A Monetary Evaluation of Ecosystem Services

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Summary

We create an ecosystem service valuation model to understand the true cost of land-use projects by modeling the value of the unaffected ecosystem services and the extent to which they would be impacted by potential land-use development. We achieve this by considering variables from the land-use project and the ecosystem of the specific location.

To measure how eco-friendly the area of the project is, we consider biome, proximity to urban centers, precipitation, cost of energy in the region, and canopy coverage.

We divide ecosystem services into direct use services and indirect use services. We draw upon a variety of well-established methods for valuation, including market-based valuation, replacement cost, avoided costs, and benefit transfer. We also utilize two data sets: The Economics of Ecosystems and Biodiversity Valuation Database (TEEB) and Energy Society's Database.

We test our model on six case studies. For each, we find the total monetary costs of the ecosystem services affected by land-use projects.

Project	**Ecological Cost (USD)**
Road construction in Cairo, Egypt	\$219
Housing in Washington, USA	\$502
Facebook MPK20 in California, USA	\$19,110
Road construction in Hobart, Australia	\$1.7 million
Vía Verde Pipeline in Puerto Rico	\$642 million
Nicaragua Canal Project	\$3.16 billion

Finally, we project our model as a function of time into the future and perform a sensitivity analysis by varying our initial parameters. Our model is robust to reasonable perturbations within an order of magnitude.

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Introduction

Our task is to create a valuation model of ecological services to quantify the economic costs of environmental degradation caused by land-use development.

Our model considers a potential project, takes into account many aspects of the location of the project, and returns a monetary value that is estimated to be the value of the ecological service. This model's purpose is to assist people in understanding the ecological cost of land-use projects in monetary terms.

The main challenge faced in creating this model is assigning a monetary value to services that do not posses this value intrinsically. To overcome this difficulty, we utilize multiple established approaches and synthesizes them into a single model.

We model land-use development projects of varying sizes in different locations. To evaluate the effectiveness and implications of our model, we perform sensitivity analysis and project our model into the future.

Definitions

- **Ecological (or Ecosystem) Services** are any services provided by an ecosystem which could be beneficiary to humans. Ecological services can be categorized into use (those which can be directly or indirectly used by humans) and non-use (those which cannot be used by humans). Controversy often arises with non-use ecological services, since it is contentious to place a price on that which offers no value. We consider non-use ecological services as "subservices" [Ecosystem Services Partnership 2019; van der Ploeg and de Groot 2010].

  The ecological services that we consider include

  - carbon sequestration,
  - water filtration,
  - flood prevention,
  - erosion prevention,
  - recreation,
  - biodiversity protection,
  - fire prevention,
  - timber,
  - fuel wood and charcoal,
  - eco-tourism,
  - micro-climate regulation,
  - biochemicals,

  - natural irrigation,
  - plants and vegetable food,
  - hydroelectricity,
  - deposition of nutrients,
  - gas regulation,
  - soil formation,
  - cultural use,
  - drainage, and
  - science/research.

- **Valuation** of a given service is the monetary value assigned to it. Since the value of a service must be of greater than or equal value than the price for consumers to purchase it, any monetary estimation of an ecological service will underestimate the true value of the service.
- **Direct Use** services are measurable services produced by the ecosystem that directly benefit humans, such as carbon sequestration and ground water recharge.
- **Indirect Use** services are services that don't directly benefit humans but augment the benefits of direct use services, e.g., biodiversity. The difficulty of measuring such services often results in calculating their demand-side valuation, i.e., the value that the service provides for humans. We use as sources for these values The Economics of Ecosystems and Biodiversity (TEEB) Database [Ecosystem Services Partnership 2019; van der Ploeg and de Groot 2010], a database of ecosystem services values from many ecosystem valuation studies. The values used were calculated based on three well-established methods for ecosystem valuation: benefit transfer, direct market pricing, and replacement cost techniques.
- **Biome** is the naturally occurring flora and fauna occupying a habitat and can be broadly categorized into terrestrial and marine [Kendeigh 1961]. We consider only terrestrial.

  The biome types that we consider are:
  - tropical forests,
  - inland wetlands,
  - coastal wetlands,
  - cultivated areas,
  - woodlands,
  - deserts,
  - forests, and
  - grasslands.

Assumptions

- **Clean water is accessible, and uncontaminated water sources vary little among one another.** Since water can be piped or trucked in, we assume that it is accessible; in our model, we consider the distance to clean water.
- **Areas in the same ecosystem classification are equally productive.** Even in ecosystems that are in the same classification, there can be huge variety. We assume that each biome is relatively uniform throughout, so that grouping by biome is sufficient to differentiate among projects.
- **Any impact scales linearly.** An increase in the area linearly affects the factors used to calculate the monetary representation of the ecological cost. For example, if one tree sequesters N kg of CO_2, then two trees sequester $2N$ kg of CO_2.
- **Energy costs accurately reflect the value of ecological services and accurately translate the costs of those services in different regions with differing energy costs.** We translate some ecological costs into monetary value by calculating the approximate energy of ecological services and using the energy cost in the region. We assume that it is possible to estimate a conversion factor.
- **There is a non-linear inversely proportional relationship between the distance from an urban area and the value of ecosystem service** [Trisos 2015; Zari 2018]. Therefore, we assume a relationship between urbanization and ecosystem services. This means that access to clean water, biodiversity, and other similar services are affected by urban proximity.

Model

Model Variables

We use different methods to evaluate the monetary cost of varying ecological services, depending on the service. We use the equations below for carbon sequestration and water filtration and purification. Where we cannot estimate the direct cost of a service, we use costs from the TEEB Database [Ecosystem Services Partnership 2019].

$$\text{cost}(D, S_i, P_{\text{urban}}, E) = \left(D + \sum_i S_i\right)(1 + P_{\text{urban}})(1 - E),$$

where

- D is the monetary value of direct use factors for the project,

- S_i is the ith service,
- P_{urban} is an index of proximity of the project to an urban setting, and
- E is the eco-friendly index for the project.

To avoid double-counting, we discard any values from the TEEB data set that deal with carbon sequestration, water purification, water filtration, and any ambiguities related to water or carbon dioxide purification.

The urban proximity index and the eco-friendly index both range from 0 to 1 and are weighting factors that affect the final cost.

- **Urban proximity index:** A value of 0 corresponds to a location very close to an urban setting, defined as 5 km or less. A value of 1 corresponds to a rural location at least 50 km from an urban environment. Urban areas have irrigation services and other utilities already in place. In rural settings, the landscape needs to be torn apart more to get the resources necessary, which leads to more damage to the ecosystem services that the land provides. We use a logarithmic scale because previous literature indicates that this relationship is nonlinear [Zari 2018].
- **Eco-friendly index:** A value of 0 corresponds to a company that puts no effort into reducing its carbon footprint or using other environmentally-friendly practices. A value of 1 corresponds to a company able to "live" in the ecosystem without damaging any of the services. For example, the Apple Park in California, USA would have a relatively high eco-friendly index, since it is the world's largest naturally-ventilated building, with 7,000 trees planted around campus and 100% renewable energy powering the campus [Miller 2018]. For our six case studies, we estimate an index value. In reality, before a construction project is started, the company can use a source for determining relative eco-friendliness, such as the 2017 State of Green Business Index [Makover et al. 2018].

Further Equations

- **Total Cost of Direct Use Services** We use a summation model with a time step of one year for the use of ecological features [Yang et al. 2018].

  $$D(C, W) = C + W.$$

  We add together the monetary cost C of the energy used by carbon sequestration and the monetary cost W of the energy used to filter water; this is the total cost of the direct use services.

- **Energy of Carbon Sequestration** The energy E_C of carbon sequestration per square meter of canopy cover is calculated by multiplying the energy E_{CO_2} of carbon sequestration per pound of CO_2 by the conversion factor E_T and then by the energy efficiency p of photosynthesis.

  $$E_C = E_{\text{CO}_2} E_T p.$$

Table 1.

Symbols, definitions, and constants.

Symbol	**Definition**
$D(C, W)$	Monetary value (USD) of direct use services from an ecological area using energy calculations.
$C(A, F_{\%}, E_{\$})$	Monetary value (USD) of carbon taken out of the atmosphere by plants
$W(P_w, A, E_{\$})$	Monetary value (USD) of water filtered by the soil
S	List of ecosystem services in the TEEB dataset.
P_{urban}	Index of urban proximity (0–1), with 0 being near an urban area and 1 being in a rural/remote area
E	Eco-friendly index
A	Area of the land-use project (m^2).
$F_{\%}$	Canopy Percentage: Percentage of foliage coverage of 1 m^2 of land (%).
$E_{\$}$	Monetary value of energy varying depending on location (USD/Joule).
u	Urban proximity (m).
P_w	Precipitation (mm/yr)
b	Biome, with data from TEEB Database [Ecosystem Services Partnership 2019]

Constant	**Value**
E_C	Energy of carbon per square meter of canopy cover (117 J/m^2).
p	Energy efficiency of photosynthesis: 26% [Lambers and Bassham 2018].
t	Time (yr).
E_{CO_2}	Energy of CO_2: $5.045 \times 10^6 \ \frac{\text{J}}{\text{lb CO}_2}$ [Evans n.d.]
E_T	Energy of CO_2 per square meter: $48 \ \frac{\text{lbs CO}_2}{1\text{m}^2}$ [Lambers and Bassham 2018]
E_m	Solar transformity: amount of energy required to produce 1 g of clean groundwater from soil due to rainfall: $22.83 \ \frac{\text{J}}{\text{g}}$ [Yang et al. 2018]
$\rho_{\text{H}_2\text{O}}$	Density of water: 997 $\frac{\text{kg}}{\text{m}^3}$

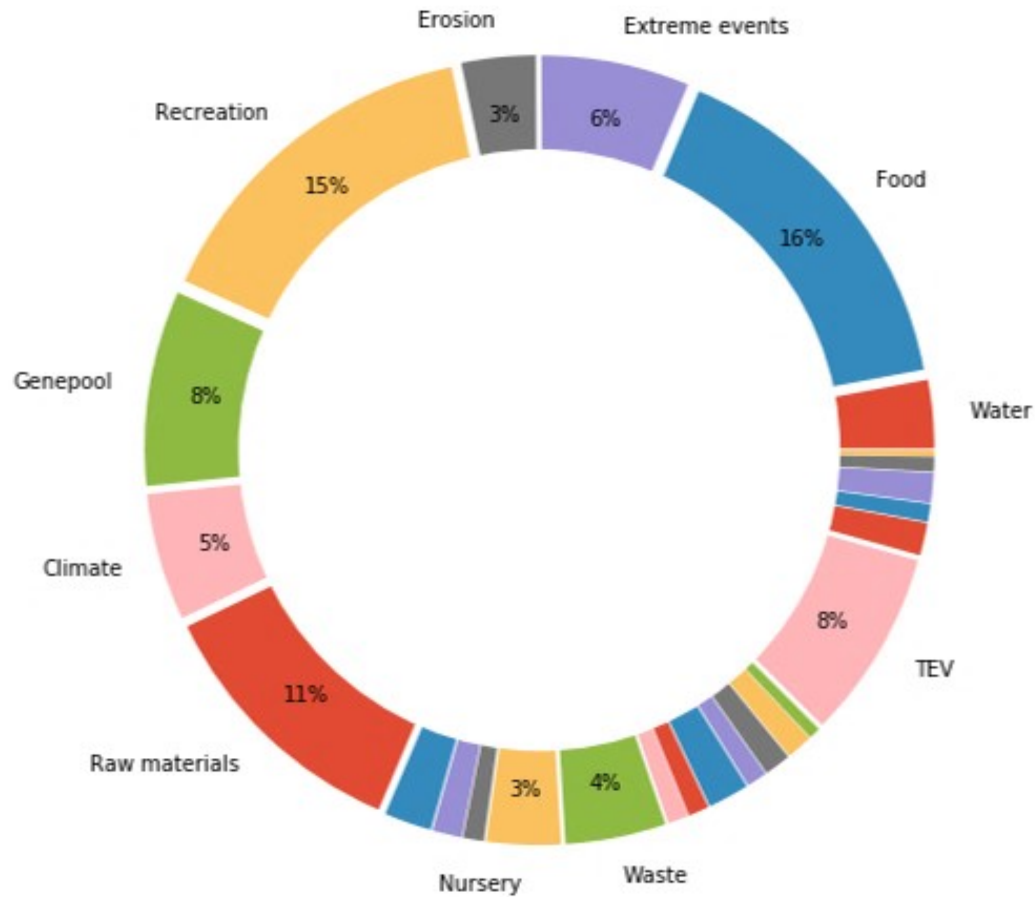

Figure 1. Resource breakdown by ecosystem service. Services that account for less than 3% of resources are not shown in the graph but are included in the analysis.

- **Cost of Carbon Sequestration** The cost C of carbon sequestration is calculated by multiplying the total area A by canopy cover percentage $F_{\%}$ and then by energy E_C used per square meter of canopy cover. We convert to USD by using the cost $E_{\$}$ of energy at the location of the land-use project.

$$C = E_{\$} E_C F_{\%} A.$$

- **Cost to Filter Water** We multiply precipitation P_w per square meter by the area A of the land-use project to find total precipitation in the area. We then multiply by density $\rho_{\mathrm{H_2O}}$ of water to convert volume to mass, and then multiply by solar transformity E_m to arrive at the total amount of energy required to clean the water. We convert to USD by using the cost $E_{\$}$ of energy at the location of the land-use project.

$$W = P_w A \rho_{\mathrm{H_2O}} E_m E_{\$}.$$

- **Index of Urban Proximity** We use a logarithmic scale for the index P_{urban} of urban proximity because of the nonlinearity between urban diversity and ecosystem services [Trisos 2015]:

$$P_{\text{urban}} = \log_{10}\left(\frac{x}{5}\right), \qquad 5 \le x \le 50.$$

Case Studies

By testing case studies, we can confirm that our model's results are logical and of the right scale.

We list case studies in order of area, from smallest to largest.

We estimate cost of environmental services for just one year. Highly relevant also would be their total cost over the lifetime of the project, using an appropriate discount rate for future costs. We do not attempt to estimate the lifetimes of these projects.

Housing in Seattle, Washington, USA

[Davey Resource Group 2011; Trimbath 2016; Choose Energy 2019; Rosenberg 2016]

The impact of individual housing on ecosystem services is generally hard to measure. In most cases, housing is built as parts of large projects that disrupts large areas of an ecosystem, yet in this case study we model a theoretical housing project in rural Washington state.

Project Cost without environmental services considered:	$300,000
Environmental services cost per year:	$ 502
Combined cost after the first year:	$300,502
Percentage increase:	0.14%

This project's large distance from the urban environment and its location in a high canopy-coverage biome are factors expected to be very influential in the cost for this project. Yet its small size and its eco-friendly index result in a very low cost to environmental systems compared to its total cost. The damaged ecosystem services would not be significant in project consideration.

Facebook MPK Building 20 in Menlo Park, California, USA

[City of Menlo Park n.d.; Electricity Local 2019; Graeber 2018; Meyers 2016]

Large companies are constantly building or remodeling their headquarters to accommodate to their significant growth. Facebook's MPK Building 20 expansion serves as a good example of such a project.

The vast majority of large company headquarters are found in urbanized areas in which local ecosystem services have already been damaged;

so even when considering the large scale of such a project, its environmental damage is relatively limited. The ecosystem services cost would likely not influence the development of the project.

Project Cost without environmental services considered:	$269 million
Environmental services cost per year:	$19,110
Combined cost after the first year:	$269 million
Percentage increase:	0.007%

Road construction in Hobart, Tasmania, Australia

[Australian biomes n.d.; Australian Government 2018; C. 2001; CityGreen Australasia n.d.]

Unlike the vast majority of Australia, Tasmania's biome is classified as a rain forest with unique flora and fauna at risk by urban development. Average road project costs in Australia are high, and the value of the ecosystem services in such a diverse part of Australia is likely to increase the project cost significantly.

Project Cost without environmental services considered:	$73 million
Environmental services cost per year:	$ 1.7 million
Combined cost after the first year:	$74.7 million
Percentage increase:	2.3%

The cost of ecosystem services would be significant in this land-use project, since the roads would affect a diverse and bountiful ecosystem. Because this project is being built relatively far away from the urban centers, it would impact pristine natural environments with a high value for ecosystem services.

Road construction in Cairo, Egypt

[Mohamed 2018; Mongabay 2018]

Cairo is an economic and cultural center also known for its abysmal traffic. Road project costs in Egypt are relatively cheaper than other parts of the world, and the desert environment of Egypt suggests a project of this type should be generally cheaper both in construction cost and in possible damage to ecosystem services.

Considering that this project is being built in a desert, the damages to ecosystem services would be low, since a desert environment does not provide many ecosystem services.

The most significant service that would be affected by the construction would be the direct use of water recharge; yet due to Egypt's significantly low precipitation, this ecosystem service does not get much use to begin with.

Project Cost without environmental services considered:	\$21 million
Environmental services cost per year:	\$218
Combined cost after the first year:	\$21 million
Percentage increase:	0.000%

Proposed Vía Verde Pipeline in Puerto Rico

[Data Basin n.d.; Marcano-Vega 2017; Vermont Law School 2012]

The Vía Verde Pipeline Project was proposed in 2009 as a landmark energy project to satisfy Puerto Rico's energy needs. The project was never completed once it proved to be controversial due to its planned route which would have covered around seven square kilometers of Puerto Rico's untouched rain forest. Since this would potentially place many local communities and endangered species at risk the monetary ecological cost would be significant.

Project Cost without environmental services considered:	\$ 800 million
Environmental services cost per year:	\$ 642 million
Combined cost after the first year:	\$1.442 billion
Percentage increase:	44.5%

The Vía Verde Pipeline would significantly damage the vast ecosystem services that the ecosystem provides to the point the project is likely not worth its cost.

Proposed Nicaragua Canal Project

[Flannery 2014; Hochleitner 2015]

The Nicaraguan government has proposed a massive project to construct a new canal to connect the Pacific and Atlantic Oceans. This proposal has proved unpopular, because the canal would cut through heavily wooded areas of Nicaraguan rain forest and cause massive disruption to the ecosystem.

Project Cost without environmental services considered:	\$45 billion
Environmental services cost per year:	\$ 3.16 billion
Combined cost after first year:	\$48.16 billion
Percentage increase:	6.6%

The Nicaragua Canal project would significantly affect the environment due to the scale of the project. The cost of the environmental services should be taken into account when making the decision about building it.

Conclusion

A significant goal of this project was the creation of a land ecosystem evaluation model that could be applied at a global scale to a series multiple different projects with different rates of impact. To achieve this goal, we develop carbon sequestration and water discharge models that can be calculated for any environment and location. The TEEB database provides a standardized dataset for the different biomes that our model treats.

By using case studies that vary in magnitude, cost, and location, we determine that our model can correctly predict the monetary cost of ecological services.

Future Projections

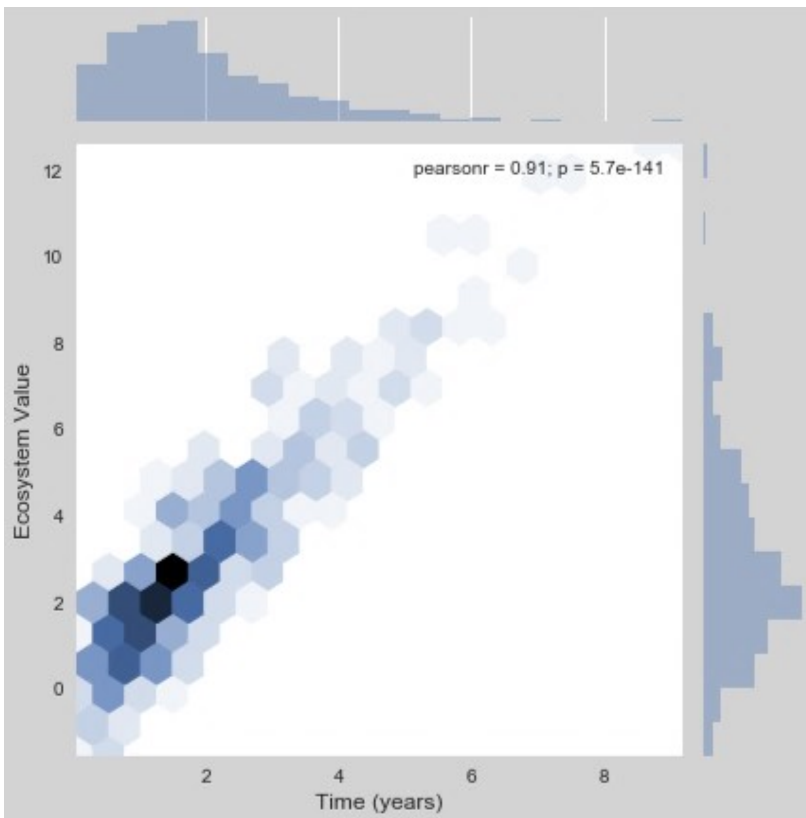

Figure 2. The change in ecosystem services valuation over time.

We project our model into the future by performing simple random perturbations. We perform a kernel density estimation corresponding to how certain we are that our model is accurate at a time t after our initial construction. The lighter shades in **Figure 2** indicate a lower certainty as time goes on since the sensitivity to initial conditions increases over time.

Sensitivity Analysis

We perform a sensitivity analysis by varying values of the parameters in our model. We vary the eco-friendly and urban proximity indexes by -0.1 to 0.1. We also vary other parameters of ecosystem services in the TEEB database, as well as carbon sequestration parameters and water filtration parameters, using bounded random values. Our model's projected costs, for all six of the case studies, vary only within one order of magnitude from the base value, which suggests some stability.

Strengths and Weaknesses

Strengths

- Multiple inputs provide for an accurate assessment of the ecological value of a chosen location.
- The model integrates multiple kinds of valuation, bridging the gap between supply-value models and demand-value models.

Weaknesses

- We do not include all possible ecological factors that could contribute to the monetary value of the ecosystem.
- We assume that grouping by biome is sufficient to differentiate among projects. Although within each biome there are differences which would affect the ecological impact of a land-use project, we do not take these into account.
- The environmental costs that we cite are for just one year, not over the lifetime of the projects.

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