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Project-Based Decision-Making for Sustainable Solar Generation Projects Using Ecosystem Service Valuation

Heidi von Korff, Stanford University, USA
Michael D. Lepech, Stanford University, USA

Proceedings Editors
Paul Chan, The University of Manchester and Robert Leicht, The Pennsylvania State University

PROJECT-BASED DECISION-MAKING FOR SUSTAINABLE SOLAR GENERATION PROJECTS USING ECOSYSTEM SERVICE VALUATION

Heidi von Korff[1] and Michael D. Lepech[2]

ABSTRACT

Solar power electric generating facilities strike a much lower environmental footprint compared to fossil-based facilities. When coupled with reduced non-renewable fuel demands, this lower footprint makes construction of solar energy sources an attractive, more sustainable source of electric power. However, as part of a sustainability-focused marketplace, solar power generators must present a business model to decision-makers, investors, and creditors that reflects sound decision-making that carefully considers the impact of their generation facilities. The research approach centers on appropriate valuation of firm-owned natural ecosystems, specifically land owned by solar generators. Such ecosystems provide services that sustain life, enable trade, and create social value (*i.e.*, natural capital).

The CENTURY Soil-Organic-Material Model, a modeling tool that couples nitrogen, sulfur, and carbon cycling on agricultural and natural grasslands was used to mathematically model the biogeochemical nutrient flows on a solar generation site both before and after construction. Using the cost of nutrient removal via a wastewater treatment plant as a substitutable engineered equivalent of nutrient cycling, a mark-to-model market-based price for ecosystem service preservation during construction of a solar generating facility was calculated and considered as part of the business case for utility-scale solar power. The dynamics of nutrient cycling due to climate change, harvesting, irrigation techniques, annual rainfall, and soil conditions were modeled. These dynamics are embodied in the soil organic matter active, slow, and passive cycles within the soil system for phosphorus, carbon, nitrogen, and sulfur on a natural grassland and a constructed solar generation site. The results show that the nitrogen removal from the site is comprised of the cumulative value of volatilization, nitrification, de-nitrification, leaching, mineralization, and harvesting each year. Fundamentally, this research looks to shift the ways in which the private sector (corporations, investors, individuals) view natural capital as a part of firm capital, financing, and decision-making.

KEYWORDS: Ecosystem service, Life cycle inventory, Ecosystem management, Sustainable development

1. INTRODUCTION

The private sector has begun to embrace environmental sustainability megatrends (Esty and Lubin, 2010). This has come as a result of private firms migrating from a “shareholder approach” (Friedman, 1962), in which management considers only the wealth maximization of firm owners or shareholders, to a broader “stakeholder approach” in which multiple demands of

[1] Graduate Student, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, USA vonkorff@stanford.edu.

[2] Assistant Professor, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, USA, mlepech@stanford.edu

entities that have direct and indirect interests in the firm are balanced (Freeman, 1984). In parallel with this migration of firm management philosophy has been an increased understanding of the role of natural ecosystems as crucial regulators of local and global environmental sustainability and a more comprehensive realization of the benefits natural ecosystems provide (Dominati *et al*., 2010). Together, this growing desire of management to consider a broader set of interests (*e.g.,* environmental sustainability) along with a deepening knowledge of the value that natural ecosystems provide, create a unique opportunity to fundamentally change the way in which large capital projects are managed and their costs and benefits weighed.

To support the notion of "value" in the context of natural ecosystems, numerous researchers have proposed methods for valuation and specific monetary values for natural environments. At the global scale, Costanza, Daily, DeGroot, and Rasstetter studied the value that natural ecosystems provide in biodiverse climates and discovered that both the ecosystems and the complex services they provide have an "irreplaceable value" (Costanza *et al.*, 1997). Looking at only a limited number of 17 ecosystem services for 16 varying biomes using a willingness-to-pay model, the economic value of global ecosystems proposed was in the range of US$16 trillion to US$54 trillion per year. The service of global nutrient cycling alone (*i.e.,* carbon cycling, phosphorus cycling, nitrogen cycling) was valued at US$17 trillion annually, compared with a 1997 US gross national product (GNP) of US$18 trillion annually (Costanza *et al.,* 1997).

Other scholars have also studied or are currently studying global and regional approaches to ecosystem service valuation that focus on ecosystem production functions (*e.g.,* Daily and Ehrlich, 1995; Sutton and Costanza, 2002; Watanabe and Ortega, 2011), the reliance of business supply chains on natural capital (*e.g.,* Lovins *et al.,* 1999; Hawkin *et al.*, 2013), ecological economics (*e.g.,* Jansson, 1994). However, there are currently no standards for objectively calculating the financial accounting value of natural ecosystems. Moreover, the global or regional nature of these models is not amenable to project-level assessment due to a lack of understanding of the site-specific evolution of ecosystem services (*i.e.,* soil formation, soil nutrient cycling) (Dominati *et al.,* 2010). In order to provide guidance for consideration of the value of ecosystem services, specifically at the scale of individual project management, and to better engage with corporate stakeholders and management, a newly introduced firm-level/project level ecosystem service framework (Comello *et al.,* 2012) is applied and expanded in this study.

The aims of this paper are two fold. The first aim is to significantly expand on the Comello framework by considering more than one ecosystem service function at a time. This consideration is accomplished by modeling the interaction between interdependent ecosystem functions of nutrient cycling. The second aim of this paper is to connect the ecosystem valuation framework to stakeholder decision-making. These aims are achieved via a case study of project-level ecosystem service valuation and follow-up discussion.

2. METHODOLOGY

The firm-level/project level ecosystem service framework applied in this study integrates ecosystem services, ecosystem functions, economic valuation, and decision-making (Figure 1). The framework guides a project or firm manager through the stages of ecosystem service assessment and economic valuation to ultimately provide the decision-maker with an understanding of the value-creating processes that are taking place on the project site and a value for these processes that begins to align the goals and objectives of the project with environmental sustainability. In the long term, this alignment enables sustainable development as a key corporate social responsibility goal (Comello, 2012).

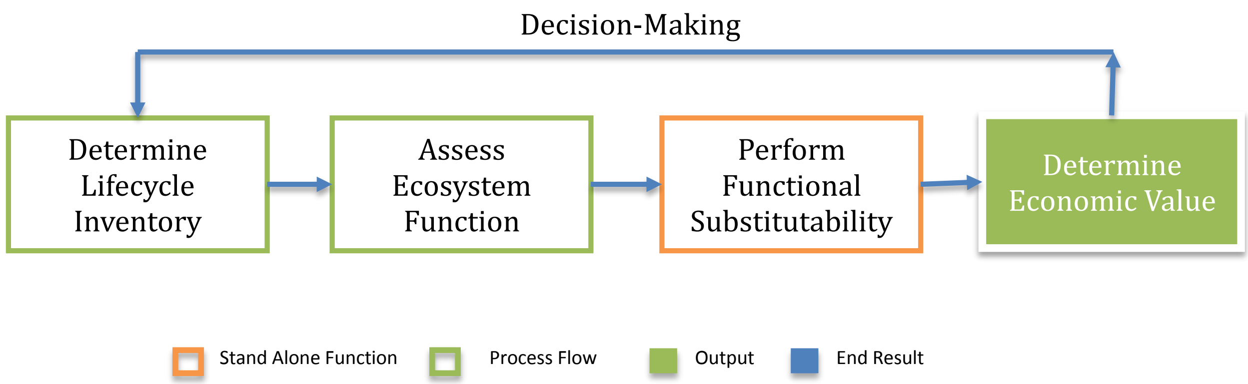

Figure 1. Firm-level ecosystem service valuation framework (adopted from Comello *et al.*, 2012)

The first stage of the framework is quantification of the environmental impact of a firm's activities or projects. This quantification is done through the construction of a life cycle inventory, one component of more conventional life cycle assessment studies. Lifecycle assessment is a tool to measure the impact of products, processes, and decisions through social, environmental, and economic indicators (EPA, 1993). The life cycle inventory, a rigorous accounting of all material, labor, capital, pollutant, and waste flows entering or leaving a site or project, is used as an input for the second stage of the framework.

Stage two identifies an ecosystem function from the set of processes that are ongoing within the natural system. These functions or processes are the physical, chemical, and biological processes across an ecosystem service, such as decomposition (Initative, 2011). Odum and Barrett were the first to measure this type of energy flow and processes based on the fundamentals of ecosystem thermodynamics (Odum and Barrett, 1971). Using ecosystem functions to characterize ecosystem services allows for a project-level assessment of ecosystem services.

The third stage of the framework implements the notion of functional substitutability to compare the fundamental function performed by a natural ecosystem to an engineered equivalent. Substitutability is a concept in economics where it establishes trade-off, and utility functions between goods and services (Comello *et al.*, 2012). For illustration, a wastewater treatment plant's biological nutrient removal process for nitrogen could be considered equivalent to a constructed wetland's nutrient cycling of nitrogen. This equivalency of function also provides the basis for valuation such that market-based values for engineered system process provision are used to value natural ecosystem processes.

The last stage in the framework supports the decision-making process. By providing a reliable, market-based value for natural ecosystem services being performed on a project site, project managers are empowered to consider a more comprehensive set of interests when deciding on implementing a project decision. Moreover, since this value for ecosystem services complies with conventional accounting rules for asset valuation, its role in affecting project finance, either positively or negatively, can be considered. By linking sustainability with project and business decisions, this ecosystem service framework is a step connecting ecosystem services, economic value, and private-sector decision-making.

3. CASE STUDY

The project location chosen for this case study is a potential small-scale solar utility installation located in Southern California. The site is located in Imperial County, California and east of the City of Brawley. The site experiences temperatures that range from 13°C in the winter to 32°C in the summer. Rainfall occurs between November and April and totals 9cm per year with evapotranspiration of 3 m/year (Johnson *et al.*, 2009). The project site is consists of 0.8 hectares of agricultural farmland (Imperial silty clay) planted with Bermuda grass, which is harvested twice annually. The farmland has been shown to provide numerous ecosystem services as part of a larger natural grassland system that can be valued as a supporting service of nutrient cycling (Zhang *et al.*, 2007). The primary question being confronted by the solar utility is whether construction of the generation facility will degrade the natural ecosystem that currently exists (a natural capital cost) more than the benefit provided by solar power (electricity commodity price). Further, the management would like to know whether the generation facility be designed and developed in such a way that natural ecosystem service provision could be maintained such that the project provides a "win-win" for stakeholders that are looking for a return on economic capital (project investors and shareholders) and conservation of natural capital (local conservationists and project neighbors).

3.1 Life cycle inventory of generation utility

The solar utility for this case study uses a proprietary solar concentrator built from reflective plastic (similar to materials commonly used in fruit juice squeeze bags) that is encased in inflated transparent tubes and placed on a shallow water basin. This technology has several advantages over competing technologies such as conventional parabolic trough reflectors by achieving high conversion efficiencies while keeping down cost of materials and installation. The Brawley site can accommodate a facility in the 200kW range. Based on the yearly average irradiance for Brawley, California, this facility can generate an annual energy output of approximately 2.1GWh. Two generation units have a 65% thermal to electrical conversion efficiency which corresponds to four collectors over adjacent trough basins. This results in the destruction of agriculture land measuring 216 meters by 24 meters, or approximately 0.5 hectares. While numerous other inputs, pollutants, and wastes are accounted in the creation of a life cycle inventory for this project, only the land disruption impacts are used for this case study. The limitation is done for brevity and clarity of illustrations. The total construction cost of this simple solar concentration system is approximately $24,000.

3.2 Definition and modeling of ecosystem functions

The identification and definition of a suitable, or set of suitable, ecosystem functions and processes that are provided on the case study site is the most challenging phase of the assessment framework. When identifying the function(s) of interest, Crossman *et al.*, (2013) note that they should include four facets; (1) that they be biophysical in nature, (2) that multiple functions represent tradeoffs or synergies with one another, (3) that they are consistent off-site effects, and (4) that they engage stakeholder involvement. The two types of modeling systems that currently analyze ecosystem services and are consistent with these facets are spatial land analysis and biogeochemical modeling. Spatial land analysis uses spatial modeling or global positioning data, along with geographic information system software (ArcGIS) to assess the processes that take place on various types of land cover. While valuable from a planning perspective, these mapping systems are not fine enough to capture ecosystem functions take place at the project site level (Crossman *et al.,* 2013). Thus, a site-specific nutrient cycling system (biogeochemical), specifically a plant-soil system, was chosen for this case study.

Biogeochemical models can provide important insights into the process and reactions of the natural environment through cycles of chemical elements (Gorham, 1991). These chemical elements (*i.e.* carbon, nitrogen, sulfur, and phosphorous) impact living organisms via the pathways through which they travel within the biological system over time. The dynamics of the elements are located above and below ground and encompass the synthesis, death, and decomposition of numerous organisms. Photosynthesis, respiration, decomposition, metabolism of nitrogen and sulfur, and weathering of soils are simulated in a biogeochemistry model in order to illuminate the nutrient cycles and their impact on living things. Most important to this work, biogeochemical models can be used to determine an ecosystem function within an ecosystem service (Schimel *et al.,* 1997).

For this case study, the CENTURY model was selected to simulate the biogeochemical flows of nutrients through plant litter, organic soil, and inorganic soil phases. The CENTURY model has been validated for a variety different land use systems including savannah, grassland, agricultural crops, and forest systems (Parton *et al.,* 1987). The model integrates climate, soil variables, and agricultural management practices within the system to simulate the effects of the nutrient cycling (Metherell *et* al., 2012).

A number of fundamental inputs are required for the CENTURY model. These are shown in Table 1 and include the latitude and longitude of the site, fraction of sand in the soil, fraction of silt in the soil, fraction of clay in the soil, bulk density of soil, number of soil layers to simulate, and weather parameters. Additionally, the land management schedule (if any) for the ecosystem is required and is shown in Table 2. Based on these site characteristics, the dynamics of the steady-state conditions of the site and measures for soil organic total carbon, aboveground carbon production, and belowground carbon production can be initially calibrated. Following this calibration, the ecosystem service on the site - nutrient cycling with the chemical elements of nitrogen, sulfur, phosphorus, and carbon flows – can be modeled over a simulated time period ranging from a few decades up to a few millennia.

An ecological spin-up was used to calibrate the CENTURY model to equilibrium, and then simulations for different nitrogen and phosphorus measurements were run. The crop condition chosen to model the case study site was grass G5 (grass, 75% warm). However, the crop nitrogen fixation and net primary production was slightly altered to reflect short grasslands (Cleveland *et al.,* 1999). The measured value of the symbiotic and non-symbiotic nitrogen fixation in short grassland was set to 2.70 kgN/ha-yr (Cleveland *et* al., 1999).

Table 1. Site parameter inputs for CENTURY (USDA, 2006)

Type of System	*Grassland*
Latitude	*32.97938*
Longitude	*-115.48559*
Percent Sand	*0.149*
Percent Silt	*0.428*
Percent Clay	*0.425*
Bulk density of soil (g/cm^3)	*1.45*
Rooting depth	*15.24 cm, up to 60 cm*
Average monthly precipitation	*6.7 cm*
Average monthly minimum temperature	*3.8 ℃ (Jan), 24 ℃ (July)*
Average monthly maximum temperature	*20.8 ℃ (Jan), 42 ℃ (July)*
Average nitrogen fixation	*0.27* gN/m^2

Table 2. Simulated land management schedule for case study site in Brawley, CA

Schedule Block	Years	Management	Repeating sequence
1	0 - 1900	Desert	1 year
2	1900 - 1970	Grassland with grazing with stochastic weather	1 year
3	1970 - 3000	Grassland with grazing, harvest twice a year, fertilized twice a year, irrigation with weather from data file	1 year

Using CENTURY, the site was simulated for nitrogen, phosphorus, and coupled nitrogen and phosphorus cycling. Results are shown in Figures 2 to Figure 5. The figures show the cycling levels of nitrogen, phosphorus, and coupled nitrogen and phosphorus at varying input levels for nitrogen and phosphorus. CENTURY simulates the cycling of these nutrients as soil organic matter turnover rates based on decomposition in active, slow, and passive “pools”, with the active pool turning over every 2 to 5 years while the passive pool turns over every 800 to 1200 years (Metherell *et al.*, 2012).

To quantify the ecosystem service being provided, nutrient cycling, the modeled land area is artificially loaded with nutrients to examine the effect on ecosystem performance. Figure 2 quantifies the change in nitrogen storage in active, slow, and passive pools on the Brawley site as nitrogen loading increases. Figure 3 quantifies nitrogen removal on the Brawley site as nitrogen loading increases. Figure 4 quantifies the change in coupled nitrogen and phosphorus flows on the Brawley site as nitrogen and phosphorus loading increases.

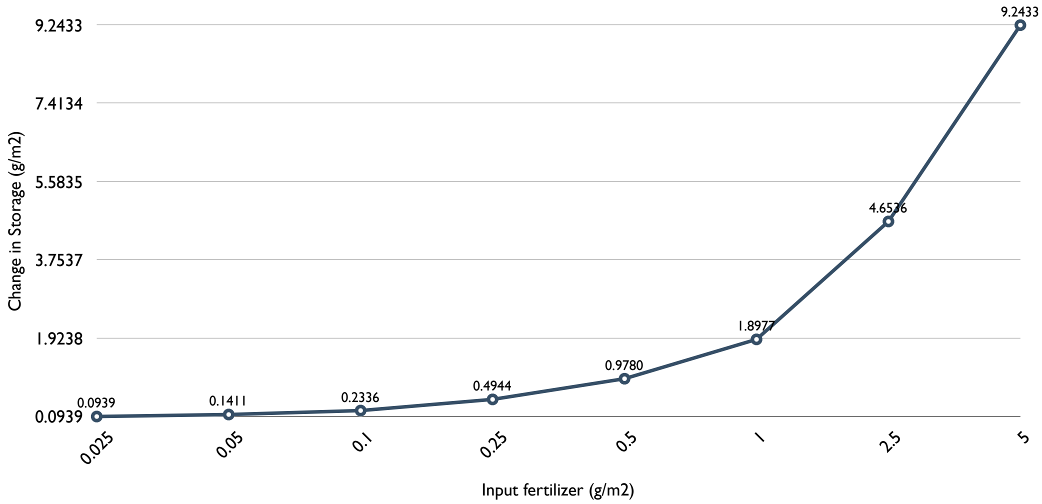

Figure 2. Change in nitrogen storage as a function of external nitrogen loading (1975)

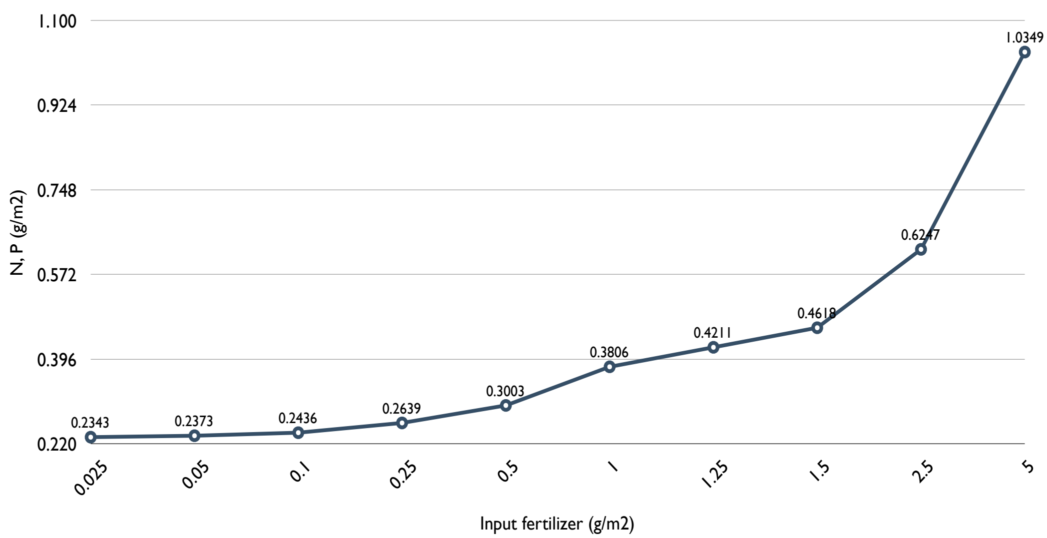

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Figure 3. Change in nitrogen removal as a function of external nitrogen loading (1975)

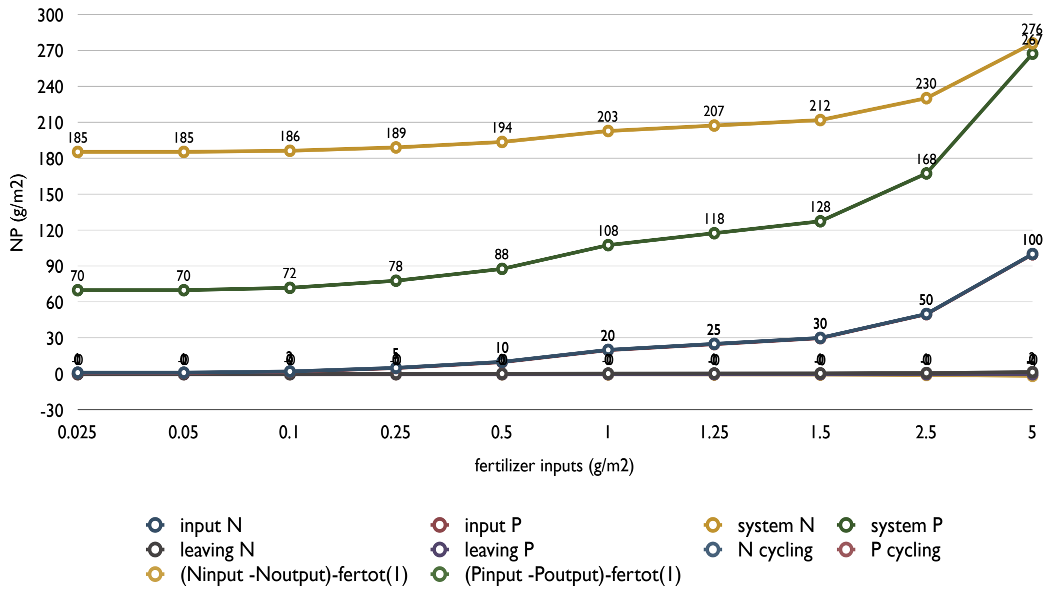

Figure 4. Change in nitrogen and phosphorus cycling as a function of external nitrogen and phosphorus loading (1975)

By simulating these different nutrient loadings we can examine the changes in nitrogen removal, phosphorus removal, nitrogen storage, phosphorus storage, nitrogen losses, phosphorus losses, and total the amount of nitrogen and phosphorus leaving the site. This change in the net amount of nitrogen and phosphorus cycling through the site is the ecosystem function taking place. Thus far, a number of conclusions can be drawn from these modeling results. Nitrogen modeling of the site (Figures 2 and 3) demonstrates that as nutrient loading is increased, the amount of the nitrogen leaving the site increases, but via a nonlinear relationship. Phosphorus modeling of the site demonstrates that as nutrient loading is increased, the amount of the phosphorus leaving the site is increased by a small amount. Finally, coupled nitrogen and phosphorus nutrient loading is considered and nitrogen removal, phosphors removal, nitrogen storage, phosphors storage, nitrogen losses, phosphorus losses, and total amount of nitrogen and phosphorus leaving the site were modeled (Figure 4). This is the most realistic nutrient loading scenario, since mono-nutrient loading is rare. Coupled nutrient modeling of the site demonstrates that as nutrient loading is increased for nitrogen and phosphorus levels, the amount of both nutrients leaving the site is decreased.

3.3 Ecosystem limit state evaluation

Unlike many capital assets that see little change in value as a function of use, natural ecosystems are susceptible to degradation over time due to overuse. Therefore, for the Brawley case site, a maximum nutrient limit state was set that does not degrade ecosystem performance over time. An ecosystem that is managed to maintain and support a number of ecosystem services is said to be in good balance and is a goal of ecosystem service valuation (Foley, 2005). Nitrogen, one of the nutrients, has a complex biogeochemistry cycle. Each stage of the nitrogen cycle goes through a transformation and forms inorganic and organic nitrogen that is essential for life. These processes of ecosystem functions are shown in Table 2

Table 2. Nitrogen transformations and cycling (Vymazal, 2007)

Process (Ecosystem function)	Transformation
Volatilization	Ammonia-N(aq)→ammonia-N(g)
Ammonification (mineralization)	Organic-N-ammonia-N
Nitrification	Ammonia-N→nitrite-N→nitrate-N
Nitrate-ammonification	Nitrate-N→ammonia-N
Denitrification	Nitrate-N→nitrite-N→gaseous N_2, N_2O
N_2 Fixation	Gaseous N_2→ammonia-N(organic-N)
Plant/microbial uptake Ammonia absorption Organic nitrogen burial	Ammonia-, nitrite-, nitrate-N→organic-N
Anaerobic ammonia oxidation	Ammonia-N→gaseous N_2

Constructed wetlands and grasslands are ideal for reducing pollutant discharge, such as high nutrient loading, without impacting the production practices of farmland (O'Geen *et* al., 2010). These ecosystems can serve as biofilters and can remove sediments, nutrients, pesticides, pathogens (Vymazal, 2007). Pollutant and nutrient removal is based on hydraulic retention time, pollutant loading rate, size, age, vegetation, climate, and hydraulic loading rate (O'Geen *et al.*, 2010). While these ecosystems can serve as removal mechanisms, keeping a balance among soil nutrients is important to living organisms and the survival of the ecosystem. The organisms tend to stay in proportion to elements of carbon, nitrogen, and phosphorus (Jackson *et al.*, 2008). Thus keeping a balance of nutrients in the ecosystem is essential to its continued operation. This balance can be determined from Figure 4. As seen, the storage levels of nitrogen and phosphorus remain relatively constant up to levels of loading of about 0.5 g/m^2. Above this level, storage levels begin to grow rapidly and upset the ecosystem balance. This is defined as the limit state of sustainable loading for the Brawley development site.

3.4 Functional substitutability

Once the ecosystem service has been modeled based on an ecosystem function it can be compared to the value of an engineered substitute. This engineered substitute, or functional substitute, is a wastewater treatment facility. In a wastewater treatment facility, an activated sludge process is used to convert nutrient-rich influent to cleaner effluent. Using a comprehensive survey conducted by the Environmental Protection Agency in 2008, the average lifecycle cost of nitrogen and phosphorus removed per unit mass by engineered wastewater treatment systems in the US was determined (EPA, 2008).

The average lifecycle cost of TP removed per unit mass was determined from a detailed survey of 8 wastewater treatment facilities, analyzing the expansion, upgrade and/or retrofit of their nutrient (TP, nitrogen, BOD) removal subsystems (EPA 2008). Unit lifecycle cost is defined as the sum of the annualized unit capital costs (20 years; 6% interest) and unit operation and maintenance (O&M) costs. The survey facilities had an average design capacity of 12.2

million m^3/yr. Major assumptions within the EPA cost study regarding cost allocation based on specific nutrients for shared equipment include: an even allocation of equipment costs if equipment could be used to remove two nutrients, and a cost allocation of 12% to phosphorus, 48% to nitrogen and 40% to biological oxygen demand if there was no clear method to breakout costs for equipment. Survey valuations are presented in US dollars adjusted for inflation (BLS 2012). The average lifecycle cost of phosphorus and nitrogen removed per unit mass is $6.14/kg and $12.56/kg, respectively.

3.5 Valuation, decision-making, and management

Based on the lifecycle unit cost of phosphorus and nitrogen removed, and the quantity of sequestered nitrogen and phosphorus at the Brawley site, the current annual value of these coupled ecosystem services is $93.50/ha. Based on a 6% interest rate and a 20 year time horizon, the net present value (NPV) of the current state of the nitrogen and phosphorus removal ecosystem service within the entire Brawley site is $391.00. The net present value (NPV) of the current state of the nitrogen and phosphorus removal ecosystem service within 0.5ha of proposed development at the Brawley site is $244.00.

For decision-making purposes, this destruction of the ecosystem asset value ($244 over the 20 year life) can be weighed against the potential opportunity for solar power generation. Unfortunately, the decision-making process in this circumstance is trivial. At current prices, the value of electricity provided to the grid is $0.0148/kWh. This results in a NPV of power production of $163,200 (20 year timeline 6% discount rate). Considering the initial construction cost of the plant, $24,000, and the initial decrease in ecosystem service asset value of $244, the total initial cost is approximately $24,250. This is balanced against a return of approximately $163,200 over the 20 year lifetime. This results in an annual rate of return of over 600%.

The explicit consideration of the stakeholder decision-making process in this paper expands upon previous studies using the Comello framework (Comello, 2013). Specifically, Comello (2013) only looked to provide a financial accounting value for the ecosystem service of phosphorus removal via tidal marsh. This valuation was done independent of a specific project development decision. In this paper, a specific project decision is being considered; whether or not the value of the ecosystem services being destroyed to install solar reflectors affects the decision to build the solar plant. As mentioned above, the NPV of solar production is far in excess of the NPV of nitrogen and phosphorus nutrient cycling making the decision somewhat trivial. However, the demonstration of this framework in a real project decision scenario is new for ecosystem service valuation.

4. DISCUSSION

The ecosystem services approach to modeling coupled nitrogen and phosphorus for land valuation is newly presented in this study. While the value of the ecosystems modeled in this case study are low, as more ecosystem services are identified and numerically modeled (*i.e.*, carbon cycling, evapotranspiration, *etc.*) the combined ecosystem service value is expected to increase. Thus, over time we expect to see greater interest in accounting for these values and considering them in the cost analysis of development decisions. Further, the conclusion of this case study is skewed by the high value of electricity being produced by the development. If this case were looking at the development of a parking lot, the decision outcome may change. These types of scenarios will be investigated in future work.

Also of interest is the dynamic nature of this ecosystem valuation. The dynamics are due to climate change, harvesting, irrigation techniques, annual rainfall, and soil conditions for the optimal growth and loss matrix for the Imperial County region. The total carbon for the soil organic matter rises to equilibrium when the dynamic growth and loss cycles level out due to harvesting of the crop and the cycling of nutrients on the land. Thus, these approaches can begin to quantify the effect of global climate change on the value of natural ecosystem assets in place – thereby changing the discussion of climate change impacts from externalities to internalized cost damage. This type of analysis is a direction of future work.

The coupled nature of the ecosystem service modeling is a component of this paper that is significantly expanded from the previous Comello framework (Comello *et al.*, 2012). As discussed above in Section 3.2, coupled nutrient modeling of the site demonstrates that as nutrient loading is increased for both nitrogen and phosphorus levels, the amount of both nutrients leaving the site is decreased (Figure 4). The notion that a synergistic interaction exists between nutrient cycles is not new. The interdependence of ecosystem services has been noted anecdotally by many others (*e.g.*, Daily and Ehrlich, 1995; Lovins *et al.*, 1999; Hawkin *et al.*, 2013). However, the quantified value of this synergy has not been previously studied. As shown in Figure 4, the marginal rates of removal of nitrogen and phosphorus change in unison up to the ecosystem limit state.

This expanded consideration of the Comello framework also serves as an important connection to broader project decision-making literature. As studied by others, the fair, open, and legitimate consideration of disparate measures of project success (*e.g.*, increased project NPV and decreased project environmental impact) is difficult and often requires the use of multiple criteria decision analysis (MCDA) frameworks (Abraham *et al.*, 2013; Yoon and Hwang, 1995). However, the use of MCDA frameworks requires value or utility theory (*e.g.*, Keeney and Raiffa, 1976; Saaty, 1980; Hwang and Yoon, 1981; Suhr, 1999) to compare options due to the disparate measures of the various attributes. By expressing ecosystem value as a part of overall project NPV, as determined using rigorous financial accounting procedures, natural ecosystem benefits can be considered on par with traditional economic benefits without introducing additional uncertainties that can be associated with utility theory (Karni and Schmeidler, 1991).

Finally, there remain a number of limitations to the model and framework as it is presented in this paper. Foremost, while numerous other inputs, pollutants, and wastes were included in the life cycle inventory, only the land disruption impacts were considered for this case study. The consideration of these other impacts would likely degrade and devalue additional ecosystem services not considered by the CENTURY model, making the development decision less favorable. However, given the large difference in value of ecosystem services and electricity discussed in Section 3.5 it is unlikely that this would change the project decision in this case study. Other limitations of the model include the lack of a rigorous allocation scheme for the value of single nutrient cycling via a wastewater treatment facility. Along these lines, Comello (Comello, 2013) proposed the use of a more rigorous thermoeconomics-based allocation scheme. But once again, due to the large difference in value discussed in Section 3.5, the decision to proceed with development appears robust.

5. CONCLUSION

The aim of this paper was two fold. The first aim was, for the first time, to consider more than one ecosystem service function at a time within a rigorous financial accounting framework. This was accomplished by modeling the interaction between interdependent ecosystem functions of nitrogen and phosphorus nutrient cycling. The second aim of this paper was to connect the ecosystem valuation framework to stakeholder decision-making. This was achieved via a case study of project-level ecosystem service valuation for a solar utility development site.

As such, this study examined the potential development of a small solar generation site in Southern California. It examined the decision-making tradeoffs between destruction of ecosystem services of nutrient cycling (nitrogen and phosphorus) and the production of electricity. This quantifying, measuring, and valuing of coupled nutrients for ecosystem services was simulated using the CENTURY model for soil organic matter. Ultimately, the value of these two ecosystem services did not reverse the plan to develop the solar generation site. However, demonstrating the numerical coupling and valuation of ecosystem services (nitrogen and phosphorus cycling) is a significant advancement in the use of the ecosystem service valuation framework for project decision-making support.

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