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Linking ecosystem service supply to stakeholder concerns on both land and sea: An example from Guánica Bay watershed, Puerto Rico

Amelia Smith[1], **Susan H. Yee**[*], **Marc Russell**, **Jill Awkerman**, **William S. Fisher**
U.S. Environmental Protection Agency, Office of Research and Development, Gulf Ecology Division, Gulf Breeze, FL 32561, USA

Abstract

Policies to protect coastal resources may lead to greater social, economic, and ecological returns when they consider potential co-benefits and trade-offs on land. In Guánica Bay watershed, Puerto Rico, a watershed management plan is being implemented to restore declining quality of coral reefs due to sediment and nutrient runoff. However, recent stakeholder workshops indicated uncertainty about benefits for the local community. A total of 19 metrics were identified to capture stakeholder concerns, including 15 terrestrial ecosystem services in the watershed and 4 metrics in the coastal zone. Ecosystem service production functions were applied to quantify and map ecosystem service supply in 1) the Guánica Bay watershed and 2) a highly engineered upper multi-watershed area connected to the lower watershed via a series of reservoirs and tunnels. These two watersheds were compared to other watersheds in Puerto Rico. Relative to other watersheds, the Upper Guánica watershed had high air pollutant removal rates, forest habitat area, biodiversity of charismatic and endangered species, but low farmland quality and low sediment retention. The Lower Guánica watershed had high rates of denitrification and high levels of marine-based recreational and fishing opportunities compared to other watersheds, but moderate to low air pollutant removal, soil carbon content, sediment and nutrient retention, and terrestrial biodiversity. Our results suggest that actions in the watershed to protect coral reefs may lead to improvements in other ecosystem services that stakeholders care about on land. Considering benefits from both coastal and terrestrial ecosystems in making coastal management decisions may ultimately lead to a greater return on investment and greater stakeholder acceptance, while still achieving conservation goals.

Keywords

Coastal communities; Coral reef; Decision-making; Ecosystem services; Land-use

1. Introduction

An integrated consideration of coastal ecosystem services (e.g., tourism, fishing, and shoreline protection) in coastal planning can not only meet conservation goals, but also

[*]Corresponding author. yee.susan@epa.gov (S.H. Yee).
[1]Current address: Department of Marine Sciences, University of New England, Biddeford, ME, 04005, USA.

lead to greater social and economic returns than assessments focused mainly on ecological endpoints (Arkema et al., 2015). However, decisions which positively affect coastal ecosystem services may have positive or negative consequences to the provisioning of other ecosystem services in the landscape (Raudsepp-Hearne et al., 2010). Policies to protect coastal resources may gain greater stakeholder support when they are responsive to the social and economic concerns of stakeholders in both the coastal zone and the watershed (Productivity Commission, 2003; Roebeling, 2006).

The multi-agency U.S. Coral Reef Task Force (CRTF) initiated a program in 2009 to address critical land-based sources of pollution impacting nearshore coral reefs outside Guánica Bay, Puerto Rico (Warne et al., 2005; Rodriguez, 2013; Bradley et al., 2016). Proposed actions to reduce runoff included changes to agricultural practices, riparian plantings, dredging of sediment-filled reservoirs, restoration of a lagoon, and development of wetlands (CWP, 2008). Workshop discussions with stakeholders, however, indicated the watershed management plan could have unintended consequences beyond protecting coral reefs (Carriger et al., 2013; Bradley et al., 2014, 2016). Controversy about the plan implementation was caused by stakeholder uncertainty about the consequences of proposed actions and a perceived lack of consideration of stakeholder concerns (Sotomayor-Ramírez and Pérez-Alegría, 2011).

Characterizing stakeholder values is a key first step to help decision-makers identify management alternatives that have a greater probability of acceptance by stakeholders (Keeney, 1992). The willingness of stakeholders to accept trade-offs will depend on both the initial starting point and the potential range of consequences (Keeney, 2002). Identifying and mapping a broad suite of ecosystem services relevant to a specific decision context can provide a more holistic assessment of the starting point and potential benefits of a coastal management plan (Egoh et al., 2012; Martínez-Harms and Balvanera, 2012).

Stakeholder concerns elicited during a Public Values Forum (Gregory and Gonzales, 2013) were used to identify and map ecosystem services endpoints relevant to the Guánica Bay water-shed management plan to restore and protect coral reefs (CWP, 2008; Carriger et al., 2013). Existing studies on ecosystem service supply for Puerto Rico have limited applicability because of a narrow focus on carbon and water ecosystem services (Gingold, 2007; Smith, 2007; Ostertag et al., 2008; Uriarte et al., 2011). To fully maximize usefulness of ecosystem services quantification for decision-making, it is necessary to identify stakeholder-relevant metrics (e.g., Laurans et al., 2013) and assess a broader suite of ecosystem services (e.g., Raudsepp-Hearne et al., 2010; Arkema et al., 2015).

Baseline measures for relevant ecosystem services were calculated by parameterizing and applying existing methods to map ecosystem service supply for the Guánica Bay watershed (e.g., Russell et al., 2013; Tallis et al., 2013). Ecosystem service supply was also mapped for all other watersheds and coastal areas in Puerto Rico in order to compare the relative supply of services in the Guánica Bay study area to the range of potential services provided across Puerto Rico. Results are considered within the context of potential management actions in the watershed and illustrate the importance of considering both coastal and terrestrial ecosystem services in coastal management decisions.

2. Methods

2.1. Study area

The upper mountainous area and lower Lajas Valley of the Guánica Bay watershed are considered distinct agricultural communities (Gregory and Gonzales, 2013; Bradley et al., 2016), with uncertain contributions of sediment and nutrient loading into the bay (Carriger et al., 2013; Bradley et al., 2016). To reflect these differences, the mapped study area was split to distinguish the lower Lajas Valley (Guánica Bay Watershed) and upper mountainous area (sub-watersheds of Lago Yahuecas, Lago Guayo, Lago Prieto, and Lago Lucchetti) (Fig. 1).

Ecosystem service supply in the Lower and Upper Guánica areas were calculated, mapped, and compared to 22 other watersheds in Puerto Rico (Fig. 1). Watershed delineations were determined by the 10-digit Hydrologic Unit Code (HUC10) for all watersheds. The Upper Guánica area comprised four smaller HUC12 sub-watersheds that overlapped with the Yauco and Añasco HUC10 watersheds (USGS National Hydrography Dataset, USGS.gov; USDA Natural Resources Conservation Services Watershed Boundary Dataset, USDA.gov). Coastal ecosystem service supply was paired with the nearest coastal watershed, where stakeholders are assumed most likely to benefit from coastal resources.

2.2. Public values forum

EPA convened a Public Values Forum in 2013 to engage a broad representation of Guánica Bay watershed community members and decision-makers in defining what is important for restoration of their watershed and the associated coastal areas (Gregory and Gonzales, 2013; Bradley et al., 2016). Five topic areas were generated through discussions (terrestrial ecology, aquatic ecology, economic, social and cultural, and governance and process), and participants self-organized to document objectives for each (Table 1; Gregory and Gonzales, 2013; Bradley et al., 2016).From the full list of objectives, those that were directly related to thesupply of ecosystem services were selected for this study (Table 2). A total of 19 ecosystem services metrics were identified as directly related to supply of ecosystem services. Information from the 2010 Coral Reef Decision Support workshop (Bradley et al., 2014) and planning documents (Carriger et al., 2013) were also used to help inform the choice of ecosystem services metrics.

2.3. Mapping ecosystem service supply

Ecological production functions were applied to translate measures of ecosystem condition from land use/land cover (LULC) and other environmental data layers (Appendix A; Table A1) to supply of ecosystem services (Wainger and Boyd, 2009; Egoh et al., 2012; Martínez-Harms and Balvanera, 2012). The ecological production functions, described in the following sections, were implemented and mapped using ArcMap (ESRI, 2010) or Invest 3.0.0 (Tallis et al., 2013). Most ecosystem services were mapped at the same resolution as LULC data (30×30 m^2; NLCD, 2008) and then averaged to calculate a mean value for each metric within each HUC10 watershed in Puerto Rico or the combined four HUC12 sub-watersheds forming the Upper Guánica study area (Fig. 1).

2.4. Air quality

Rates of air pollutant removal depend on the downward flux of particles intercepted by the tree canopy (Nowak et al., 2008; Russell et al., 2013) and can be calculated as:

$$Relative\ pollutant\ removal = \%canopy\ cover \times deposition\ \ velocity \times pollutant\ concentration \tag{1}$$

Because atmospheric pollutant concentration can vary widely across space and time, we standardized across watersheds by calculating the removal rate per unit concentration of particulate matter greater than 10 μ,m (PM_{10}), assuming a pollutant concentration of 1 g/m^3, and applying a typical deposition velocity of 1.25 cm/s (Lovett, 1994).

2.5. Water quality and quantity

Long-term average water yield was estimated for each HUC12 sub-watershed as the difference between total precipitation and the amount absorbed by the different land cover classes using a reservoir hydropower production model (InVEST 3.0.0; Tallis et al., 2013). Each land cover class was assumed to have different capacities for retaining water, depending on root depths and evapotranspiration coefficients (Appendix A, Table A2). The final water yield estimate represents a long-term average amount of water runoff after retention by vegetation and land.

The maximum rainwater storage capacity of the landscape during a major precipitation event (in^3/in^2) depends on soil moisture retention (S) and initial abstraction of water by vegetation (Ia), and can be estimated by the curve number method (USDA and NRCS, 1986; Lim et al., 2006):

$$Maximum\ retained\ volume = S + Ia = 1.05 \times \left(\frac{1000}{CN} - 10\right) \tag{2}$$

Curve numbers (CN) were calculated based on the mean distribution of hydrologic soil groups for each region (Appendix A, Table A4) in each land cover class at a resolution of 30 × 30 m^2 (Appendix A, Table A3). Retention was then converted from inches to mm^3/mm^2.

Denitrification rates were assigned to each land cover class, applying the mean of rates for natural sub-tropical ecosystems obtained from the literature (Appendix A, Table A3; Russell et al., 2013). To calculate rates of denitrification for developed land cover classes, a fixed rate of denitrification for urban lawns was assumed for all land not covered by impervious surface.

Nutrient retention was estimated by first calculating water yield and establishing the quantity of nitrogen or phosphorous retained by different land cover classes using a water purification model (InVEST 3.0.0; Tallis et al., 2013). Different land cover classes have different capacities for retaining nutrients, depending on the efficiency of vegetation in removing either nitrogen or phosphorous and the rates of nitrogen or phosphorous loading (Appendix A, Table A2). Sediment retention was estimated by applying the Universal Soil Loss Equation (USLE) in each HUC12 sub-watershed using a sediment retention

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model (InVEST 3.0.0; Tallis et al., 2013). The calculated capacity of a land parcel to retain sediment depends on cover and management factor, management practice factor, and sediment retention efficiency (Appendix A, Table A2).

2.6. Soil quality

Carbon content in soil and nitrogen fixation rates were assigned to each land cover class, applying the mean of rates for natural sub-tropical ecosystems obtained from the literature (Appendix A, Table A3; Russell et al., 2013). To calculate rates of nitrogen fixation for developed land cover classes, a fixed rate of nitrogen for urban lawns was assumed for all land not covered by impervious surface (NLCD, 2008). Similarly, soil carbon content for developed land cover classes was also calculated assuming an urban lawn soil content for pervious surfaces, in addition to an urban forest soil content for land covered by tree canopy (USGS, 2013). Additionally, the percent of area occupied by important, prime, or potentially prime farmland was calculated for each watershed (e.g., USDA and NRCS, 2008a,b,c,d, 2009a, 2012b), where designation is based on soil properties, flooding frequency, irrigation, water table drainage capacity, and wind erodibility (USDA and NRCS, 2009b).

2.7. Terrestrial ecology and economic opportunities

The percent of each watershed covered by forest habitat was quantified as a measure of its relative importance. The number of threatened and endangered species (USFWS, 2013) was mapped by summing the number of species with overlapping spatial distributions (Gould et al., 2008). Similarly, the potential for eco-tourism was quantified as the number of rare, endemic, and charismatic fauna with overlapping spatial distributions (Lepage, 2003; Gould et al., 2008; Miller and Lugo, 2009). The percent tree canopy cover (USGS, 2013) in developed areas was calculated in each HUC10 watershed as an estimate of the potential for temperature regulation through shade production.

2.8. Aquatic ecology and economic opportunities

Beach opportunities in each HUC10 watershed were quantified as the percent of coastline length designated as recreational beach (Google Earth, 2013; Travel and Sports, 2013). The total area of coral reef habitat and the total area of mangrove habitat associated with the nearest watershed was calculated from maps of benthic habitats (NOAA, 2008). The value of finfish ($\$/m^2$) and the relative value of fishing, snorkeling, and swimming opportunities were calculated as weighted averages of values assigned to individual benthic habitat groups (Mumby et al., 2008) depending on the relative coverages of benthic habitats associated with each watershed (Yee et al., 2014). Maps of benthic habitats for Puerto Rico (NOAA, 2008) were assigned to habitat groups (Mumby et al., 2008) based on benthic habitat descriptions (Kendall et al., 2002; Appendix A, Table A4).

2.9. Spatial patterns across metrics

Principal component analysis (PCA) was applied to evaluate similarities in the spatial distribution of the 19 ecosystem services metrics within watersheds across the landscape (Quinn and Keough, 2002). Analyses were run using the “rda” function of package “vegan” using the software R (www.r-project.org). To explain patterns of potential supply of ecosystem services in relation to gradients in land cover, correlations between environmental vectors and the PCA ordination were calculated using the “envfit” function in R. Percent of each land cover type and mean elevation in each watershed were examined as potential explanatory variables.

3. Results

Nineteen metrics of ecosystem service supply were mapped for the HUC10 watersheds in Puerto Rico (Fig. 2). The upper and lower portions of the Guánica study area were mapped separately and compared to the other watersheds in Puerto Rico (Fig. 3; Table 3).

3.1. Lower Guánica

The Lower Guánica region had the seventh highest overall supply of ecosystem services among all watersheds in Puerto Rico (Fig. 3). This region had one of Puerto Rico’s largest estimated areas of mangrove and coral reef habitat, which contribute to potential economic opportunities including marine-based recreation and fishing. Lower Guánica also had a relatively large portion of coastline designated beach (Table 3). Supply of non-aquatic ecosystem services within the Lower Guánica watershed was moderate compared to other watersheds, including greater than the highly urbanized areas of San Juan and Bayamón but well below the heavily forested watersheds of Arecibo and Añasco (Fig. 3). Lower Guánica ranked among the five lowest watersheds in terms of the ability of the environment to regulate air pollution, yield water, and provide forest habitat of economic and cultural importance. Although the percentage of potential farmland was high, only 14% of this was existing farmland. Nitrogen fixation, nitrogen retention, phosphorus retention, and sediment retention were among the lower estimates throughout Puerto Rico. The Lower Guánica Region did have higher rates of denitrification compared to other watersheds in Puerto Rico.

3.2. Upper Guánica

Excluding marine-based ecosystem services, the Upper Guánica study area had the third highest overall supply of ecosystem services across all the watersheds in Puerto Rico (Fig. 3). Air pollutant removal, water yield, and rainwater retention in the Upper Guánica area were among the highest estimates across all Puerto Rico watersheds (Table 3). Terrestrial ecosystem services of potential cultural and economic importance (e.g., area of forest habitat, biodiversity of charismatic and endangered species, and shading in urban areas) were also among the highest estimates observed across Puerto Rico. Upper Guánica also had the lowest portion of potential farmland, although rates of nitrogen retention, phosphorous retention, and nitrogen fixation were high. However, the ability of the environment to retain sediment was among the lowest across Puerto Rico. Low sediment retention could be attributed to the watershed’s average elevation (approximately 637m) and slope (approximately 19°), which were amongst the highest in Puerto Rico.

3.3. Spatial patterns across metrics

The first three principal components (PC) from PCA explained 67% of the variability among watersheds (Fig. 4a; Table 4). Area of forested habitat was one of the strongest drivers of differences in ecosystem service supply across watersheds, along with air pollutant removal, nitrogen fixation, rainwater retention, and numbers of threatened and charismatic species (strongest positive loading on PC1; Fig. 4a; Table 4). Soil carbon content and tree canopy for shading (PC2) and marine recreational and fishing opportunities (PC2, PC3) were also strong drivers distinguishing watersheds (Fig. 4a; Table 4). The Upper and Lower Guánica watersheds were almost opposite in their supply of ecosystem services. Upper Guánica had high supply of ecosystem services associated with higher forest cover (e.g., air pollutant removal, rainwater retention, nitrogen and phosphorous retention, charismatic species, and threatened species), similar to levels in other highly forested watersheds including Arecibo, Añasco Yaguez, and Yauco (Fig. 4b). Lower Guánica, in contrast, was more similar to low elevation coastal watersheds where farmland quality, denitrification, marine habitat, and marine-based opportunities tended to be high. Watersheds with high sediment retention and low water yield were positively associated with greater mangrove and coral reef area (Fig. 4a). Sediment retention in Puerto Rico watersheds was not highest in watersheds with high forest cover, but instead was strongly negatively correlated with elevation. This contrasted patterns for nitrogen and phosphorous retention, which were positively related to forest land cover. Low elevation barren lands, shrub lands, and woody wetlands had the greatest rates of sediment retention (Fig. 4b).

4. Discussion

4.1. Ecosystem service supply in the Guánica Bay watershed

The Upper Guánica study area had the third highest overall supply of terrestrial ecosystem services across Puerto Rico. The Lower Guánica study area, in contrast, was generally low for most terrestrial ecosystem services, but the highest across Puerto Rico in coastal ecosystem services. The differences between the lower and upper areas was strongly related to forest habitat cover and elevation. Moreover, terrestrial ecosystem service supply across Puerto Rico was most strongly related to forest habitat cover. Less than 35% of the Lower Guánica watershed was covered with forest, compared to more than 70% in Upper Guánica. The Lower Guánica watershed instead exhibited the greatest area of coral reef habitat across Puerto Rico. However, the relative value of fishing and recreational opportunities derived from marine habitats was only slightly above the median for Puerto Rico, perhaps because of a similarly high proportion of less desirable habitats (e.g., macroalgae) in the same area.

4.2. Considering impacts of management actions on ecosystem services

The distribution of ecosystem services can help to inform actions proposed by the watershed management throughout the Guánica watershed. For example, nutrient retention was related to forest cover, suggesting that management actions proposed to reduce sediment runoff by improving vegetative cover (e.g., switching from sun-grown to shade-grown coffee) could have secondary benefits toward preserving the quality of farmland. Moreover, forest cover was positively associated with a suite of ecosystem services, indicating that actions such as reforestation could benefit a number of stakeholder goals (e.g., improving air quality, charismatic and threatened species, and rainwater retention) in addition to potential benefits for coral reefs. Levels of these ecosystem services were already relatively high in the upper part of the watershed, indicating actions targeted to the lower watershed may lead to a broader suite of potential gains.

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Sediment retention in the Guánica study area as a whole was lower than most other Puerto Rico watersheds, particularly the upper portion. Throughout Puerto Rico, sediment retention was associated with availability of coral and mangrove habitat. Previous studies have shown that coral degradation is linked to sediment loading due to smothering and reducing light for photosynthesis (Rogers, 1990; Philipp and Fabricius, 2003). Throughout Puerto Rico, rates of sediment retention were strongly affected by the steep elevation regardless of land cover. This suggests that management efforts targeted at changing land cover in the Upper Guánica area (e.g., hydroseeding and agricultural practices) may be less effective at protecting coral reefs, simply because of the challenges in over-coming steep slopes. Furthermore, sediment loads from the upper portion of the Guánica watershed may be trapped by the lower portion of the Guánica watershed because of its higher sediment retention rate, thus potentially reducing the sediment loading into adjacent coral reefs and mangroves.

4.3. Implications for coastal resource management

This study serves to raise awareness of potential trade-offs in watershed management and the need to consider the overall suite of benefits, or potential negative consequences, of a decision. Strategies to protect coastal resources often do not account for potential effects on terrestrial resources (Productivity Commission, 2003; Roebeling, 2006). Our study illustrates that a consideration of terrestrial ecosystem services could influence management options to protect coastal resources. For example, actions were proposed in the Guánica watershed management plan to achieve two key objectives: 1) improving sediment retention and 2) protecting coral reefs (CWP, 2008). Our analysis, like others (Bousquin et al., 2014), indicates actions in the upper watershed to improve sediment retention may be less impactful in protecting coral habitat than actions in the lower watershed. However, the potential smaller relative effects of actions in the upper watershed on sediment retention may still be worth pursuing when they are augmented by maintaining or improving other ecosystem services that stakeholders care about (e.g., air quality regulation, agricultural quality, economic and cultural opportunities in terrestrial habitats).

4.4. Quantifying stakeholder objectives

In order for stakeholders or decision-makers to weigh potential trade-offs, objectives must be measured and quantified. Our analysis focused on ecosystem service supply; that is, the production of services without knowledge or economic value of their use. Other studies, in contrast, have quantified the economic value of ecosystem services (Gingold, 2007; Smith, 2007). Economics-based assessments, however, can be controversial if important variables that are difficult to monetize are left out. In many cases, non-economic metrics may be more appropriate to represent stakeholder concerns (Gregory et al., 2012). Though not entirely comprehensive in terms of economic (e.g., dollar value) or health outcomes (e.g., rates of asthma) that may sometimes be more meaningful to stakeholders, our study illustrates a baseline quantification of a suite of ecosystem service supply linked explicitly to stakeholder concerns within the context of a watershed management plan.

5. Conclusions

Decision-making is an iterative process (Gregory et al., 2012), and the analysis presented here is a first step toward characterizing the potential trade-offs and benefits of coastal management decisions throughout a watershed. Identifying potential consequences of decisions is extremely difficult, particularly when scientific knowledge and data are incomplete (Knol et al., 2010). This study addressed one area of uncertainty raised by stakeholders by identifying stakeholder-relevant ecosystem services and quantifying their baseline values, but did not go as far as to predict outcomes of specific alternative decision scenarios. Often, however, the goal of assessments is not to develop extensive quantitative predictive models, but to provide enough information to expose key trade-offs, identify shared benefits, and facilitate communication between stakeholders and decision-makers (Gregory et al., 2012). Our study illustrates that actions in the watershed to protect coral reefs may lead to improvements in other ecosystem services that stakeholders care about on land. Consideration of both coastal and terrestrial benefits in coastal management may ultimately lead to decisions that gain a greater return on investment and greater stakeholder acceptance, while still achieving conservation goals.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Appendix A.

Table A1

Ecological condition data layers used as input to ecological production functions.

Ecosystem Service Metric	Data Layer (Source)
Atmospheric pollution removal	Percent canopy cover (USGS, 2013)
Water availability	LULC (NLCD, 2008) Digital elevation (USGS, 2006) Mean annual precipitation (NOAA, 2008) Soil depth, available water content, average annual potential evapotranspiration (2008a-b, 2009a,b, 2012a-b)
Volume of rainwater retained	LULC (NLCD, 2008) Hydrologic soil groups (2008a-b, 2009a,b, 2012a-b)
Denitrification rate/Nitrogen fixation	LULC, percent impervious surface (NLCD, 2008)
Nitrogen retention rate/Phosphorous retention rate	LULC (NLCD, 2008)
Sediment retention rate	LULC (NLCD, 2008)
	Digital elevation (USGS, 2006)
	Rainfall erosivity index, soil erodibility (NOAA, 2008)

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Ecosystem Service Metric	Data Layer (Source)
Soil carbon content	LULC, percent impervious surface (NLCD, 2008) Percent canopy cover (USGS, 2013)
Farmland quality	Important, prime, or potentially prime farmland (e.g., 2008a-b, 2009a, 2012a-b)
Forest habitat cover	LULC (NLCD, 2008)
Richness of endangered or threatened species/ Richness of rare, endemic, or charismatic species	Species distribution (Gould et al., 2008)
Temperature regulation through shading	LULC (NLCD, 2008) Percent canopy cover (USGS, 2013)
Beach recreational opportunities	Coastline designated beach (Google Earth 2013; Travel and Sports, 2013)
Coral reef habitat area/Mangrove habitat area/ Value of finfish stock/Relative value of fishing, snorkeling, and swimming opportunities	Benthic habitat coverage (NOAA, 2008)

Table A2

Biophysical parameters for Puerto Rico to implement reservoir hydropower model, water purification model, and sediment retention model (InVEST 3.0.0; Tallis et al., 2013).

LULC	Maximum Vegetative Root Depths (mm)[1]	Plant Evapo-transpiration Coefficient[2]	Rates of Nitrogen Loading (kg/ha/yr)[3]	Rates of Phosphorus Loading (kg/ha/yr)[3]	Vegetation Efficiency of Filtering Nitrogen (%)[4]	Vegetation Efficiency of Filtering Phosphorus (%)[4]	Cover and Management Factor[5]	Management Practice Factor[6]	Sediment Retention Efficiency[4]
Open Water	0	1000	0.00	0.00	0	0	0.000	0.000	0.000
Developed, Open Space	0	550	15.56	1.04	0	0	0.000	0.000	0.000
Developed, Low Intensity	0	428	15.56	3.04	0	0	0.000	0.000	0.000
Developed, Medium Intensity	0	278	15.56	5.04	0	0	0.000	0.000	0.000
Developed, High Intensity	0	153	15.56	7.04	0	0	0.000	0.000	0.000
Barren Land	0	500	3.40	0.10	0	0	0.900	0.000	0.000
Evergreen Forest	7300	1000	5.70	0.01	100	100	0.006	0.000	1.000
Shrub/ Scrub	5100	398	6.79	1.30	100	100	0.030	0.000	0.500
Herbaceous	2600	650	6.79	1.30	100	100	0.110	0.000	0.500
Hay/ Pasture	2600	850	16.27	0.10	100	100	0.030	1.000	1.000
Cultivated Crops	2100	650	16.27	3.10	50	50	0.500	0.500	0.500
Woody Wetlands	5200	1100	5.70	0.01	100	100	0.030	0.000	1.000

LULC	Maximum Vegetative Root Depths (mm)[1]	Plant Evapo-transpiration Coefficient[2]	Rates of Nitrogen Loading (kg/ha/yr)[3]	Rates of Phosphorus Loading (kg/ha/yr)[3]	Vegetation Efficiency of Filtering Nitrogen (%)[4]	Vegetation Efficiency of Filtering Phosphorus (%)[4]	Cover and Management Factor[5]	Management Practice Factor[6]	Sediment Retention Efficiency[4]
Emergent Herbaceous Wetlands	2600	1100	6.79	1.30	100	100	0.110	0.000	1.000

1. Canadell et al., 1996.

2. Allen et al., 1998.

3. Reckhow et al., 1980.

4. Tallis et al., 2013.

5. Wischmeier and Smith, 1978.

6. Stone and Hilborn, 2012.

Table A3

Rates of denitrification, nitrogen fixation, and carbon sequestration estimated as the mean of typical values from literature surveys. Rates for developed land use classes represent averages across Puerto Rico calculated for each watershed from urban lawn or urban tree rates. Curve numbers were based on the mean distribution of soil types in each land cover class.

LULC	Denitrification[1] (g N/m^2/yr)	Nitrogen fixation[2] (g N/m^2/yr)	Carbon in soil[3] (g C/m^2)	Curve number[4]
Open Water	5.17	0.00	143	0.00
Developed, Open Space	1.26	0.01	12177.9	79.11
Developed, Low Intensity	0.92	0.01	8876.4	78.21
Developed, Medium Intensity	0.50	3.55×10^{-3}	4826.5	88.59
Developed, High Intensity	0.15	1.05×10^{-3}	1454.5	93.26
Barren Land	0.00	0.00	3380	89.88
Evergreen Forest	0.25	33.94	5861.7	60.05
Shrub/Scrub	0.00	0.00	5000	71.38
Herbaceous	0.00	0.01	5139.1	84.44
Hay/Pasture	0.89	0.97	4452.3	78.78
Cultivated Crops	38.33	0.68	4452.3	80.19
Woody Wetlands	17.53	0.00	11100	74.57
Emergent Herbaceous Wetlands	37.23	0.00	7798.9	88.17
Urban lawn	1.4	0.01	13460	
Urban tree	–	–	180[5]	

1. Reddy et al., 1989; Tsai, 1989; Walbridge and Lockaby, 1994; Chestnut et al., 1999; Mosier et al., 2004; Seitzinger et al., 2006; Raciti et al., 2011.

2. Carpenter et al., 1978; Espinoza, 1997; Freiberg, 1998; Ley and D'Antonio, 1998; Brenner et al., 1999; Grossman, 2003; Herridge et al., 2008.

3. Houghton et al., 1991; McGuire et al., 1995; Ravindranath et al., 1997; Houghton, 1999; Masera et al., 2001; Ni, 2001; Pouyat et al., 2002; Chabra et al., 2003; Grau et al., 2004; Silver et al., 2004; Li et al., 2005, 2006; Bernal and Mitsch, 2008; Marín-Spiotta et al., 2008, 2009; Ostertag et al., 2008.

4. USDA and NRCS, 2008a-b, 2009a,b, 2012a-b.

[5.] 300 g C/m2 for urban trees (Pouyat et al., 2002), 60% of which is attributed to soil (Nowak and Greenfield, 2009).

Table A4

Values of finfish stock and relative values of gmarine-based recreation for each benthic habitat class, using value scores from Mumby et al., 2008 and benthic habitat descriptions from Kendall et al., 2002.

Benthic Habitat	Value of finfish stock ($200US/m^2)	Fishing, snorkeling swimming opportunities
Sand, mud	0.26	3
Linear reef, spur and groove reef, reef colonized pavement with channels[1]	3.61	2.5
Patch reef, scattered coral rock	0.38	3
Reef colonized pavement or bedrock[2]	0.54	1
Hardbottom, reef rubble or uncolonized[3]	0.34	1
Mangrove	0.05	0
Seagrass, continuous or patchy >30%[4]	0.23	0
Seagrass, patchy <30%[5]	1.94	1
Macroalgae	1.88	1

[1.] *Acropora palmata* or *Montastraea/Orbicella* reef.

[2.] Dense gorgonians.

[3.] Sparse gorgonians.

[4.] Dense or medium density seagrass.

[5.] Sparse seagrass.

Appendix B.: Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2016.11.036.

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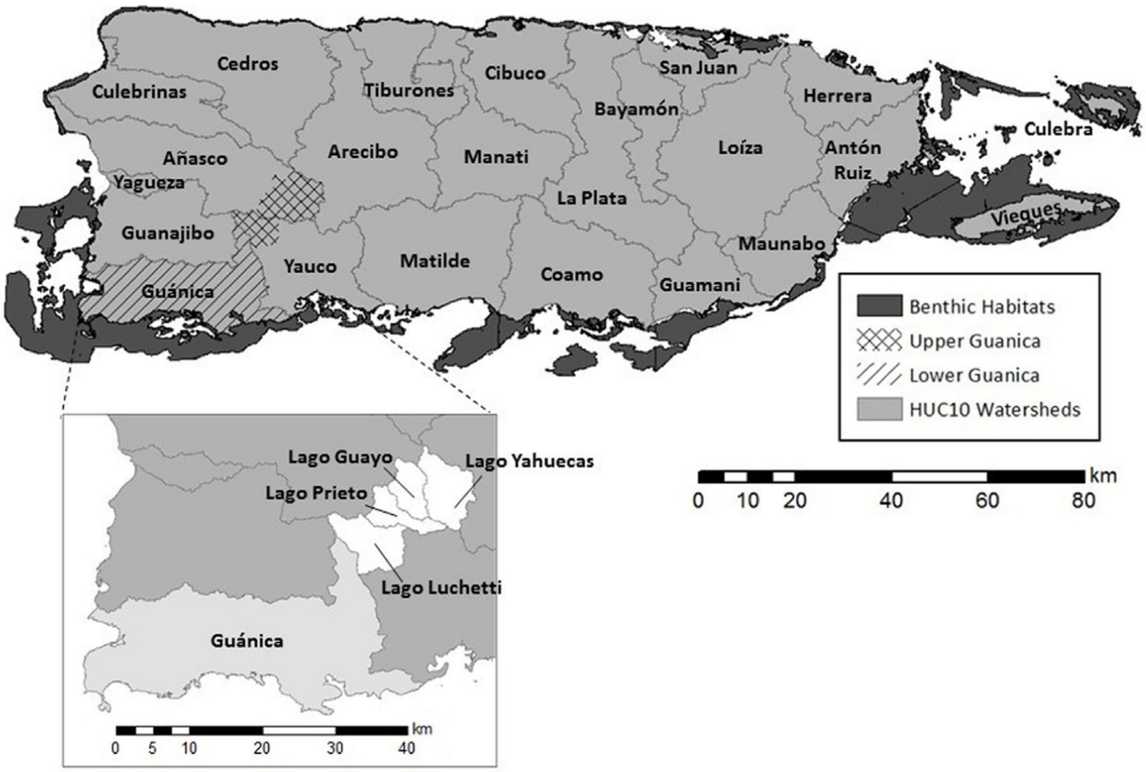

Fig. 1.

The watersheds of Puerto Rico, and the upper and lower portions of the Guánica Bay study area. Inset shows the four sub-watersheds comprising the Upper Guánica Bay study area.

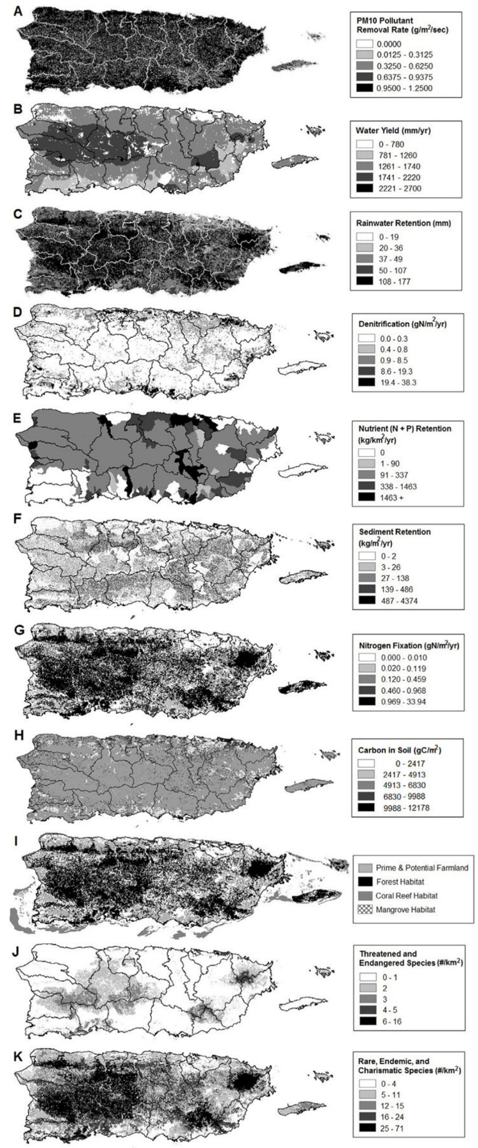

Fig. 2.

Maps of ecosystem service supply (Table 3) across Puerto Rican watersheds. Nitrogen retention and phosphorous retention were highly correlated and combined to a single map (E). For convenience, ecosystem services defined by discrete habitat metrics (forest, farmland, coral, and mangroves) were also combined to a single map (I). Tree canopy for shading is based on% canopy cover, as is the map of pollutant removal (A), and is therefore not shown separately. Finfish stock and marine recreation map directly onto benthic habitats (I) and are not shown separately.

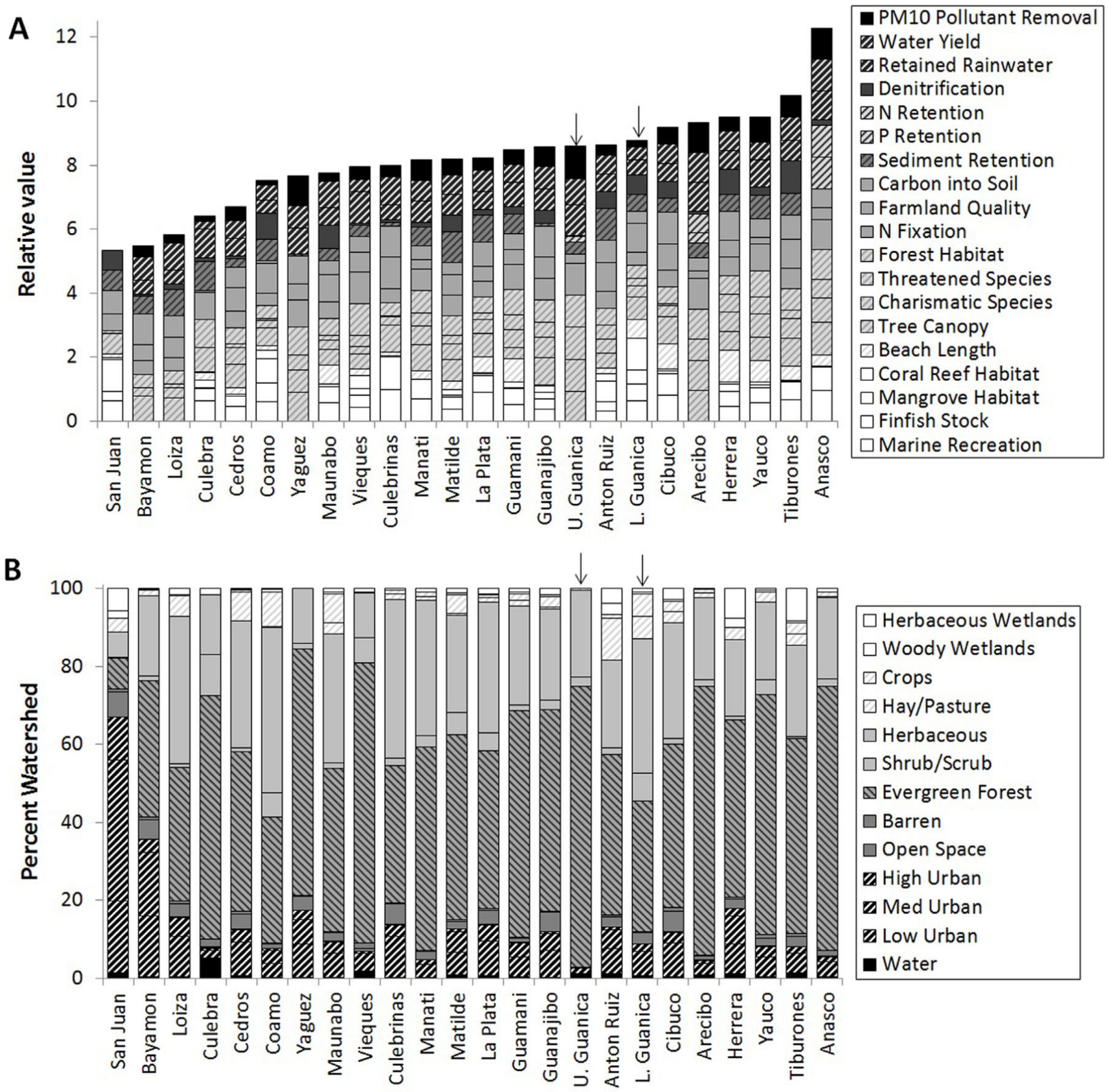

Fig. 3.

Relative values of (A) ecosystem service supply and (B) land cover in each Puerto Rico watershed. Ecosystem services metrics were linearly scaled from 0 to 1 based on the minimum and maximum of each across all of Puerto Rico. Arrows indicate Upper and Lower Guánica study areas.

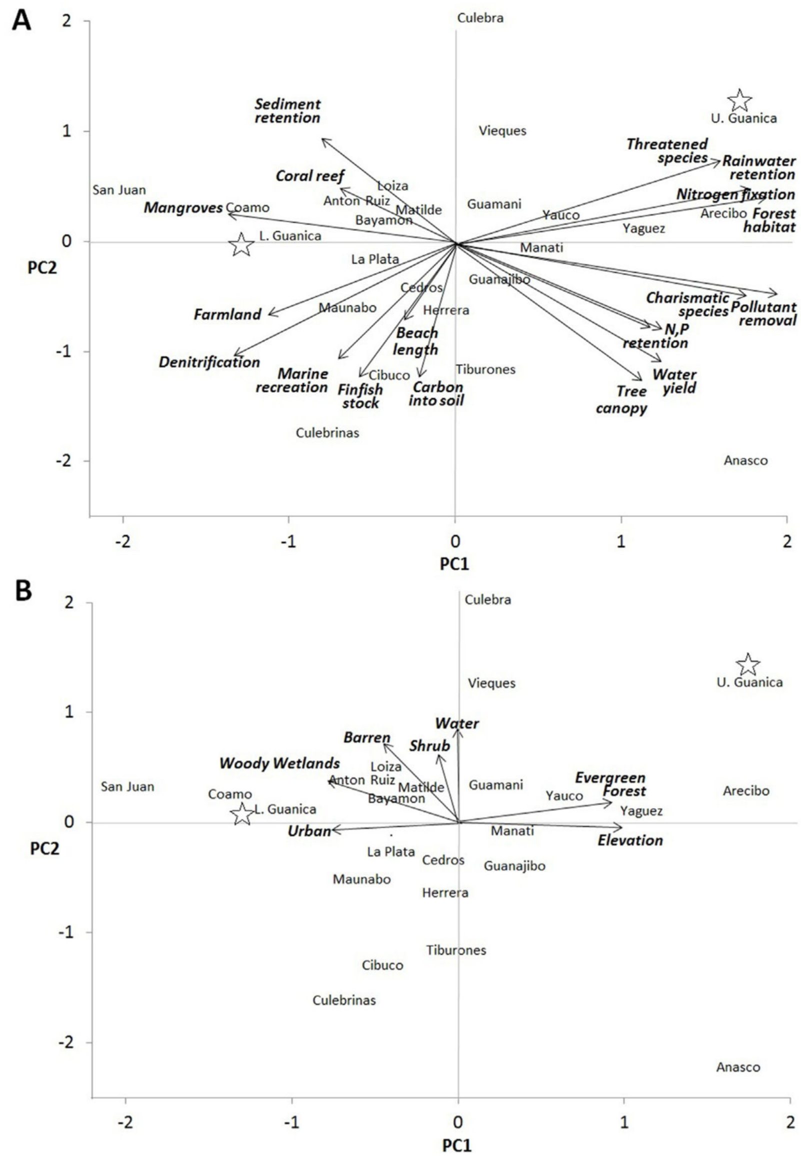

Fig. 4.

Ordination plot showing the distribution of watersheds along the first two factors identified in PCA. The direction of the arrows indicates (A) the ecosystem services metrics and (B) the environmental variables that were correlated with a given PC axis.

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Table 1

Stakeholder objectives identified in the 2013 Public Values Forum (from Gregory and Gonzales, 2013).

Category	Stakeholder Objectives
Terrestrial Ecology	T1. Meet future water demands (Agriculture and development)
	T2. Restore and conserve habitat for important species
	T3. Reduce contamination from agriculture effluent
	T4. Reduce storm water runoff
	T5. Reduce soil loss and maintain productivity of land
	T6. Understand relative contribution/origins of sediment throughout watershed
	T7. Preserve forest habitats
	T8. Protect endangered and threatened wildlife species
Aquatic Ecology	A1. Restore lagoon natural processes to absorb nutrients and filter sediments
	A2. Restore shallow water coral reefs (reduce nutrient loads; enhance fish biomass)
	A3. Reduce human contamination
	A4. Protect endangered and threatened marine species
	A5. Protect mangrove habitats
	A6. Protect marine habitat for migratory birds
Economy	E1. Demonstrate economic value of ecosystem services
	E2. Estimate net benefit of best management practices
	E3. Protect infrastructure of reservoirs
	E4. Promote community economic benefits and improve employment opportunities
	E5. Increase sustainable economic development (eco-tourism, beach opportunities)
	E6. Increase agricultural activities and productivity; preserve agricultural farmland
	E7. Restore commercial and sport fisheries
	E8. Increase renewable energy production (hydroelectric, alternative energies)
Social	S1. Promote quality of life for people in Guánica Bay watershed
	S2. Maintain small scale farming opportunities and way of life
	S3. Reinforce cultural heritage and traditional livelihoods (artisanal fishing)
	S4. Improve well-being and human health (water quality, air quality (asthma), food security, health and safety of agriculture workers)
	S5. Improve recreational opportunities
	S6. Promote education, specifically environmental attitudes and behaviors

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Category	Stakeholder Objectives
	S7. Maintain sufficient potable water for citizens (quantity and quality)
	S8. Expand spiritual and aesthetic opportunities (commune with nature)
Process	P1. Improve monitoring and feedback of current actions
	P2. Reduce uncertainty about outcomes of management actions
	P3. Meet legal & political requirements
	P4. Better integration and communication across agencies, and with citizens
	P5. Demonstrate respect for all citizens
	P6. Enhance opportunities for meaningful public participation
	P7. Improve fairness in resource management and decision process
	P8. Establish clear criteria for land use planning

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Table 2

Ecosystem goods or service metrics corresponding to stakeholder objectives.

Ecosystem Service Metric	Stakeholder Objectives
Atmospheric pollution removal (PM_{10} deposition velocity)	
Water availability (mean annual water yield)	T1. Meet future water demands (Agriculture and Development); E8. Increase hydro-electric power generation; S7. Maintain sufficient potable water for citizens;
Volume of rainwater retained	T4. Reduce stormwater runoff
Denitrification rate	S4. Improve human health (water quality)
Nitrogen retention rate/Phosphorous retention rate	T3. Reduce contamination from agricultural effluent; T5. Maintain productivity of land; S4. Improve human health (water quality); A1. Restore natural processes to absorb nutrients; A2. Reduce nutrient loading to coral reef habitats;
Sediment retention rate	T3. Reduce contamination from agricultural effluent; T5. Reduce soil loss; T6. Understand origins of sediment; A1. Restore natural processes to filter sediments; A3. Reduce contamination; S4. Improve human health (water quality)
Nitrogen fixation rate/Soil carbon content/Farmland quality	E6. Preserve agricultural farmland; S2. Maintain small scale farming opportunities & way of life
Forest habitat cover	T7. Preserve forest habitat; E5. Increase eco-tourism; S5. Improve recreational opportunities; S8. Expand spiritual and aesthetic opportunities (commune with nature)
Richness of endangered or threatened species	T8. Protect endangered & threatened wildlife
Richness of rare, endemic, or charismatic species	T2. Restore and conserve habitat for important species; E5. Increase eco-tourism; S8. Expand spiritual and aesthetic opportunities (commune with nature)
Temperature regulation through shading (tree canopy cover)	E8. Increase renewable energy production
Beach recreational opportunities (% of coastline length as beach)	E5. Increase eco-tourism and beach opportunities; S5. Improve recreational opportunities; S8. Expand spiritual and aesthetic opportunities (commune with nature)
Coral reef habitat area	A2. Restore shallow water coral reefs (enhance fish biomass); A4. Protect threatened and endangered marine species; A6. Habitat for marine birds; E5. Increase eco-tourism;
Mangrove habitat area	A5. Protect mangrove habitats; A6. Habitat for marine birds
Value of finfish stock	E7. Restore commercial and sport fisheries; A2. Enhance fish biomass; S3. Reinforce traditional fishing livelihoods
Relative value of fishing, snorkeling, and swimming opportunities	E5. Increase eco-tourism; S5. Improve recreational opportunities; S3. Reinforce traditional fishing livelihoods; S8. Expand spiritual and aesthetic opportunities (commune with nature)

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Table 3

Mean ecosystem service supply within the upper and lower portions of the Guánica study area, as compared to the minimum, median, and maximum across all HUC10 watersheds in Puerto Rico. Bold values indicate values in Guánica that were higher than the median.

Ecosystem Service Metric	Min	Median	Max	Upper Guánica	Lower Guánica
PM_{10} pollutant removal ($g/m^2/s$)	16.5	34.94	59.86	**59.86**	25.55
Water yield (m^3/m^2/year)	0.65	1.38	1.81	**1.59**	1.12
Retained rainwater (mm^3/mm^2/rain event)	57.15	112.72	148.08	**144.95**	100.29
Denitrification (g/m^2/yr)	0.32	1.18	4.61	0.40	**2.88**
Nitrogen retention (kg/km^2/yr)	0	109.61	4.0×10^{20}	**7.00×10^{18}**	3.11
Phosphorus retention (kg/km^2/yr)	0	6.12	7.7×10^{20}	**1.30×10^{13}**	0.02
Sediment retention (kg/m^2/yr)	23.60	83.97	133.08	66.73	83.15
Nitrogen fixation (g/m^2/yr)	2.72	15.91	24.66	**24.66**	11.47
Soil carbon content (g/m^2)	5472.8	5882.6	6144.2	5659.2	5714.7
Farmland quality (% potential farmland/watershed)	5.89	23.96	37.59	5.89	**34.96**
Forest habitat (% per watershed)	7.86	46.53	72.05	**72.05**	33.37
Threatened & endangered species (#/km^2)	0.42	0.97	2.23	**2.23**	0.87
Rare, endemic, & charismatic species (#/km^2)	5.68	14.16	23.65	**23.65**	11.97
Tree canopy in urban areas (% per watershed)	11.39	31.09	38.30	**36.49**	29.92
Coastline designated beach (% per watershed)	0	5.69	25.92	0.00	**15.09**
Coral reef habitat (km^2)	0	10.63	226.55	0.00	**226.55**
Mangrove habitat (km^2)	0	0.45	18.76	0.00	**8.16**
Value of finfish stock ($200US/$m^2$)	0	1.21	2.87	0.00	**1.49**
Fishing, snorkeling opportunities (relative value)	0	1.25	2.33	0.00	**1.50**

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Table 4

Loadings and percent contribution of ecosystem service metrics onto the first three PC axes in PCA. Loadings greater than |0.4| are in bold.

	Loadings			Percent contribution			
Ecosystem Service Metric	PC1	PC2	PC3	PC1	PC2	PC3	
PM_{10} pollutant removal	**0.97**	−0.23	−0.09		8.49	3.15	1.49
Water yield	**0.63**	**−0.54**	−0.29		5.52	7.39	4.80
Retained rainwater	**0.9**	0.26	0.34		7.88	3.56	5.63
Denitrification	**−0.57**	−0.32	0.24		4.99	4.38	3.97
Nitrogen retention	**0.6**	−0.38	0.25		5.25	5.20	4.14
Phosphorus retention	**0.61**	−0.39	0.28		5.34	5.34	4.64
Sediment retention	**−0.41**	**0.51**	0.11		3.59	6.98	1.82
Nitrogen fixation	**0.94**	0.22	0.29		8.23	3.01	4.80
Soil carbon content	−0.11	**−0.61**	**−0.56**		0.96	8.34	9.27
Farmland quality	**−0.67**	**−0.51**	−0.04		5.87	6.98	0.66
Forest habitat	**0.94**	0.22	0.29		8.23	3.01	4.80
Threatened & endangered species	**0.79**	0.39	0.29		6.92	5.34	4.80
Rare, endemic, & charismatic species	**0.88**	−0.23	−0.11		7.71	3.15	1.82
Tree canopy in urban areas	**0.56**	**−0.61**	−0.28		4.90	8.34	4.64
Coastline designated beach	−0.16	−0.35	**0.58**		1.40	4.79	9.60
Coral reef habitat	−0.35	0.27	0.51		3.06	3.69	8.44
Mangrove habitat	−0.68	0.14	0.09		5.95	1.92	1.49
Value of finfish stock	−0.3	−0.6	0.69		2.63	8.21	11.42
Fishing, snorkeling opportunities	−0.35	−0.53	0.71		3.06	7.25	11.75
Proportion of variance explained	0.38	0.16	0.13				