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 in which they are impacted by the land use development. Due to these considerations the model is most capable of evaluating the value of ecosystem services that are most likely to be damaged by land development. We achieve this by considering variables from the land use project itself and variables from the location the project will be built in.

The variables we consider for the project are the area and how eco-friendly it is. The variables we consider for the environment of the projects are the biome, its proximity to urban centers, precipitation, cost of energy in the region, and canopy coverage.

When evaluating the ecosystem services themselves, we divided the type of services into two broad categories: direct and indirect use services. We draw upon a variety of well-established methods for valuation including, but not limited to: market-based valuation, the replacement cost method, avoided costs, and benefit transfer. We also utilize two data sets: The Economics of Ecosystems and Biodiversity Valuation Database (TEEB) and Emergy Society's Database.

Our model is tested on six different case studies, finding the total monetary cost of the ecosystem services affected by land use projects:

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

Table 1: Case studies.

Finally, given that our model is dynamic, 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 to within an order of magnitude.

Is this a monetary evaluation of ecosystem services?

ICM Contest Question E

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Contents

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

1.1 Definitions

1. **Ecological Services**

   An **ecological (or ecosystem) service** is any service 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) and controversy often arises with non-use ecological services as it is contentious to place a price on that which offers no value. We choose to consider non-use ecological services as "subservices"[27].

   The ecological services we consider include but are not limited to: *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, hydro-electricity, deposition of nutrients, gas regulation, soil formation, cultural use, drainage, and science/research.*

2. **Valuation**

   The **valuation** of a given service is the monetary value assigned to that service. Since the value of a service must be greater than or of equal value to the price for consumers to purchase a service, any monetary estimation of an ecological service will underestimate the true value of the service.

3. **Direct Use**

   Direct Use services describe measurable services produced by the ecosystem which directly benefit humans, such as carbon sequestration and ground water recharge.

4. **Indirect Use**

   Indirect use services are services that don't directly benefit humans, but augment the benefits of other direct use services; e.g. biodiversity. Since this is difficult to measure, this often results in calculating their demand side valuation; i.e. the value the ecosystem service provides for humans. We use The Economics of Ecosystems and Biodiversity (TEEB) Database[27] as sources for these values, a compiled database of ecosystem services values from many ecosystem valuation studies. The values used for the ecosystem services were calculated based on three well-established methods for ecosystem valuation: benefit transfer, direct market pricing, and replacement cost techniques.

5. **Biome**

   The **biome** is the naturally occurring flora and fauna occupying a habitat and can be broadly categorized into terrestrial and marine[17], although we only consider terrestrial.

   The biome types we consider are: *tropical forests, inland wetlands, coastal wetlands, cultivated, coral reefs, fresh water, coastal, multiple ecosystems, woodlands, deserts, forests [temperate and boreal], grasslands, urban, and marine*.

2 Assumptions

- **Clean water is accessible and uncontaminated water sources vary little between each other.** Since water can be piped or trucked in, we assume that it is accessible and in our model we consider the distance to clean water.

- **Areas in the same ecosystem classification are equally productive.** Even in ecosystems that are 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 between 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 cost of those services in different regions with differing energy costs.** We translated some ecological costs into monetary value by calculating the approximated energy of ecological services and using the energy cost in the region. We are assuming that it is possible to estimate a conversion factor.

- **There is a non-linear inversely proportional relationship between the distance from an urban areas and the value of ecosystem service[25,28].** 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.

3 Model

3.1 Model Variables

We used different methods to evaluate the monetary cost of different ecological services depending on the service. We use the equations described 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[27].

$$(D + \sum_i S_i)(1 + P_{urban})(1 - E) \tag{1}$$

In order to avoid double-counting, we discard any values from the TEEB data set which 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 zero to one and are weighting factors which affect the final price.

For the urban proximity index, a value of zero corresponds to a location which is very close in proximity to an urban setting, defined as 5 km or less. A value of one corresponds to a rural location far from an urban environment, at least 50 km. This is because 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 non-linear[28].

For the eco-friendly index, a value of zero corresponds to a company which puts no effort into reducing its carbon footprint or using other environmentally friendly practices. A value of one corresponds to a hypothetical company which is able to symbiotically live in the ecosystem without damaging any of the services and fully operating within the parameters of the ecosystem. For example, the Apple Park built in California, US 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[19]. For the six case studies we estimate an index value. In reality, before a construction project is started, the company can use an index for determining this, such as the 2017 State of Green Business Index[8].

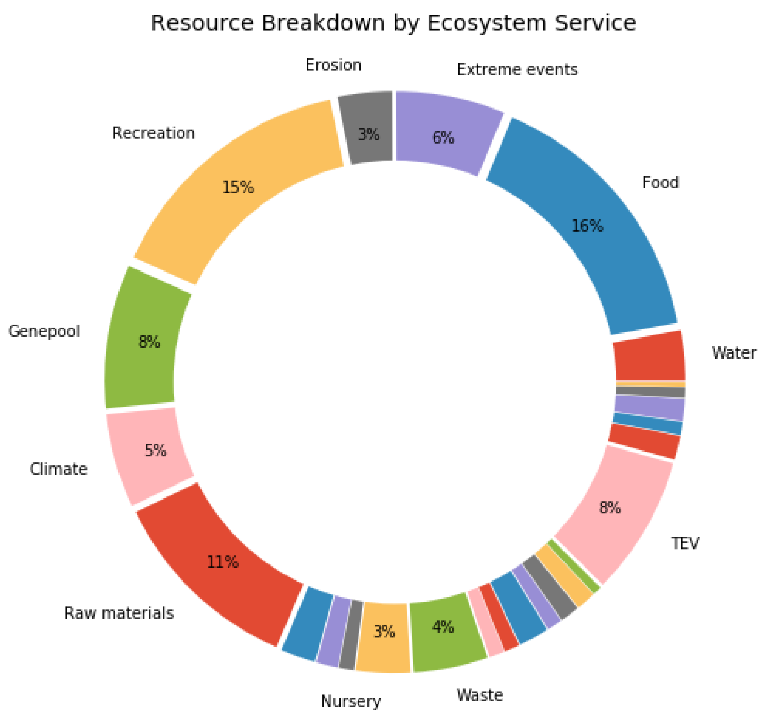

Figure 1: The most relevant ecosystem service categories by number of occurrences, not broken into sub services. Any service which accounted for less than 3% of the resources was omitted from the graph but not from analysis.

Symbol	Definition
$D(C,W)$	The monetary value (USD) of Direct Use factors from an ecological area using energy calculations. Takes in C and W.
$C(A, F_{\%}, E_{\$})$	Monetary value(USD) of carbon taken out of the atmosphere by plants, with respect to A, $F_{\%}$, and $E_{\$}$ (USD).
$W(P_w, A, E_{\$})$	Monetary value(USD) of water filtered by the soil, with respect to P_w, A, $E_{\$}$ (USD).
A	Area of the land use project (m^2).
$F_{\%}$	Canopy Percentage: The percent that foliage covers one square meter of land (%).
$E_{\$}$	Monetary value of energy varying depending on location (USD/Joules).
u	Urban proximity (m).
P_{urban}(u)	An index of urban proximity from 0 to 1, with 0 being near an urban area and 1 being in a rural/remote area
P_w	precipitation (mm/year)
b	Biome, with data taken from TEEB Database[27]
S	A Python list of the ecosystem services as described in the TEEB data set. The S_ith variable is an ecosystem variable, for example raw materials.
Constants	**Value**
E_C	Energy of carbon per square meter of canopy cover (117 J/m^2).
p	Energy efficiency of photosynthesis: 26%[15].
t	Time (1 year).
E_{CO_2}	Energy of CO_2 in Joules per pound of CO_2 $5.045x10^6$ $\frac{J}{lb\ CO_2}$[10]
E_T	Energy of pounds of CO_2 per meter squared. 48 $\frac{lbs\ CO_2}{1\ m^2}$[15]
E_m	Solar Transformity: the amount of emergy required to produce 1 Joule of clean groundwater from soil due to rainfall. 22.83 $\frac{J}{g}$[22]
ρ_{H_2O}	Density of water: 997 $\frac{kg}{m^3}$

Table 2: Symbols, definitions, and constants.

We use a summation model with a time-step of one year for the use of ecological features[22].

$$D(C, W) = C + W \tag{2}$$

Here we add together the monetary cost of the energy used by carbon sequestration and the monetary cost of the energy used to filter water. This is the total cost of the Direct Use services.

$$E_C = E_{CO_2} E_T p \tag{3}$$

This equation finds the energy of carbon sequestration per square meter of canopy cover. This is calculated by multiplying the energy of carbon sequestration per pound of CO_2 by the conversion factor to turn this value into energy of carbon sequestration per meter squared. Then this is multiplied by the energy efficiency of photosynthesis.

$$C = E_{\$} E_C F_{\%} A \tag{4}$$

This equation calculates the cost of the energy used by carbon sequestration. The energy of carbon is calculated by taking the total area and multiplying it by canopy cover percent in order to estimate the total area in which photosynthesis is occurring. We then multiply the total canopy cover by the energy produced per square meter of canopy cover to find the total energy of carbon sequestration in the area, and convert that into US dollars by using the cost of energy relative to the location of the land use project.

$$W = P_w A(\rho_{H_2O}) E_m E_{\$} \tag{5}$$

This equation calculates the cost of the energy used by the soil to filter water. By multiplying precipitation per square meter and area of the land use project we find the total precipitation in the area. We then multiply by the solar transformity to end up with the total amount of emergy required to clean the water from precipitation. We can convert this into US dollars by using the cost of energy relative to the location of the land use project.

$$P_{urban} = log(\frac{x}{5}) \tag{6}$$

This equation calculated the index for urban proximity and it works for values between 5 and 50 kilometers. If the environment is close enough, or less than 5 kilometers, then it is considered to have an index of 0 and if it is farther than 50 kilometers it is considered rural and to have an index of 1. The logarithmic scale, again, is because of the non-linearity between urban diversity and ecosystem services[25].

4 Case Studies

By testing case studies, real world examples that can be applied to our model, we can confirm that our model's results are logical and on the right scale.

The following case studies are listed in order from smallest to largest area (m^2).

4.1 Housing in Washington, United States[14,3,24,23]

The impact of individual housing on ecosystem services is generally hard to measure. In most case 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 projects large distance from the urban environment and its location in a high canopy coverage biome were factors expected to be very influential in the price inflation for this project yet its small size and is eco-friendly index resulted in a very low environmental systems cost compared to its total monetary cost. In this case the damaged ecosystem services would not be significant in project consideration.

4.2 Facebook MPK Building 20 in Menlo Park, United States[13,9,4,5]

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 for projects such as these.

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%

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.

4.3 Road construction in Hobart, Australia[6][12][18][1]

Hobart is the regional capital of Tasmania, Australia. Unlike the vast majority of Australia, Tansmania'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 million
Percentage increase:	2.3%

The cost of ecosystem services would be significant in this land use project as the roads would affect a diverse and bountiful ecosystem. As 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.

4.4 Road construction in Cairo, Egypt[20][7]

Cairo is the capital of Egypt and considered an economic and cultural center for the entire region, yet it is 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.

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%

Considering this project is being built in a desert the damages to ecosystem services would be low. The desert environment of Egypt does not provide many ecosystem services and in truth it does not need to. Considering local characteristics the most significant part of the model 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.

4.5 The proposed Vía Verde Pipeline project in Puerto Rico[21,2,26]

The Vía Verde Pipeline Project was proposed as a landmark energy project to satisfy Puerto Rico's energy needs in 2009. The project was never completed once it proved to be controversial due to its planned route which would have covered around seven square km 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.

4.6 The proposed 2013 Nicaragua Canal project between the Pacific and Atlantic Oceans[16,11]

Recently the Nicaraguan government proposed a massive project to construct a new canal to connect the Pacific and Atlantic oceans. This proved unpopular since 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:	\$47.16 billion
Percentage increase:	6.6%

The Nicaragua Canal project was always expected to significantly affect the environment around were it was built due to the scale of the project. While it would likely not significantly affect its construction its still demonstrate a significant impact.

5 Conclusion

A significant goal from the onset 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 developed carbon sequestration and water discharge models that took inputs that were valid in every environment and location. We incorporate the TEEB database as it provided a standardized data set for the different biomes our model encapsulates.

By using case studies that varied in magnitude and cost, we were able to determine that our model correctly predicted the monetary cost of ecological services.

5.1 Future Projections

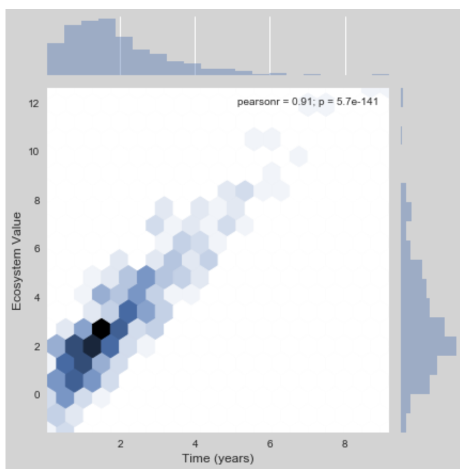

Figure 2: The change in ecosystem services valuation over time.

We project our model into the future by performing simple random perturbations. We perform a kernel density estimation at the graphs corresponding to how certain we are that our model is accurate at a time t after our initial construction.

The lighter shades indicate a lower certainty as time goes on as the sensitivty due to initial conditions varies heavily into time.

5.2 Sensitivity Analysis

We perform a sensitivity analysis by varying initial parameters of the values in our model. We vary the eco-friendly and urban proximity index from -0.1 to 0.1. We also vary other initial parameters of ecosystem services that are given by the TEEB database as well as carbon sequestration parameters and water filtration parameters with bounded random values. Our model, for all six of the case studies, vary only within one order of magnitude for the value at present, which suggests some stability.

5.3 Strengths and Weaknesses

Strengths

- Our constants are backed up by validation tests, which confirm our model.
- Multiple inputs provide 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.
- One of the assumptions, and inevitably weaknesses of our model, is that we assume that grouping by biome is sufficient to differentiate between projects. Within each biome there are differences which would affect the ecological impact of a land use project, but we do not take these into account.

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