orange circle) are unequal in this example, with $A_{F1} < A_{G1}$ and $VC_F > VC_G$. The dotted rectangles show the net loss in *ESV* when considering both value coefficients as constant, following by multiplying the difference between the value coefficients for tropical forest and grassland by the area changes from the past to the current and the future land allocation.

service provisioning is a function of land area and show how the reductions in ecosystem service supply (by shrinking area) of tropical forests would increase the opportunity costs of their future losses (blue dashed curve in Fig. 3). Shrinking area of tropical forest is assumed when moving from left to right in the Figure.

For simplicity, we assume that grasslands (expanding from left to right in Fig. 3) are the only replacement system for tropical forests (Pendrill et al., 2022). In Fig. 3, the marginal benefit of grassland ecosystem services decreases with each additional hectare gained by tropical forest conversion, while the opportunity costs of losing tropical forest increase. We imply that changes in *ESV* are ignored in the actual decision-making about land-use allocation and that the land allocation thus tends towards a market-based equilibrium (right part with green triangle in Fig. 3). This equilibrium is achieved where the marginal market net-benefit obtained by establishing one hectare of grassland is equal to the marginal market net-benefit of losing one hectare of tropical forest (see e.g., Knoke et al., 2011 for a similar stylised example).

In our example (Fig. 3), we first assume that the current value coefficients and the land area covered (50 % and 50 %) are equal for grassland *G* and tropical forest *F*, with $VC_G = VC_F$. Applying Eq. 1 under this assumption means that ΔESV is the same for both LULC types, regardless of assessing past or future land-use changes, so that we obtain neither economic gains nor economic losses.

Instead, if we use endogenous value coefficients depending on the area allocated to the LULC type under consideration, $VC(A)$, to assess ***past*** LULC changes (see Costanza et al., 2014 or Sannigrahi et al., 2018), we actually obtain an economic gain achieved by past land-use changes towards the current land allocation, i.e., A_{G1} and A_{F1}. A_{G0} and A_{F0} are the past areas covered by grassland and tropical forest. We have here:

$$\int_{A_{G0}}^{A_{G1}} VC_G(A)dA > \int_{A_{F0}}^{A_{F1}} VC_F(A)dA \tag{3}$$

In contrast, assessing ***future*** land-use changes (for example, in Kubiszewski et al., 2017; Kubiszewski et al., 2020) (towards A_{G2} and A_{F2}) reveals economic losses because we have then:

$$\int_{A_{G1}}^{A_{G2}} VC_G(A)dA < \int_{A_{F1}}^{A_{F2}} VC_F(A)dA \tag{4}$$

This finding does not change, if we assume unequal land area and unequal constant value coefficients for tropical forest and grassland, such as $A_{F1} < A_{G1}$ and $VC_F > VC_G$ (Fig. 4).

Under this assumption ($A_F < A_g$; $V_{CF} > V_{CG}$), estimates of ΔESV form rectangles (area under lines parallel to the X-axis for corresponding land-cover changes ΔA in Fig. 4), implying that the area covered by a specific LULC type has no impact on the marginal benefit of an additional hectare gained or lost.

In Fig. 4, the rectangles delimited by dotted lines show the overall loss of ecosystem value, estimated as $L = \Delta A \cdot (VC_F - VC_G)$, if $VC_F > VC_G$. Comparing the rectangles for past and future land-use changes indicate a net loss of ecosystem service value, even though the past land-use change is accompanied by a gain in ecosystem service value, as the green triangle in Fig. 4 is larger than the magenta triangle left of the current land allocation point.

Whether we obtain an under- or overestimation of gains and losses of ecosystem service value by applying constant value coefficients depends on the considered example. However, we may almost always assume biases when using constant ecosystem service value coefficients for large land-use changes. In rare cases, assessing large land-use changes with constant and endogenous value coefficients may show identical results. For example, when land-use changes on the left and right sides of the intersection of the $VC(A)$ functions and both functions are identical (see Fig. 3), both methods will coincide and no net value gains and losses will result, provided that the constant value coefficients are identical.

3. Value coefficients as variable marginal benefits

Treating value coefficients as the marginal willingness to pay for the ecosystem services from an additional hectare of grassland or forest land allows us to describe the influence of the abundance/scarcity of ecosystem services (proxied by the land cover allocated to a specific LULC type) by inverse demand functions. Inverse demand functions have been used as natural models for price formation processes in fish resources (e.g., Tran et al., 2019; Barten and Bettendorf, 1989) or for milk and corn (e.g., Knoke et al., 2011).

We constructed hypothetical inverse demand functions that yield numerical values for value coefficients which are equal to the current value coefficients for the year 2011 land cover corresponding to tropical forests and grasslands in Costanza et al. (2014, Tab. 3 therein, based on data from de Groot et al., 2012). The general relationship is shown in Eq. 5, with A_c being the current land area in hectares covered by the respective LULC type, $VC(A)$ the endogenous and VC the current value coefficient:

$$VC(A) = VC \cdot \left(\frac{A_c}{A}\right)^{|\varepsilon_{VC}|} \tag{5}$$

$|\varepsilon_{VC}|$ in Eq. 5 is the absolute value of the land-cover elasticity of $VC(A)$.

In contrast, concerning supply, we assume that the level of ecosystem service provision for any given area of land cover allocated to a specific LULC type is independent of prices (this is an implication of the character of many ecosystem services as public goods, see Franklin and Pindyck, 2018). This results in a strictly vertical supply function (e.g., Costanza et al., 1997; Knoke et al., 2021).

4. Numerical illustration

Our numerical example assesses the changes of *ESV* associated with tropical forest cover losses of 642 million hectares between 1997 and 2011, according to Costanza et al. (2014, Tab. 3 therein). The same publication suggests applying current value coefficients of US$ 5382 and 4166 per hectare per year, respectively, for tropical forest and grassland/rangeland (hereafter only grassland). It indicates a current land-cover area of 1258 10^6 ha (tropical forest) and 4418 10^6 ha (grassland). Applying Eq. 1 the net loss of *ESV* is then:

$$\Delta ESV = (4166 - 5382)\frac{US\$}{ha \cdot yr} \cdot 642 \cdot 10^6 ha = -0.78 \cdot 10^{12}\frac{US\$}{yr}$$

This loss is constant regardless of whether we consider past or future periods (Table 1).

The numerical relationships we applied when assuming endogenous $VC(A)$ were as follows, implying a constant elasticity coefficient of $|\varepsilon_{VC}| = 1$ for simplicity:

$$\text{Tropical forest}: \ VC(A) = 5382 \left[\frac{US\$}{ha \cdot yr}\right] \cdot \frac{1258 \cdot 10^6 [ha]}{A [ha]} \tag{6}$$

$$\text{Grassland}: \ VC(A) = 4166 \left[\frac{US\$}{ha \cdot yr}\right] \cdot \frac{4418 \cdot 10^6 [ha]}{A [ha]} \tag{7}$$

The resulting hypothetical demand and supply functions are illustrated in Fig. 5.

Inserting Eq. 6 and Eq. 7 into the integral function of Eq. 2, we then calculated changes of ESV^* for grassland and tropical forest LULC changes of ± 642 106 ha and used these LULC changes to assess past and future periods. The results (Table 1) show that instead of net losses resulting from assessing past LULC changes, using endogenous $VC(A)$ shows a gain in ESV^* caused by the LULC change assessed. However, losses estimated for future LULC changes were 2.9 times the losses obtained from applying constant value coefficients. The bias of the losses obtained from using constant value coefficients for this example would be + 0.88 10^{12} US$ per year (losses overestimated for past losses) and −1.55 10^{12} US$ per year (losses underestimated for future losses).

4.1. Sensitivity studies

Here we tested the impact of the size of the land-cover elasticity of the endogenous value coefficients (ε_{VC}) on the results. We assumed that the bias we have found from applying constant value coefficients depends on the assumed land-cover elasticity of the endogenous value coefficients, which controls how the value coefficients change in response to changes in land-cover allocation. Suppose the land-cover elasticity of the value coefficient shows a high absolute value. In that case, the marginal benefit curve becomes steeper where a given LULC type is scarce, but flatter where it is abundant. We carried out sensitivity studies for more elastic ($|\varepsilon_{VC}| = 2$) and more inelastic value coefficients ($|\varepsilon_{VC}| = 0.5$).

Table 2 shows that the bias of applying constant value coefficients grows under higher land-cover elasticity while it shrinks under lower land-cover elasticity of the value coefficient. Depending on the land-cover elasticity assumed, the bias when using constant value coefficients can be up to ± 51 % in the case of tropical forest and up to ± 15 % for grassland in the example given in Table 2.

4.2. Suggestion

In light of this, we suggest Eq. 8 to aggregate the changes of value flows of ES for various LULC types in future studies; l is a subscript for a specific LULC type and L is the number of considered LULC types.

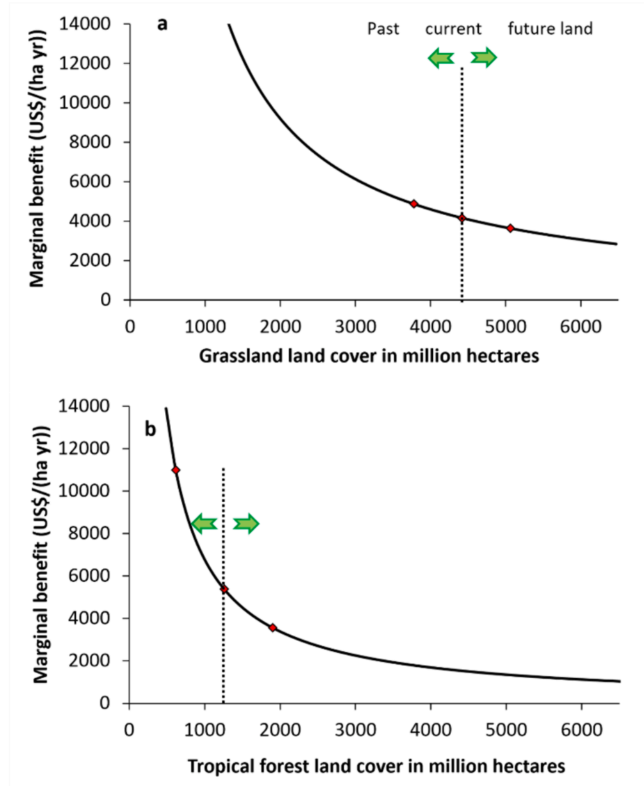

Fig. 5. Assumed hypothetical demand (black) and supply functions (dotted).

Table 1
Theoretical example for changes in ecosystem value associated with LULC changes, assuming current land area allocation as the start situation.

LULC type	Period	Land-cover change [106 ha]	*ESV* change applying constant *VC* [10^{12} US$]	*ESV** change applying endogenous $VC(A)$ [10^{12} US$]	Net losses applying constant VC_c [10^{12} US$]	Net losses/gains applying endogenous $VC(A)$ [10^{12} US$]
Grasslands	Past	+642	+2.67	+2.89	**−0.78**	**+0.10**
Tropical forest	Past	−642	−3.46	−2.79		
Grasslands	Future	+642	+2.67	+2.50	**−0.78**	**−2.33**
Tropical forest	Future	−642	−3.46	−4.83		

Table 2
The bias of applying constant value coefficients under different assumptions concerning elasticity for changes from tropical forest to grassland.

Scenario	Elasticity of $VC(A)$	Annual ESV change applying constant VC [10^{12} US$]		Annual ESV^* change applying endogenous $VC(A)$ [10^{12} US$]			Bias of change estimates per hectare of LULC change [%]	
	ε_{VC}	(1) Tropical forest	(2) Grass-land	(3) Tropical forest	(4) Grass-land	(5)[(4) − (3)] Gain minus loss	[(1) − (3)] ÷ (3) ·100 Tropical forest	[(2) − (4)] ÷ (4) ·100 Grassland
Past	−2.0	−3.46	2.67	−2.29	3.13	0.84	51 %	−15 %
Past	−1.0	−3.46	2.67	−2.79	2.89	0.10	24 %	−7%
Past	−0.5	−3.46	2.67	−3.10	2.78	−0.32	11 %	−4%
Future	−2.0	−3.46	2.67	−7.06	2.34	−4.72	−51 %	15 %
Future	−1.0	−3.46	2.67	−4.83	2.50	−2.33	−28 %	7 %
Future	−0.5	−3.46	2.67	−4.07	2.58	−1.49	−15 %	4 %

$$\Delta ESV = \sum_{l=1}^{L} \int_{A_{l1}}^{A_{l2}} VC_l(A_l)dA \tag{8}$$

Applying Eq. 8 to determine the change in ESV for larger areas raises the practical problem of finding suitable estimates for the respective land-cover elasticities (cf. Eq. 5). The information required can be taken from previous valuation studies if they have determined ecosystem value coefficients for different area sizes, enabling ecosystem value coefficients to be formulated as a function of area size A (and possibly, additional explanatory variables X) such that $VC = f(A, X)$. Choice experiments using area size as an attribute when determining the value of some (set of) ecosystem services could offer a suitable data source for this purpose (e.g., Koetse et al., 2017; Liekens et al., 2013; Spencer-Cotton et al., 2018). Cross-sectional analyses of different valuation studies could also be used separately or in combination with choice experiment data—provided, again, information on the size of the valued area is included, and the area sizes differ between constituent studies. Specialised databases facilitate searching for suitable studies (e.g. the Global Ecosystem Service Valuation Database [ESVD] provided by the Foundation for Sustainable Development, 2021).

The elasticity sought can be estimated by a double log regression, here accounting for the basic structure of our assumed inverse demand function (see Eq. 5):

$$\ln VC(A, X) = \beta_0 + \beta_1[\ln A_c - \ln A] + \beta_n \ln X_n + u, \tag{9}$$

where VC is the aggregated value coefficient (monetary units per hectare per year) of some ecosystem services, β_n are parameters to be estimated, A_c is current and A is the future land cover area, X is an optional vector of further explanatory variables, and u is the error term. In the double log formulation, the parameters β_{1-n} can be directly interpreted as elasticities (Kennedy, 2001; Stobbe, 1991, p. 129), and hence β_1 would be the land-cover elasticity $|\varepsilon_{VC}|$ of $VC(A)$.

Fig. 6 shows an example estimation of possible land-cover elasticity derived from value coefficients published for pollination services (adopted from the Foundation for Sustainable Development, 2021). We excluded a possible vector X for further explanatory variables for this analysis. The resulting empirical estimate for the land-cover elasticity of the included values of pollination services was close to 1 ($|\varepsilon_{VC}| = 1.193$).

When using aggregated values from the literature, it is essential to be aware of the extent of the market analysed there. Most valuation studies examine the willingness to pay of a limited population, e.g., the population of a single country. However, the ecosystem service(s) in question might benefit others as well (this would typically be expected for global public goods, which are of global benefit). Neglecting this additional willingness to pay implies that the aggregate ESV is underestimated and most likely also leads to elasticity estimates that are biased downwards.

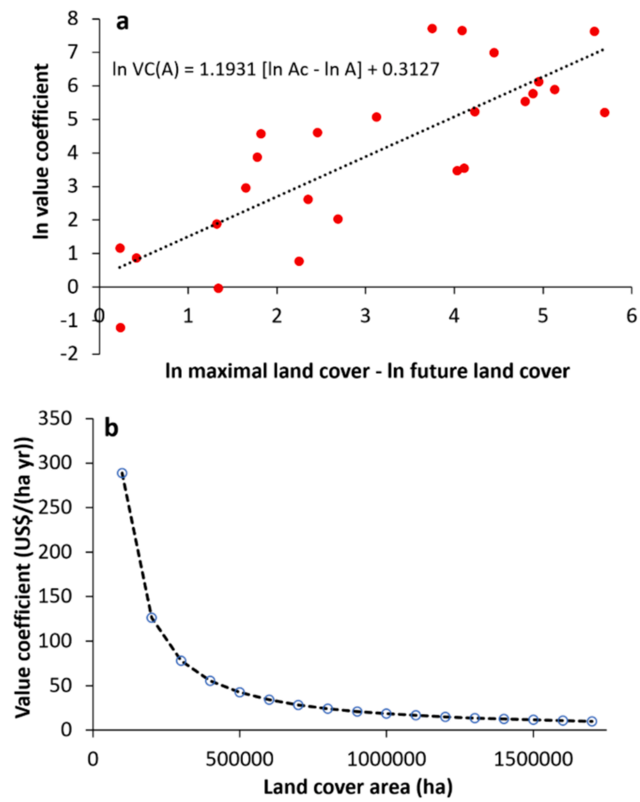

Fig. 6. a. Land-cover elasticity $|\varepsilon_{VC}| = 1.193$ of value coefficients for pollination services, estimated with a double log function. The independent variable $[lnA_c - lnA]$ obtains larger values for small and smaller values for large future land-cover areas A, because we have used the maximal land cover provided by the data in Foundation for Sustainable Development (2021) as the current land cover A_c. However, the land-cover elasticity of the value coefficients is independent of the choice of A_c. b. Resulting example relationship between ecosystem service value coefficient (VC) and land cover area. Data adopted from Foundation for Sustainable Development (2021), who integrated them from the study of Borges et al. (2020).

5. Discussion and conclusions

The use of constant value coefficients to assess the economic contribution of ES to our well-being has become a standard in pragmatic assessments of LULC changes, even in cases where large (nonmarginal) land-use changes are involved. Constant value coefficients are easy to apply and explain, contributing to this approach's broad spread and great success. The associated studies help raise awareness and show the importance of ES compared to other economic contributions to human well-being. In light of potential concerns about this method, it has been anticipated that more complex and sophisticated valuation techniques would lead to larger value estimates than those associated with constant value coefficients (Costanza et al., 2014). One might thus be inclined to assume that applying constant value coefficients guarantees safe lower bounds of the true economic value of the changes in ESV associated with LULC changes.

Our results, however, show that this assumption is not justified. Valuing past LULC changes using current constant value coefficients may suggest net-losses of *ESV*, where actually net-gains had been achieved. Because marginal benefits decline with more abundant, and increase with scarcer, supply, ***past*** gains in *ESV* will always be underestimated when using constant current value coefficients and past losses will be overestimated. In contrast, using constant current value coefficients to value ***future*** LULC changes will always overestimate gains, but underestimate losses of *ESV* (possibly severely so).

We show how marginal changes result in different *ESV* changes depending on where such changes happen on the demand curve, with higher *ESV* changes under increasing scarcity. This implies that changes associated with the scarcer natural forest are of greater magnitude than those associated with grasslands on the flatter part of the scarcity curve. When we replace one land cover with another, the point where those ESV changes are equal is the point when gains in a lower market-valued LULC type produce a net loss and vice versa. If LULC value coefficients would appropriately account for *ESV* in its market value this bias might not happen, as market forces would tend towards the point of equilibrium.

However, such a general conclusion requires careful interpretation, because our example is limited to considering only two LULC types, whereas land-use changes causing the loss of tropical forests lead to alterations of the land allocation to many LULC types (Knoke et al., 2023). Such multiple changes in land allocation are not considered in our stylised examples. In addition, any benefits from risk attenuation through intended land-use diversification are excluded from our study. Finally, while our considerations may apply to the expansion of grasslands into tropical forests (i.e., under decreasing tropical forests), compensating for past forest loss by expanding tropical forest cover (under tropical forest increases) will imply different value curves. Mature forests differ in their ecosystem service composition from newly established forests. The restoration of tropical forests on abandoned grasslands can be achieved through natural succession (e.g., Ngo Bieng et al., 2021) or active reforestation (e.g., Nunes et al., 2020). In both cases, however, waiting for the future ecosystem services of young forests to fully develop implies a reduced economic value compared to a mature tropical forest that already provides the services. Hence, any habitat equivalency analysis (e.g., Desvousges et al., 2018) would most likely suggest that a significantly larger area of secondary forest succession or reforestation would be required to compensate for a given area of lost tropical forest. One may, therefore, assume that the value curve for reestablishing tropical forests will differ from the value curve representing losses of mature tropical forests. However, applying constant value coefficients also suffers from these limitations.

Other limitations include considering only the impact of changes in the supply of ecosystem services associated with LULC changes; we ignore other issues with applying ecosystem service value coefficients. For example, using unit value benefit transfer to apply published *VC* to other situations can be problematic without context-specific adjustments (e.g., Czajkowski et al., 2017). In our numerical example, we assumed that ecosystem service supply and demand are homogenously distributed across the area covered by a given LULC type. Still, such naïve spatial aggregation may be problematic (Addicott and Fenichel, 2019). Some ecosystem services are location-specific and cannot be scaled up to the whole land-cover area of a LULC type (for example, the opportunity for recreation or protection against gravitational hazards). However, we are not aware of any arguments which would mitigate the biases associated with using constant value coefficients in principle. Our sensitivity studies have shown that these biases remained substantial even under smaller land-cover elasticities of our value coefficients.

We have also assumed that the demand curves for ecosystem services remain unchanged. This assumption might be unrealistic in light of population and per capita income increases (Drupp et al., 2024), both of which make it likely that demand curves will shift upwards (Magalhães Filho et al., 2021) and generate further value changes. Value coefficients would then depend not only on land area covered by a given LULC type but also on time (e.g., Kindu et al., 2018; Knoke et al., 2021). Temporal changes of value coefficients and associated *ESV* have recently been studied mainly in urban areas (Bryan et al., 2018; Li et al., 2021; Zhou et al., 2022), while Drupp and Hänsel (2021) have studied how future scarcity of non-market goods may drive policy evaluation. Shifts in ecosystems service demand curves may impact gains or losses in *ESV*; if these lead to higher land-cover elasticities, the bias associated with using constant value coefficients will be exacerbated.

Against this backdrop, we conclude that using endogenous ecosystem service value coefficients that account for issues such as the relative abundance of the ecosystem services (Simpson, 2017), the resource stock currently available (Addicott and Fenichel, 2019) or the area presently covered by a specific LULC type (which is efficiently measured by remote sensing techniques, see Kindu et al., 2016) would improve the empirical realism of the assessment results. Because they use easy-to-measure land-cover area as the biophysical unit of assessment, our suggested amendments would not unduly complicate the valuation process. Thus, we should adopt these amendments to capture the intuitive assumption that the degree of scarcity will impact *VC*, unless we have better information to reject this assumption.

Using unit value benefit transfer is simple and intuitive for non-economists, so we expect this approach to continue to be applied. However, we strongly suggest using endogenous rather than constant value coefficients when assessing large changes in land allocation. Doing so will improve the reliability, and ultimately the credibility, of the method while retaining the great advantage of using readily accessible land-cover area data as the basis for estimating *ESV*.

CRediT authorship contribution statement

Thomas Knoke: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Peter Elsasser:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Mengistie Kindu:** Writing – review & editing, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data sources used are appropriately cited or reported in the text.

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References

Addicott, E.T., Fenichel, E.P., 2019. Spatial aggregation and the value of natural capital. J. Environ. Econ. Manag. 95, 118–132. https://doi.org/10.1016/j.jeem.2019.03.001.

Alfonso, A., Zorondo-Rodríguez, F., Simonetti, J.A., 2017. Perceived changes in environmental degradation and loss of ecosystem services, and their implications in human well-being. Int J Sust Dev World 24, 561–574. https://doi.org/10.1080/13504509.2016.1255674.

Arowolo, A.O., Deng, X., Olatunji, O.A., Obayelu, A.E., 2018. Assessing changes in the value of ecosystem services in response to land-use/land-cover dynamics in Nigeria. Sci. Total Environ. 636, 597–609. https://doi.org/10.1016/j.scitotenv.2018.04.277.

Assefa, W.W., Eneyew, B.G., Wondie, A., 2021. The impacts of land-use and land-cover change on wetland ecosystem service values in peri-urban and urban area of Bahir Dar City, Upper Blue Nile Basin. Northwestern Ethiopia. Ecol Process 10. https://doi.org/10.1186/s13717-021-00310-8.

Barten, A.P., Bettendorf, L.J., 1989. Price formation of fish. Eur. Econ. Rev. 33, 1509–1525. https://doi.org/10.1016/0014-2921(89)90075-5.

Batabyal, A.A., Kahn, J.R., O'Neill, R.V., 2003. On the scarcity value of ecosystem services. J. Environ. Econ. Manag. 46, 334–352. https://doi.org/10.1016/S0095-0696(02)00040-2.

Biedemariam, M., Birhane, E., Demissie, B., Tadesse, T., Gebresamuel, G., Habtu, S., 2022. Ecosystem service values as related to land use and land cover changes in Ethiopia: a review. Land 11, 2212. https://doi.org/10.3390/land11122212.

Braat, L.C., de Groot, R., 2012. The ecosystem services agenda:bridging the worlds of natural science and economics, conservation and development, and public and private policy. Ecosyst. Serv. 1, 4–15. https://doi.org/10.1016/j.ecoser.2012.07.011.

Bryan, B.A., Ye, Y., Zhang, J., Connor, J.D., 2018. Land-use change impacts on ecosystem services value: Incorporating the scarcity effects of supply and demand dynamics. Ecosyst. Serv. 32, 144–157. https://doi.org/10.1016/j.ecoser.2018.07.002.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Chang. 26, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002.

Czajkowski, M., Ahtiainen, H., Artell, J., Meyerhoff, J., 2017. Choosing a functional form for an international benefit transfer: evidence from a nine-country valuation experiment. Ecol. Econ. 134, 104–113. https://doi.org/10.1016/j.ecolecon.2017.01.005.

Daily, G.C., Ruckelshaus, M., 2022. 25 years of valuing ecosystems in decision-making. Nature 606, 465–466. https://doi.org/10.1038/d41586-022-01480-x.

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., ten Brink, P., van Beukering, P., 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1, 50–61. https://doi.org/10.1016/j.ecoser.2012.07.005.

Desvousges, W.H., Gard, N., Michael, H.J., Chance, A.D., 2018. Habitat and resource equivalency analysis: A critical assessment. Ecol. Econ. 143, 74–89. https://doi.org/10.1016/j.ecolecon.2017.07.003.

Dietz, S., Hepburn, C., 2013. Benefit–cost analysis of non-marginal climate and energy projects. Energy Econ. 40, 61–71. https://doi.org/10.1016/j.eneco.2013.05.023.

Drupp, M.A., Hänsel, M.C., 2021. Relative prices and climate policy: How the scarcity of nonmarket goods drives policy evaluation. Am. Econ. J. Econ. Pol. 13, 168–201. https://doi.org/10.1257/pol.20180760.

Drupp, M.A., Hänsel, M.C., Fenichel, E.P., Freeman, M., Gollier, C., Groom, B., Heal, G.M., Howard, P.H., Millner, A., Moore, F.C., Nesje, F., Quaas, M.F., Smulders, S., Sterner, T., Traeger, C., Venmans, F., 2024. Accounting for the increasing benefits from scarce ecosystems. Science (New York N.Y.) 383, 1062–1064. https://doi.org/10.1126/science.adk2086.

Farley, J., 2008. The role of prices in conserving critical natural capital. Conserv. Biol. J. Soc. Conservat. Biol. 22, 1399–1408. https://doi.org/10.1111/j.1523-1739.2008.01090.x.

Fisher, B., Turner, K., Zylstra, M., Brouwer, R., Groot, R. de, Farber, S., Ferraro, P., Green, R., Hadley, D., Harlow, J., Jefferiss, P., Kirkby, C., Morling, P., Mowatt, S., Naidoo, R., Paavola, J., Strassburg, B., Yu, D., Balmford, A., 2008. Ecosystem services and economic theory : integration for policy-relevant research. Ecological Applications 18, 2050–2067.

Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. Ecol. Econ. 68, 643–653. https://doi.org/10.1016/j.ecolecon.2008.09.014.

Foundation for Sustainable Development, 2021. Ecosystem Services Valuation Database 1.0. https://www.esvd.info/ (accessed 14 January 2023).

Franklin, S.L., Pindyck, R.S., 2018. Tropical forests, tipping points, and the social cost of deforestation. Ecol. Econ. 153, 161–171. https://doi.org/10.1016/j.ecolecon.2018.06.003.

Frélichová, J., Vačkář, D., Pártl, A., Loučková, B., Harmáčková, Z.V., Lorencová, E., 2014. Integrated assessment of ecosystem services in the Czech Republic. Ecosyst. Serv. 8, 110–117. https://doi.org/10.1016/j.ecoser.2014.03.001.

Gollier, C., 2010. Expected net present value, expected net future value, and the Ramsey rule. J. Environ. Econ. Manag. 59, 142–148. https://doi.org/10.1016/j.jeem.2009.11.003.

Gong, X., Chang, C.-C., 2022. Monetized estimates of the ecosystem service value of urban blue and green infrastructure and analysis: A case study of Changsha. China. Sustainability 14, 16092. https://doi.org/10.3390/su142316092.

Heal, G., 2000. Valuing ecosystem services. Ecosystems 3, 24–30. https://doi.org/10.1007/s100210000006.

Johnston, R.J., Rosenberger, R.S., 2009. Methods, trends and controversies in contemporary benefit transfer. J. Econ. Surv. https://doi.org/10.1111/j.1467-6419.2009.00592.x.

Kennedy, P., 2001. A guide to econometrics, 4th ed. MIT Press, Cambridge, Mass., p. 468

Kindu, M., Schneider, T., Teketay, D., Knoke, T., 2016. Changes of ecosystem service values in response to land use/land cover dynamics in Munessa-Shashemene landscape of the Ethiopian highlands. Sci. Total Environ. 547, 137–147. https://doi.org/10.1016/j.scitotenv.2015.12.127.

Kindu, M., Schneider, T., Döllerer, M., Teketay, D., Knoke, T., 2018. Scenario modelling of land use/land cover changes in Munessa-Shashemene landscape of the Ethiopian highlands. Sci. Total Environ. 622–623, 534–546. https://doi.org/10.1016/j.scitotenv.2017.11.338.

Knoke, T., Steinbeis, O.-E., Bösch, M., Román-Cuesta, R.M., Burkhardt, T., 2011. Cost-effective compensation to avoid carbon emissions from forest loss: An approach to consider price–quantity effects and risk-aversion. Ecol. Econ. 70, 1139–1153. https://doi.org/10.1016/j.ecolecon.2011.01.007.

Knoke, T., Kindu, M., Schneider, T., Gobakken, T., 2021. Inventory of forest attributes to support the integration of non-provisioning ecosystem services and biodiversity into forest planning—from collecting data to providing information. Curr. Forestry Rep. 7, 38–58. https://doi.org/10.1007/s40725-021-00138-7.

Knoke, T., Hanley, N., Roman-Cuesta, R.M., Groom, B., Venmans, F., Paul, C., 2023. Trends in tropical forest loss and the social value of emission reductions. Nat Sustain 6, 1373–1384. https://doi.org/10.1038/s41893-023-01175-9.

Koetse, M.J., Verhoef, E.T., Brander, L.M., 2017. A generic marginal value function for natural areas. Ann. Reg. Sci. 58, 159–179. https://doi.org/10.1007/s00168-016-0795-0.

Kreuter, U.P., Harris, H.G., Matlock, M.D., Lacey, R.E., 2001. Change in ecosystem service values in the San Antonio area. Texas. Ecol. Econ. 39, 333–346. https://doi.org/10.1016/S0921-8009(01)00250-6.

Kubiszewski, I., Costanza, R., Anderson, S., Sutton, P., 2020. The future value of ecosystem services: global scenarios and national implications. In: Ninan, K.N., Larigauderie, A. (Eds.), Environmental Assessments: Scenarios, Modelling and Policy. Edward Elgar Publishing, ProQuest Ebook Central, Cheltenham, UK, Northampton, MA, Ann Arbor.

Li, J., Chen, H., Zhang, C., Pan, T., 2019. Variations in ecosystem service value in response to land use/land cover changes in Central Asia from 1995–2035. PeerJ 7, e7665.

Li, R., Shi, Y., Feng, C.-C., Guo, L., 2021. The spatial relationship between ecosystem service scarcity value and urbanization from the perspective of heterogeneity in typical arid and semiarid regions of China. Ecol. Ind. 132, 108299 https://doi.org/10.1016/j.ecolind.2021.108299.

Liekens, I., Schaafsma, M., de Nocker, L., Broekx, S., Staes, J., Aertsens, J., Brouwer, R., 2013. Developing a value function for nature development and land use policy in Flanders, Belgium. Land Use Policy 30, 549–559. https://doi.org/10.1016/j.landusepol.2012.04.008.

Magalhães Filho, L., Roebeling, P., Bastos, M.I., Rodrigues, W., Ometto, G., 2021. A global meta-analysis for estimating local ecosystem service value functions. Environments 8, 76. https://doi.org/10.3390/environments8080076.

Müller, A., Knoke, T., Olschewski, R., 2019. Can existing estimates for ecosystem service values inform forest management? Forests 10, 132. https://doi.org/10.3390/f10020132.

Ngo Bieng, M.A., Souza Oliveira, M., Roda, J.-M., Boissière, M., Hérault, B., Guizol, P., Villalobos, R., Sist, P., 2021. Relevance of secondary tropical forest for landscape restoration. For. Ecol. Manage. 493, 119265 https://doi.org/10.1016/j.foreco.2021.119265.

Nunes, S., Gastauer, M., Cavalcante, R.B., Ramos, S.J., Caldeira, C.F., Silva, D., Rodrigues, R.R., Salomão, R., Oliveira, M., Souza-Filho, P.W., Siqueira, J.O., 2020. Challenges and opportunities for large-scale reforestation in the Eastern Amazon using native species. For. Ecol. Manage. 466, 118120 https://doi.org/10.1016/j.foreco.2020.118120.

Ouyang, Z., Song, C., Zheng, H., Polasky, S., Xiao, Y., Bateman, I.J., Liu, J., Ruckelshaus, M., Shi, F., Xiao, Y., Xu, W., Zou, Z., Daily, G.C., 2020. Using gross ecosystem product (GEP) to value nature in decision making. Proc. Natl. Acad. Sci. USA 117, 14593–14601. https://doi.org/10.1073/pnas.1911439117.

Pearce, D., 1998. Cost benefit analysis and environmental policy. Oxf. Rev. Econ. Policy 14, 84–100. https://doi.org/10.1093/oxrep/14.4.84.

Pearce, D., 2007. Do we really care about Biodiversity? Environ. Resource Econ. 37, 313–333.

Pendrill, F., Gardner, T.A., Meyfroidt, P., Persson, U.M., Adams, J., Azevedo, T., Bastos Lima, M.G., Baumann, M., Curtis, P.G., de Sy, V., Garrett, R., Godar, J., Goldman, E.D., Hansen, M.C., Heilmayr, R., Herold, M., Kuemmerle, T., Lathuillière, M.J., Ribeiro, V., Tyukavina, A., Weisse, M.J., West, C., 2022. Disentangling the numbers behind agriculture-driven tropical deforestation. Science (New York, N.Y.) 377, eabm9267. https://doi.org/10.1126/science.abm9267.

Rolfe, J., Windle, J., Johnston, R.J., 2015. Applying benefit transfer with limited data: unit value transfers in practice. In: Johnston, R.J., Rolfe, J., Rosenberger, R.S., Brouwer, R. (Eds.), Benefit Transfer of Environmental and Resource Values: A Guide for Researchers and Practitioners. Springer, Netherlands, Dordrecht, s.l., pp. 141–162

Sannigrahi, S., Bhatt, S., Rahmat, S., Paul, S.K., Sen, S., 2018. Estimating global ecosystem service values and its response to land surface dynamics during 1995–2015. J. Environ. Manage. 223, 115–131. https://doi.org/10.1016/j.jenvman.2018.05.091.

Simpson, R.D., 2017. The simple but not-too-simple valuation of ecosystem services: basic principles and an illustrative example. J. Environ. Econ. Policy 6, 96–106. https://doi.org/10.1080/21606544.2016.1184594.

Spangenberg, J.H., Settele, J., 2010. Precisely incorrect? Monetising the value of ecosystem services. Ecol. Complex. 7, 327–337. https://doi.org/10.1016/j.ecocom.2010.04.007.

Spencer-Cotton, A., Kragt, M.E., Burton, M., 2018. Spatial and scope effects: valuations of coastal management practices. J. Agric. Econ. 69, 833–851. https://doi.org/10.1111/1477-9552.12301.

Stobbe, A., 1991. Mikroökonomik. Springer, Berlin Heidelberg, Berlin, Heidelberg, s.l., p. 598

Teeb, 2010. The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations. Earthscan, London and Washington.

Toman, M., 1998. Why not to calculate the value of the world's ecosystem services and natural capital. Ecol. Econ. 25, 57–60. https://doi.org/10.1016/S0921-8009(98)00017-2.

Tran, N., Chu, L., Chan, C.Y., Genschick, S., Phillips, M.J., Kefi, A.S., 2019. Fish supply and demand for food security in Sub-Saharan Africa: An analysis of the Zambian fish sector. Mar. Policy 99, 343–350. https://doi.org/10.1016/j.marpol.2018.11.009.

Troy, A., Wilson, M.A., 2006. Mapping ecosystem services: Practical challenges and opportunities in linking GIS and value transfer. Ecol. Econ. 60, 435–449. https://doi.org/10.1016/j.ecolecon.2006.04.007.

Turner, K.G., Anderson, S., Gonzales-Chang, M., Costanza, R., Courville, S., Dalgaard, T., Dominati, E., Kubiszewski, I., Ogilvy, S., Porfirio, L., Ratna, N., Sandhu, H., Sutton, P.C., Svenning, J.-C., Turner, G.M., Varennes, Y.-D., Voinov, A., Wratten, S., 2016. A review of methods, data, and models to assess changes in the value of ecosystem services from land degradation and restoration. Ecol. Model. 319, 190–207. https://doi.org/10.1016/j.ecolmodel.2015.07.017.

van der Ploeg, S., Groot, R.S. de, Wang, Y., 2010. The TEEB Valuation Database: overview of structure, data and results. Wageningen, the Netherlands.

Wang, B., Hu, C., Li, J., 2022. Coupling and coordination relationship between the tourism economy and ecosystem service value in southern Jiangsu, China. Int. J. Environ. Res. Public Health 19. https://doi.org/10.3390/ijerph192316136.

Weitzman, M.L., 2012. The Ramsey discounting formula for a hidden-state stochastic growth process. Environ. Resour. Econ. 53, 309–321. https://doi.org/10.1007/s10640-012-9594-y.

Zhou, X., Yang, L., Gu, X., Zhang, L., Li, L., 2022. Scarcity value assessment of ecosystem services based on changes in supply and demand: A case study of the Yangtze River Delta City Cluster, China. Int. J. Environ. Res. Public Health 19. https://doi.org/10.3390/ijerph191911999.