VALUING FOREST NATURAL CAPITAL AND ECOSYSTEM SERVICES IN A BIOECONOMIC FRAMEWORK

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Abstract
Temperate forests support human well-being through providing many ecosystem services. According to the economic theory, forest ecosystems are a form of capital, often referred to as natural capital and thus are productive assets to society. Assets such as forest stands, soil and forest species are created by ecosystem processes that vary through time and space. Therefore, accurate valuation of forest ecosystems requires consideration of the underlying ecological dynamics that create and produce ecosystem services. We present a valuation framework that allows us to measure the shadow prices of individual forest ecosystem components as natural capital assets that is consistent with economic capital theory. Simultaneously, we account for biophysical and economic feedbacks of the system and incorporate three pathways by which the forest ecosystem affects human welfare.

Key words: ecosystem services, natural capital, forest dynamics, shadow prices

Introduction
Natural capital is one of the productive assets of the economic system, alongside reproducible or human capital. Capital assets represent a stock of wealth that can be used in the future to produce social benefits. Natural capital creates flows of goods and services, which we call ecosystem services. Natural capital can include not only assets such as commercial forests, but also ecosystem components such as forest soil, forest species, or the forest as a sink for carbon sequestration.
Natural systems can contribute to human welfare by providing ecosystem services in three ways, depending on how they enter the social utility function: (i) as an input to the production of market goods (e.g. timber), (ii) as an input to the household production function to produce non-market goods (e.g. recreational experience while picking forest fruits), (iii) as a source of non-use values associated with the existence of the species (e.g. existence value). Forest ecosystems can also affect human welfare through the pathway (i) by influencing the economic production indirectly (e.g. watershed protection, managing climate). For example, the uptake of carbon from the atmosphere by forest ecosystems can weaken the climate change impacts and thus can indirectly affect the production of market goods in the pathway (i).
According to Dasgupta (2014) and Bastien-Olvera and Moore (2022), the value of the total natural capital stock W_n (e.g. forest ecosystem) at time t can be expressed as the sum over individual natural assets n_i (e.g. forest biomass, soil, species) multiplied by their shadow price $p_i(t)$, thus

$$W_n(t) = \sum_i p_i(t) \cdot n_i(t) \quad (1)$$

The shadow price is a critical parameter for measuring the total value of natural capital. The shadow price measures the scarcity of the natural asset and represents the present value of the flow of net benefits that society assigns to an additional unit of the natural asset. The price dynamic is determined by the socio-economic programs, conditional on the ecological dynamic of the ecosystem and human impacts.

Theoretical framework
The theoretical concept developed for this paper is grounded on the work of Mäler (1991), Dasgupta (2009), and Fenichel and Abbott (2014). Let $n(t)$ be the stock of forest ecosystem that represents valuable natural capital asset available at time t. The state of forest ecosystem changes according to the following equation of motion

$$\dot{n}(t) = g(n) - h(n) \quad (2)$$

where $g(n)$ is a natural growth function, and $h(n)$ is the use of any ecosystem components of forest by the economy.
We assume that there is only one homogeneous good $q(t)$ produced that can be produced according to the following production function

$$q(t) = f\big(k, l, n, h(n)\big) \quad (3)$$

where k and l is the amount of reproducible capital and labor used in the production of q.

Further, we consider cases where forest ecosystem figures in household production. Let the household production function is

$$r(t) = y(n, v) \quad (4)$$

where v is the number of visits to the forest. The function $y(n, v)$ combines the stock of the forest asset n with a market good such as v to produce another commodity r – a recreational experience, which is a non-market environmental good.

In our model, we suppose that households have preferences towards consumption of traditional market goods and services q, non-market environmental goods r and existence of forest assets such as wildlife species n. Hence, household preferences are represented by household utility function. Instantaneous utility of households $U(t)$ is given by the following household utility function

$$U(t) = u(n, r, q) \quad (5)$$

which is concave and twice differentiable.

The value function – intertemporal welfare function – evaluating the present value of net benefits at time t takes the form

$$V(n(t)) = \int_t^\infty u\big(n(\tau), r(\tau), q(\tau)\big)\, e^{-\delta(\tau - t)} d\tau \quad (6)$$

where δ is the social discount rate ($\delta > 0$) and $n(\tau)$ evolves through time according to equation (2).

Given the value function (6), the shadow price, or marginal value, of the forest ecosystem asset n at time t is defined as (Dasgupta, 2009)

$$p\big(n(t)\big) = \partial V\big(n(t)\big) / \partial\, n(t) \quad (7)$$

and in general, the shadow price is a function of the state variable considered in the ecological model (2). Definition (7) states that the shadow price of the ecosystem asset represents the change in the net present value to society as a result of holding more amount of the asset in place (Fenichel and Abbott, 2014).

Shadow price of a forest ecosystem asset

Following Dasgupta and Mäler (2000), and Fenichel and Abbott (2014), differentiating (5) with respect to t, rearranging the results to yield the expression for $V(n)$ and differentiating $V(n)$ with respect to n, we obtain the following equation for the shadow price

$$p(n) = \frac{u_n(n, r, q) + \dot{p}(n)}{\delta - \big(g'(n) - h'(n)\big)} \quad (8)$$

where

$$u_n(n, r, q) = u'_n + u'_y \cdot y'_n + u'_f \cdot \big(f'_n + f'_h \cdot h'(n)\big) \quad (9)$$

Equation (8) states that the marginal value of an ecosystem asset is equal to the marginal ecosystem service flows (marginal dividends), $u_n(n, r, q)$, adjusted by price change (capital gains or losses), $\dot{p}$, divided by a social discount rate, δ, adjusted for biophysical or anthropogenic processes of appreciation or depreciation.

Biophysical processes are represented by the marginal growth of forest asset, $g'(n)$, which arises from the additional amount of stock. On the other hand, anthropogenic processes are represented by the marginal human impact on the forest ecosystem (e.g. timber harvest), which is a consequence of the additional amount of stock.

Marginal dividends $u_n(n, r, q)$ are formed of three terms (see equation (9)), representing the ways how ecosystem services can influence human welfare. The first term u'_n is the marginal utility from the existence of forest species (pathway (iii)). The second term $u'_y \cdot y'_n$ can represent the marginal utility from picking forest fruits (pathway (ii)). And the last term $u'_f \cdot \big(f'_n + f'_h \cdot h'(n)\big)$ can represent the marginal value of the timber stock, which encompasses the household's marginal valuation of the timber stock u'_f and the second part of the term is the marginal productivity of the timber stock in production (pathway (i)).

Discussion and conclusion

Whether the aim is to measure the value of an individual ecosystem asset, the total value of an entire ecosystem, or to estimate welfare changes associated with proposed forest management, the bioeconomic framework – incorporating the dynamics of ecological processes and human impacts and reflecting the different pathways through which ecosystem services influence human welfare – provides a useful and theoretically consistent way, how to derive scarcity values (shadow prices) for individual ecosystem assets.

However, this cannot be achieved without appropriate data and models simulating ecosystem processes, the response of ecosystems to human impacts, and without valuation studies providing marginal values of final ecosystems goods and services.

It is also worth noting that this comprehensive valuation framework is based on a complex bioeconomic system, which is determined by non-linear relationships and scientific uncertainties. Compared to the reproducible capital, non-convexities are prevalent in ecosystems, ecosystems can collapse abruptly and human impacts on the ecosystem are mostly irreversible (Barbier, 2013).

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Souhrn

Lesy mírného pásma poskytují lidské společnosti různorodé toky statků a služeb – nazývané ekosystémovými službami, které se podílejí na tvorbě rozmanitých forem společenských přínosů. Podle ekonomické teorie lze považovat lesní ekosystémy za formu kapitálu, označovaného často jako přírodní kapitál, a patří tedy mezi produktivní aktiva společnosti. Tato produktivní aktiva, jako jsou lesní porosty, lesní půda či lesní druhy rostlin a živočichů, jsou vytvářeny ekosystémovými procesy, které jsou variabilní v čase a prostoru. Pro exaktní ocenění lesních ekosystémů je proto důležité začlenit do hodnotícího rámce ty ekologické procesy, které se významně podílejí na tvorbě ekosystémových služeb. Tento článek představujeme hodnotící rámec, který umožňuje měřit stínové ceny jednotlivých složek lesního ekosystému jako aktiv přírodního kapitálu, který je v souladu s ekonomickou teorií kapitálu. V systému modelu jsou uvažovány jak biofyzikální a ekonomické zpětné vazby, tak jsou zohledněny tři způsoby, kterými mohou ekosystémové služby lesa ovlivňovat společenský užitek.

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