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Supplementary Information for

Assessing Ecological Infrastructure Investments

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Authors listed alphabetically. W.A. & E.P.F. designed and led research. A.E. collected social survey data and led its analysis. M.R.R. led econometric analysis. P.L-S. & M.R.R. led economic modeling with A.E. A.E, L.C. & M.R.R conducted land-use analysis. J.S.H., F.L.O., J.A.R & R.F.S. collected and analyzed hydrological data with A.E. and M.R.R. R.F.S. computed lake level depth relation. E.P.F led writing of the main text. A.E., P.L-S. & M.R.R. led writing of the SI. W.A., E.P.F., J.S.H., F.L.O. & R.F.S. conceived project. All authors contributed to writing.

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Supporting Information Text

Historic lake levels and draft restrictions

The Autoridad del Canal de Panama (Panama Canal Authority, or acronym ACP) guarantees different draft levels at different lake depths. The ACP manages the Panama Canal's original centennial locks so that declines in Gatun Lake's level trigger restrictions for Panamax ships (Figure S1). For example, if Lake Gatun exceeds 24.0 m, then ships are guaranteed 12.0 m of draft (depth to keel below water line), which is the draft required by a fully loaded Panamax ship. The much larger and heavier NeoPanamax ships that transit the new lock expansion require additional draft availability, up to 15.2 m for a fully loaded ship. A Gatun Lake level at or above 25.9 m guarantees a draft availability of 15.2 m. At levels below 25.9 m, NeoPanamax draft restrictions are triggered (Figure S1).

Marginal benefits of water

The effect of a marginal increase in lake levels is estimated using data on the Panama Canal's monthly transits and tons of cargo between 2008 and 2016, and toll revenues from 2008 to 2014.[*] Data on Gatun Lake levels are available for 1972 to 2015, and rainfall data are available for 2005 to 2015.[†] We estimate the relationship between toll revenue and lake level as

Equation S1. $Revenue_t = \beta_0 + \beta_1 Lake\ Level_t + \beta_2 (Lake\ Level_t)^2 + \boldsymbol{X\gamma} + \boldsymbol{\mu_T} + \epsilon_t,$

where t is the month of observation, $\boldsymbol{X}$ is a matrix of other observable variables that condition for variation, $\beta_0, \beta_1, \beta_2$ and $\boldsymbol{\gamma}$, a vertical vector, are parameters to be recovered, μ_T is a year fixed effect, and ϵ_t is an error term. Lake level is defined in the equation as the difference from the mean historical dry-season lake levels (26.09 m) and ranges from -1.2 m (May 2014) to 0.55 m (Dec 2011). Lake level squared is included to detect if the marginal value of water declines with increases in lake depth. An alternative hypothesis is that the marginal value is constant up until the flooding constraint creates a kink in the benefits function, resulting in $\beta_2 = 0$.

The coefficients, β_1 and β_2, provide an estimate for the effects of a marginal increase in lake levels on toll revenues, but lake levels and revenues are simultaneously determined because water is lost with transits, which lowers the lake. Thus, we expect an ordinary least squares estimate of the parameters in Equation S1 to be biased and inconsistent. To identify consistent and unbiased estimates of β_1 and β_2, we use a two-stage least squares, instrumental variable approach (1). In the first stage, we use five-month

[*] http://logistics.gatech.pa/en/assets/panama-canal/statistics
[†] http://biogeodb.stri.si.edu/physical_monitoring/downloads/ACP_Rainfall_hourly.zip

cumulative rainfall prior to month t as an instrumental variable for lake level and lake level squared in month t. In estimating the marginal effect with the quadratic lake level term, we follow Wooldridge (1) and use the square of the instrumental variable. The first stage equations are

Equation S2. $Lake\ Level_t = \alpha_{10} + \alpha_{11} Rainfall_t + \alpha_{12}(Rainfall_t)^2 + \boldsymbol{X\kappa} + \boldsymbol{\mu_T} + \omega_{1t}$

Equation S3. $(Lake\ Level_t\ )^2\ = \alpha_{20} + \alpha_{21} Rainfall_t + \alpha_{22}(Rainfall_t)^2 + \boldsymbol{X\kappa} + \ \boldsymbol{\mu_T} + \omega_{2t},$

where $\alpha_{10}\ to\ \alpha_{22}$ and $\boldsymbol{\kappa}$ are parameters to be recovered and ω_{1t} and ω_{2t} are idiosyncratic error terms. Five-month cumulative rainfall is excluded from Equation SI 1 because it does not affect shipping demand or supply and only affects toll revenues via lake levels. We reject the null hypothesis of weak instruments in the linear (F-statistic =113.9, p-value ≈ 0.000) and quadratic cases (F-statistic = 57.8, p-value ≈ 0.000 for the linear term and F-statistic = 57.7, p-value ≈ 0.000 for the quadratic term).

For the instrumented value of squared lake levels, we also use the predicted value of the first stage of the linear equation (Eq S2) as the second instrumental variable following Wooldridge (1). This equation provides an alternative to (Eq S3) and is

Equation S4. $Lake\ Level_t^2 = \alpha_{10} + \alpha_{21} Rainfall_t + \alpha_{22}(\widehat{lake\ level_t})^2 + \boldsymbol{X\kappa} + \boldsymbol{\mu_T} + \omega_{1t},$

where $\widehat{lake\ level_t}$ is the predicted lake level from Equation S2.

Forecasted lake levels from Eq SI 2, and Eq SI 3 (or SI 4) in the squared case, are used in Eq SI 1 to purge the endogeneity of lake levels. Estimates of the coefficients of lake level and lake level squared in the second stage (columns 3-5) along with ordinary least squares estimates (columns 1-2) are provided in Table S1. We also consider a quantile regression (2) of the effect of lake level on toll revenues at the 25th and 75th percentiles of toll revenues in a 2SLS procedure. These two regressions estimate the effect of lake level at the lower and higher end levels of toll revenues and help explain nonlinearity in the relationship between lake levels and toll revenues. The results for the 25th percentile are shown in column (6), and the results for the 75th percentile are shown in column (7).

Our preferred specification, column (3) in Table S1, estimates that a 1-centimeter increase in Lake Gatun's levels above the average dry-season level results in a constant \$164,700 increase in revenue per month per cm, with a standard error of \$35,400 (p-value < 0.01). Columns (4) and (5) show that the squared lake level term is not estimated with sufficient precision to distinguish it from zero. Moreover, the quadratic term has no discernable effect on the linear term. The estimates from the quantile regressions are suggestive of a concave relationship between lake level and toll revenue, but the effects are not distinguishable from each other and suggest a linear model. The reason that we find no evidence of nonlinear effects is likely that Gatun Lake rarely reached spill levels in the data (5 months in 6 years of data). Alternatively, revenue could increase proportionally with lake level until the spill level of Gatun Lake is reached, at which point increase in lake level has no (or negative) marginal effect on revenue, i.e., the benefits function is kinked. Regardless, nonlinearities are likely to be small in the dry season. This justifies the use of a constant marginal value of water.

Ecological production functions – agroforestry conversion

Enhanced sponge effect (ESE)

Non-parametric measurement of the enhanced sponge effect (ESE) is a critical part of the ecological production function. We use watershed runoff data from two adjacent catchments (3) – a 142.3 ha forested catchment and a 181.7 ha catchment of swidden agriculture and pasture. Swidden agriculture, also known as shifting cultivation, is the practice of rotating land between cultivation and regeneration. Aside from land cover and use, these catchments are similar in terms of soil texture, geology, slope distribution, and topography metrics.

Automatic water-level measurements collected on five-minute intervals using non-vented electronic water-level sensors with data stored on digital programmable loggers supported by approximately bi-weekly manual water-level observations using a fixed staff gauge at each weir enabled flow rate computation. Manual observations allowed detection and post-processing of automatically recorded water levels to adjust for weir blockages and sensor drift.

Non-vented pressure sensors measure the combined effects of changes in water level and barometric pressure. We adjusted measurements to compensate for the effects of barometric pressure using a time-series editor from the Watershed Modeling System developed by Aquaveo, LLC.[‡] Water levels can change because of changes in the flow of water and because of partial blockage of the weir by floating debris. Blockage of weirs by debris is a frequent occurrence in tropical catchments. The availability of manually logged water-level metadata allowed manual editing of the water depth measurements using a time-series editor to correct for sensor drift and partial blockages.

The weirs used in this study were constructed in 1979. The streambeds behind these weirs have filled with sediment up to the level of the weir because the streams carry sand-sized sediment particles. Therefore, flows were computed using the flow versus water level relationships developed by Ogden *et al.* (4), who studied the effects of sedimentation on the relationship between flow and water level as a function of weir sedimentation. This allowed calculation of the rate of discharge of water from each catchment on five-minute intervals.

[‡] https://www.aquaveo.com/about-us

The constructed weirs in each watershed featured a two-stage design. The first stage consisted of a large, short-crested, concrete triangular weir for measuring high flows. Water passing over this large weir poured into a secondary basin, which featured a steel sharp-edged triangular weir that allowed accurate low flow measurements below 0.03 m^3 s^{-1}. These accurate low-flow measurements are important in the dry season, for checking the quality of the high flow measurements, and for detecting weir blockages and sensor drift.

Rain gauge data, from three clusters of three tipping-bucket rain gauges, located in or on the periphery of the study catchments, allowed evaluation of event flows during occasional periods when the rank order of flow between forest and mosaic land uses differed from expectations. The use of rain gauge data allowed detection of occasional rainfall events with highly non-uniform rainfall where one of the two adjacent watersheds received substantially more rainfall than the other watershed. A rain gauge operated by the ACP, located within the boundary of the swidden mosaic catchment, ensured the general agreement of the measured rainfall by the rain gauge network.

Runoff rates (mm h^{-1}), rather than absolute flow, allow comparison of hydrological response for areas of different sizes. Dividing flow values (m^3 s^{-1}) by catchment area provides runoff rates.

Runoff rates from the forest and mosaic catchment allowed creation of flow runoff curves. These runoff curves are constructed by sorting *N* runoff values in descending order, and plotting them versus their rank which, for the i^{th} measurement, is given by *'i'* divided by ($N + 1$). Plots were generated for water years, because water years are largely uncorrelated with each other. A water year starts in May (see Table S2 for exact dates) and is defined as an approximately one-year period from the beginning of one wet season to the beginning of the next. The percentage difference of runoff between the forest and mosaic catchments was calculated as

Equation S5. $Diff_{Forest-Mosaic} = \frac{Runoff_{Forest} - Runoff_{Mosaic}}{Runoff_{Mosaic}} \times 100\%$

The percent difference curve was evaluated over the entire year and for the dry season only. The average of the effective annual sponge effect (Table S2) is negative because forests use more water than pasture on a water-year basis. Calculating an appropriate dry-season ESE is not as simple as segregating the data into wet and dry season because occasional rainfall events during the dry season increase runoff and confound the analysis. To control for the impacts of these high runoff events, we focus on low flow time periods, which almost exclusively occur in the dry season. We derived runoff duration curves for the forest and mosaic catchments for each water year by calculating the arithmetic average of the percentage difference for positive runoff differences for runoff quantiles where the sign of the percentage difference (Equation S5) switches from negative to positive. These runoff values represent the dry season, and their average value is 11.7% (Table S2). This is the value we use for the dry-season ESE.

The runoff duration curves used in this analysis resulted from over 600,000 water level measurements for both weirs. Using similar data Ogden *et al.* (4) report that uncertainties in flow measurements are <5%. The sheer quantity of these data minimizes the effect of random errors when performing analysis with runoff duration curves. Data from the 2014 water year are not included in the data analysis because this anomalous year had greater runoffs from the forest compared to mosaic catchments during high flows for unknown reasons. We consider this water year an outlier. If this water year were included in the analysis, the average dry-season ESE would increase to 13.5%.

Enhanced Sponge Effect and Gatun Lake levels

Gatun Lake levels are driven in part by the size of the ESE and in part by management. We consider two water management strategies, extractive use and *in situ* use. Both are constrained so that lake volumes never exceed storage capacity. The extractive strategy uses the increased volumes resulting from the ESE to increase toll revenues by increasing transits and tonnage during the dry season. Water is spilled into the ocean via the lock system as the water arrives. The *in situ* strategy assumes transits remain constant and increases toll revenues by enabling increased tonnages per transit.

We use 4 years, 2012 to 2015, of river discharge data (Table S3) and 40 years, 1972 to 2015 (excluding 1999, 2001 and 2012, when some or all data are not available), of Gatun Lake level data to forecast the implications of an ESE on monthly river discharge and lake levels. We show the expected increase in average monthly lake levels for *in situ* (Figure 4) and extractive water management (Figure S2). Even with the inclusion of all convertible lands, NeoPanamax draft restrictions (horizontal line at 25.9 m) cannot be avoided in an average year.

Increases in dry-season river discharge volumes are converted into lake level rise using a water depth and lake volume relation for Gatun Lake derived from a 10-m resolution IFSARE-based digital terrain elevation model (DTEM) (5) collected on April 30, 1998. At that time, the water level of Gatun Lake was 24.0 m, which was near the historic low. The area of the lake surface was determined from a DTEM at half-meter intervals between 24.0 and 27.0 m, inclusive. The area at 23.0 m was set to zero and a cubic spline under tension was fit through these areas, starting at 23.0 m, and then integrated to give the depth-volume relation (Figure S3).

Erosion and sedimentation reductions

Equilibrium sediment yields (Mg ha^{-1} yr^{-1}) for the six major river basins of the Panama Canal Watershed (PCW) are compared to average annual measured sediment yields (Mg ha^{-1} yr^{-1}), including landslide erosion, for the same six river basins (6) in Table S4. Equilibrium sediment yield curves are derived using relationships between solute chemistry and runoff and account for surficial and deep erosion because landslides are the primary process controlling solute and solid load composition in tropical mountainous terrain (7). Average annual measured yields are based on 16 years (1981 – 1996) of daily water discharge and suspended sediment concentration data collected for the Pequeni, Boquerón and Chagres Rivers, which make up the Alajuela sub-watershed, and on ten years (1987 – 1996) of daily data collected for the Gatun sub-watershed and the Cirí Grande-Trinidad sub-watershed (7). No data were available for the Caño Quebrado sub-watershed so Cirí Grande-Trinidad measures are used as proxies for the Caño Quebrado sub-watershed. Equilibrium yields are based on equilibrium erosion rate models for upland landscapes on igneous or metamorphic bedrock, which is the bedrock that underlies most of the PCW (7). These erosion rates closely approximate the sediment yields of stable tropical forests – like those of the PCW (8) – and provide a baseline for comparison with measured yields. River basin sizes and forest cover percentages are from Stallard and Kinner (6).

The difference between measured and equilibrium sediment yields are used to estimate the impact of land-use change on physical erosion rates. Watersheds with agricultural or grazing lands, especially those with bare slopes, paths, roads and building sites, show empirical sediment yields that exceed those under a steady-state (7). Total increases in sediment yields, after the removal of natural vegetation, are strongly driven by landslides in Panama, especially within the more mountainous regions of the Cirí Grande-Trinidad and Alajuela sub-watersheds (6). We do not use the Universal Soil Loss Equation (USLE), a surficial agricultural erosion model, because it does not capture landslides and the USLE has not been calibrated to the PCW (7). Long-term measurements of sediment yields at a river-basin scale also offered improved scalability of our estimates relative to the small spatial scales generally employed by USLE (7).

The difference in sediment yield, in Mg ha^{-1} yr^{-1}, between a hectare of non-forested land, *NFSY*, and a hectare of forested land, *FSY* by river basin, i, is calculated as:

Equation S6. $(NFSY - FSY)_i = \frac{(Measured\ Sediment\ Yield_i - Equilibrium\ Sediment\ Yield_i)(Forest\ Area_i + NonForest\ Area_i)}{(NonForest\ Area_i)}$

We assume that forested lands produce sediments at equilibrium erosion rates and are representative of agroforestry lands. Differences between measured and equilibrium sediment rates are assumed to result from greater sediment yields on non-forested lands. Implicit in our calculation is the assumption that all non-forested lands contribute equally to higher sediment rates. This may overestimate convertible lands' contributions to sediment yield because roadways and semi-developed lands, which are not convertible, are important contributors to sediment yields (9).

Benefits of avoided dredging

The economic benefit of sedimentation reductions is reduced dredging costs to the ACP. We use area-weighted averages to scale-up river basin sediment yield data to a sub-watershed level for inclusion in the economic analysis (Table S5). We use sediment yield rates from the neighboring Cirí Grande-Trinidad sub-watershed to estimate sediment yield differences for Caño Quebrado. Sediment yield is converted to dredge volume using a conversion of 1.2Mg m^{-3} (7).

Avoided dredging costs are estimated using a dredging cost of \$8.90 m^{-3} of sediment based on the cost (\$100.4M) of deepening the Gatun Lake channel between 2002 and 2008 via the removal of 12.4M m^3 of sediment (10). Table S5 presents the annual avoided dredging costs for the conversion of one hectare of land to an agroforestry system. Dredging costs for the Alajuela sub-watershed are calculated assuming that the ACP will not begin to dredge Alajuela Lake, which has not been dredged since its creation in 1935, and that Madden Dam has a sediment trapping efficiency of 90% (11). Subsequently, only 10% of the reduction in sediments in the Alajuela sub-watershed would be captured as a benefit of agroforestry adoption. The avoided dredging costs are reduced to \$59 for this sub-watershed.

Physical and social extent of the market

The physical extent of the market was determined from geographic data. The social extent of the market was determined using an in-person stated preference survey conducted with 711 landowners in the PCW between February and September 2016. A sub-set of convertible land, convertible Chagres National Park land, was considered separately due to the larger hydrologic-value of public lands located within the Alajuela sub-watershed. To find the extent of the market for the entire PCW, we found the extent of the market for each of four sub-watersheds and summed them (Table S6).

Sub-watersheds of the Panama Canal Watershed

We use the seven primary rivers in the PCW – Chagres, Boquerón, Pequeni, and Gatun in the east, and Cirí Grande, Trinidad and Caño Quebrado in the west – to divide the PCW into four primary drainage catchments, or sub-watersheds (Figure 1, main text). The Alajuela sub-watershed includes the Chagres, Boquerón and Pequeni Rivers that drain into Alajuela Lake. The Alajuela sub-watershed encompasses approximately 92,000 ha of public protected land inside Chagres National Park and a small portion, 1,200 ha, of the southeastern border of Portobelo National Park. The Gatun sub-watershed includes Gatun River located to the east of the Panama Canal. Located within this sub-watershed are the highly developed and populated Panama-Colon corridor, Soberania National Park, and small areas of Camino de Cruces, Portobelo and Chagres National Parks. The Cirí Grande-Trinidad sub-watershed includes these two western most rivers and Altos de Campana National Park, which is the southeastern most tip of the region. Caño Quebrado sub-watershed includes the Caño Quebrado, Hules and Tinajones Rivers in the west-central region of the watershed.

Physical extent of the market: convertible and private convertible lands

Within the watershed, 54.7% of lands are currently forested with an additional 2.5% in timber plantations and 0.3% in agroforestry. A further 3.5% is urban and about 0.8% is mining lands or bare soil. These land types are not convertible. Only 116,520 ha (38.3%) of the watershed is considered convertible land. This includes pasture land (75,833 ha), crop land (3,221 ha), young regenerating forests that form part of the shifting cultivation cycle (30,702 ha), and lands covered by the invasive canal grass *Saccharum spontaneum* (6,763 ha).[§] There are 9,669 ha of convertible land within Chagres National Park in the Alajuela sub-watershed. Convertible lands in Chagres National Park are located primarily along the Boquerón and Pequeni rivers and the shores of Alajuela Lake. 4,578 ha of convertible land are located in the protected areas in the other three sub-watersheds. The remaining 102,273 ha of convertible land are located outside protected areas and distributed across the PCW. Not all lands outside protected areas are privately managed. Land tenure in Panama is not always clear and many landowners are absent or land is owned by educational or religious organizations or by government entities and corporations. We use a sample land title coverage created by the ACP and the United Nations Development Programme (UNDP)** for the Cirí Grande-Trinidad sub-watershed to account for land ownership across the watershed. The available land ownership data suggest that 88% of convertible lands outside of protected areas are privately owned. Adjusting convertible lands located outside of protected areas by 88%, implies that 89,830 ha of the watershed is private convertible land (Table S6).

Social extent of the market - enrollable convertible lands

We use information on the breakdown of landowners inside and outside of the ecological infrastructure supply market – the amount of land they own and the amount of land that they would supply for ecological infrastructure – to determine the social extent of the market. We surveyed an average of six landowners in 111 randomly selected communities across 28 counties of the PCW between February and September 2016. Research ethics approvals were received by the Institutional Review Boards of the Smithsonian Institute (Protocol # HS14024), Yale University (Protocol # 1403013671), and the Research Ethics Board of the University of Alberta (Study ID Pro00057029 and Pro00061378). We also received approval from the Panamanian Instituto Nacional de Cultura (National Institute of Culture,

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[§] Digital data provided by the Unidad del Sistema de Informacion Geografica de la Autoridad del Canal de Panama. The document has not been verified by the Autoridad del Canal de Panama and is not an official document of that entity.

** http://www.pa.undp.org/content/panama/es/home/operations/projects/environment_and_energy/apoyo-a-catastro-y-titulacion-en-la-cuenca-hidrografica-del-cana.html or acronym INAC in Spanish). The number of communities sampled per county was weighted by the percentage of the agricultural land held within the county of the PCW. In total, we contacted 806 landowners, and 711 (88%) participated in the survey. Surveyed landowners manage approximately 9% (26,618 out of 303,755 ha) of the total land in the PCW, but 19% of the convertible land base (22,227 ha out of 116,520 ha) and 21% of the pasture lands (16,269 ha out of 75,833 ha). The survey sampled subsistence producers, small landowners, commercial crop producers, and livestock ranchers with large operations.

Respondents were surveyed about their willingness to participate in incentive programs for the conversion of traditional crop and pasture land to an agroforestry system. The contracts offered to landowners were specified to include detail that would be required in a PES program and were based in part on pilot programs carried out in the region. Each contract included details on the program length (10 years for silvopastoral and coffee with payments or subsidized loans offered for years 1 through 5, 20 years for timber with payments of subsidized loans offered over the entire 20-year period) as well as details on the farming methods and approaches. Penalties for non-compliance were included in the description of each program as were the details, including timing, of technical assistance. The three levels of insurance offered include coverage for events such as weather or insect related failures. Specific forms of contracts were randomized across the sample to assess the impact of program characteristics. A wide range of payment (or subsidized loan) amounts were offered to landowners designed to cover cases where programs could be beneficial to landowners after establishment with little subsidy to cases where very high payments were required. Payment amounts offered were based on historical pilot programs in the area, opportunity cost analysis and focus group discussions with landowners and technical experts. Follow up information collected included questions on reasons for enrolling or not enrolling in programs as well as expectations about future prices and costs associated with the programs proposed. A follow-up question collected information on how many hectares of each convertible land type they would enroll. To improve the reliability of responses and identify strategic responses, we used an auction "framing" script and follow-up questions (12).

We asked landowners whether they would accept or reject a contract offer for a program and why. 484 landowners surveyed accepted at least one of the incentive programs presented to them. These respondents were considered to be market participants. Another 70 landowners rejected all the programs offered to them, but they were considered market participants because they stated that they disliked particular program attributes. The 157 landowners considered outside the market rejected all agroforestry programs, and provided generic responses in follow-up questions (13). Some examples were provided in the main text.

We calculate the amount of convertible land that was potentially enrollable by sub-watershed as the product of private convertible land and the percentage of sampled convertible land owned by market participants (Table S7). Summing across sub-watersheds yields 71,750 ha (80%) of potentially enrollable convertible land (Table S6). Actual enrollable convertible land, the measure of the social extent of the market, is calculated by multiplying potential enrollable convertible land by the percentage that market participants stated would be enrolled with a contract for ecological infrastructure (Table S7). There are 16,061 ha of enrollable convertible lands that could be supplied to the ecological infrastructure market (Table S6).

Ecological infrastructure costs

The costs of a land conversion program can be divided into direct costs and opportunity costs, and technical assistance costs. Program administration costs are not included in our cost estimates. Information on the cost of land conversion was collected through the stated preference survey, which provides a behaviorally grounded estimate of opportunity costs. We calculate annual per hectare willingness to accept (WTA) for participation in an agroforestry program to estimate the cost of land conversion. Total program costs are the sum of the WTA values and the cost of providing the technical assistance presented to landowners as part of the agroforestry program.

The stated preference survey presented landowners three randomly ordered and assigned agroforestry programs (coffee, silvopastoral, and timber) with the following attributes: payment method (direct payment or subsidized loan), technical assistance level (low or high), and program insurance (protection from having to repay part or all of the financial incentive in the case of non-compliance or project failure). Choice decisions were collected using a stochastic payment card (14) that presented eight payment options. A landowner's land conversion WTA is assumed to lie within the switch point interval, which is explained in the main text. Landowners used the payment cards to indicate the probability of their participation at each contract offer level: 100%, 75%, 50%, 25% and 0%. The selection of 100% or 75% was coded as program acceptance. Selection of 50%, 25% or 0% were coded as program rejection. We estimate WTA using the information collected on the first payment card offered to the participant that included a randomly assigned combination of medium or high insurance and high technical assistance.

We calculate an average landowner discount rate using the variation in payment streams, program lengths, and program method across the different programs offered to respondents. We assume individuals use a single parameter exponential discounting process to convert future payments to present value. A discount rate of 5.6% was estimated by random effects logit model. We use the estimated discount rate to calculate present values for the payment and subsidized loan. Then, we annuitize the value to obtain annual per hectare costs for all incentive payment levels across direct payment and loan mechanisms. WTA values were calculated across the three agroforestry programs presented within our survey, but we only use costs from the silvopastoral program, which was the least-cost and most popular program. We assume that all three agroforestry programs provide the same ESE. We also assume a 100% success rate for land conversion. The survey offered landowners insurance against failure, which let us control for risk-aversion preventing program uptake. We ignore insurance costs in our analysis. These assumptions likely underestimate the cost of contracting for ecological infrastructure. Increasing the program costs would lead to smaller programs than we estimate in the main text.

The technical assistance costs are estimated on a per landowner (farm) basis. Technical assistance cost estimates use the experience of Yale's Environmental Leadership Training Initiative (ELTI, http://elti.yale.edu/). ELTI runs landowner workshops and training seminars on silvopastoral systems in the Azuero region of Panama as well as training programs for technicians in the public and private sector within the PCW. On the advice of ELTI staff, we assumed that each landowner receives five two-day workshops over the life of the agroforestry program, a management plan designed for the landowner's farm, monthly field visits in years 1 and 2 and biannual visits thereafter, and an annual compliance evaluation. Calculations assume \$80 (USD) per day for field transportation expenses (\$1,100 per month truck rental fee and \$500 per month for fuel expense; 20 workdays per month), and \$75 per technician per day field expense (\$1,500 per month; 20 workdays per month) and \$500 per student per day total workshop expense. Management plans are expected to take 1 day per farm with field visits and compliance evaluations are expected to take 0.5 days per farm.

For each sub-watershed, the switch point interval coupled with landowner-provided information on program enrollment can be used to create a WTA curve for land enrollment. The inclusion of technical assistance costs results in a marginal cost curve, or supply curve, for land enrollment in a silvopastoral program (Figure 2 and 5, main text). We use a bootstrapping process to estimate sample variation from the stated preference survey. First, we sample with replacement landowners from each sub-watershed 200 times. Then, for each sample, we draw 100 times from within the switch point interval, using draws from a uniform distribution. We then add technical assistance costs to yield total land conversion cost. For each sample, random draw, and sub-watershed, we order costs from lowest to highest. For each sub-watershed, we compute the mean and 95% confidence interval of costs and mean hectares enrolled.

Evaluating ecological infrastructure

We calculate the total expected revenue increases associated with ecological infrastructure for the social and physical extent of the market for ESE percentage of 0%, 11.7%, and 31.1% and for *in situ* and extractive water use management strategies. We assume that ship transiting costs are largely fixed costs and that additional revenues from increased tonnage capacity are net benefits to the ACP. Benefits are calculated by multiplying the constant marginal toll revenue benefit (\$164,700 cm^{-1} $month^{-1}$) by the average increase in monthly lake levels associated with an ESE and then adding the dredging benefit (Table 1 and S8). Extractive use, which does not allow water to accumulate, produces 10% of the revenues provided by the *in situ* use for a given ESE percentage. Benefits are based on historical Gatun Lake levels, but the ACP has recently made investments expected to increase the maximum operational level of Gatun Lake by 45 cm. If realized, this 45-cm increase would decrease the chances of draft (tonnage) restrictions. This may reduce the marginal benefit of ESE driven increases in the height of Gatun Lake and the benefits of ecological infrastructure.

Marginal benefits are the sum of marginal revenues from raising the level of Gatun Lake and avoided dredging costs. Avoided dredging costs for the Gatun sub-watershed are \$39 ha^{-1} and \$6 ha^{-1} for the Cirí Grande-Trinidad sub-watershed. Under an 11.7% ESE with a 7-year delay for the enhanced sponge effect to materialize, marginal revenue from raising the level of Gatun Lake is \$41 ha^{-1} for Cirí Grande-Trinidad and \$26 ha^{-1} for Gatun (Figure 5, Panel A). Under 31.1% ESE with a 7-year delay or a 11.7% ESE that starts immediately, marginal revenue is \$108 per ha for Cirí Grande-Trinidad and \$68 for Gatun. An increase in ESE from 11.7% to 31.1% would increase total marginal benefit per ha for Cirí Grande-Trinidad to the extent that they exceed marginal benefits from the Gatun sub-watershed (Figure 5, Panel B main text).

Market clearing analysis for the size of the feasible program

We used the mean annual marginal costs and mean annual marginal benefits, which includes raising Gatun Lake and avoided dredging costs, to estimate net benefits of the conversion of all enrollable convertible lands and all convertible lands by sub-watershed. Net benefits are estimated for the *in situ* water management. Marginal revenue per hectare depends on the lake levels, as a result, the process of finding the market clearing equilibrium, which represents the feasible program size, is recursive. First, marginal revenues were estimated assuming the full market extent. Next, the market clearing equilibrium was estimated. Then, the marginal revenue per hectare was re-estimated and compared to the original estimates. Since the relationship between lake levels and volume of water is approximately linear, the estimates are close to the original estimates.

Some respondents on the WTA survey accepted programs with loan payment vehicles and positive interest rates. We treat these hectares as if they can be enrolled at zero cost. These lands are not currently providing ESE because of credit market failures or other institutional barriers, rather than a missing market for ecosystem infrastructure. Benefits were estimated under two different assumptions: ESE development is delayed by 7-years or ESE benefits are provided immediately. For both cases, we estimate discounted annual benefits. We estimate the present value and then annualize the present value using the

ACP's financing rate 2.34%. We show the area converted, cumulative increase in dry-season levels of Gatun Lake, net benefits, and benefit-cost ratios of an ESE 11.7% and ESE 31.1% with a 7-year lag for the *in situ* (Table 1 main text) and extractive water use (Table S8) strategies. Extractive water use leads to substantially lower net benefits, but greater benefit-cost ratios (Table S8). This happens because extractive water relative to *in situ* management relies more heavily on water and less heavily on the managerial skill. An ESE of 31.1% was chosen as an upper-bound for the economic analysis. It represents an ESE that would achieve a market clearing program of the same size – hectares enrolled – as a program with an ESE of 11.7% with no lag in the ecological production function (i.e., if dry-season base flow benefits occurred in the first year of agroforestry adoption). An ESE of 31.1% slightly exceeds the largest ESE that has been measured in the PCW, which makes this level useful as an extreme upper bound.

The Rio Indio Dam alternative

The proposed Rio Indio Dam and reservoir (15) will be capable of providing an annual water supply of 1,200 million cubic meters that will increase Gatun Lake's average monthly levels by 74 cm – reaching its spill level in all months – under *in situ* water use and by 24 cm under extractive water use (Table S9). The proposed cost is \$303M in 2003 dollars. Updating these costs to 2015 dollars using the project's annual cost inflation of 6% yields a cost of \$610M. The annualized cost of the project over 20 years would be \$38.5M (Table S9).

This implies that an increase in the height of Gatun Lake costs \$521,000 cm^{-1} under *in situ* water management and \$1,605,000 cm^{-1} under extractive water management. The Rio Indio Dam project is projected to take 8 years to construct and we adjust the calculated benefits to reflect this delay. We estimate an annual benefit of \$118.8M from the *in situ* use and \$38.5M from the extractive use of the increased water supply. With an annual cost of \$38.5M, the net benefits associated with *in situ* management are \$80.3M, but the net benefits associated with extractive management would be close to zero, but slightly negative.

Figures

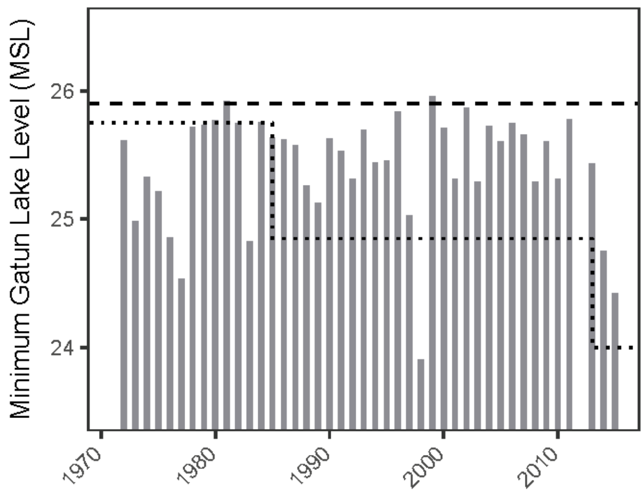

Figure S1. Minimum annual Gatun Lake levels in meters above sea level (MSL). Dotted line shows draft restriction levels for the centennial locks. Dashed line shows draft restrictions for the new NeoPanamax locks (25.9 m). There are missing data in 2012.

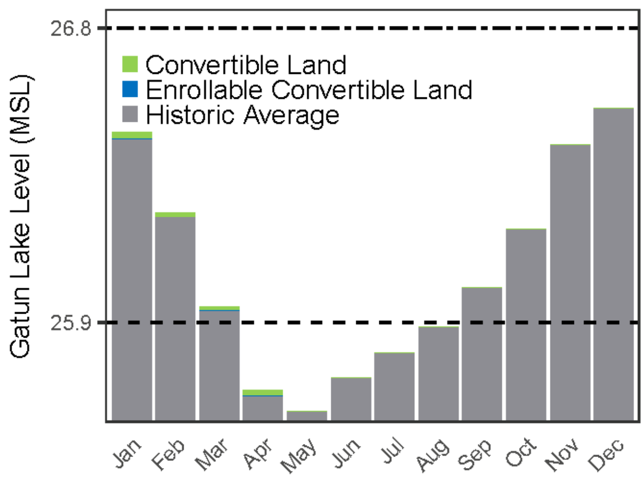

Figure S2. Average monthly Gatun Lake levels (m) by market extent assuming extractive water management and an ESE of 11.7%. The upper (double-dashed) and lower (dashed) horizontal bars are the reservoir spill level and NeoPanamax draft restriction levels, respectively.

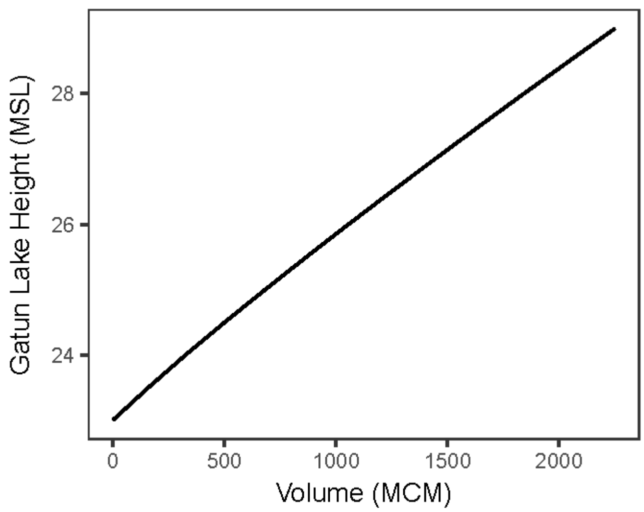

Figure S3. A water depth and lake volume relation for Gatun Lake derived using a 10-m resolution IFSARE-based digital terrain elevation model.

Tables

Table S1. Point estimates (standard errors) from econometric models for the effect of lake levels on toll revenues in USD.

	Ordinary Least Square		*Instrumental Variable*			*Quantile Regression*	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Lake level (from Dry-season average)	102.0***	109.8***	164.7***	176.5***	172.6***	179.3	140.7
	(27.2)	(27.7)	(35.4)	(37.6)	(36.2)	(98.5, 212.1)	(99.0, 218.1)
Lake level squared		0.6		1.2	0.8		
		(0.5)		(0.9)	(0.7)		
Year = 2009	2,136.7	2,300.7	2,354.7	2,663.6	2,560.8	5.8×10^{3}	6.8×10^{2}
	(4,595.0)	(4,572.6)	(4,783.0)	(4,802.9)	(4,757.9)	(-4.8×10^{3}, 1.8×10^{308})	(-1.8×10^{308}, 8.0×10^{3})
Year = 2010	6,515.6	6,314.6	7,135.9	6,706.6	6,849.4	8.9×10^{3}	8.3×10^{3}
	(4,601.9)	(4,580.3)	(4,794.2)	(4,816.7)	(4,770.6)	(-1.16×10^{3} , 1.8×10^{308})	(-1.8×10^{308}, 1.0×10^{34})
Year = 2011	27,914.5***	28,283.0***	27,803.1***	28,531.7***	28,289.3***	2.7×10^{4}	3.0×10^{4}
	(4,594.3)	(4,579.0)	(4,781.8)	(4,829.7)	(4,771.3)	(1.8×10^{4}, 1.8×10^{308})	(-1.8×10^{308}, 3.1×10^{4})
Year = 2012	35,738.8***	36,088.7***	35,915.5***	36,591.0***	36,366.3***	3.8×10^{4}	3.6×10^{4}
	(4,594.7)	(4,578.5)	(4,782.4)	(4,827.3)	(4,770.2)	(2.9×10^{4}, 1.8×10^{308})	(-1.8×10^{308}, 3.9×10^{4})
Year = 2013	35,789.8***	36,329.5***	36,413.3***	37,435.5***	37,095.4***	3.8×10^{4}	3.6×10^{4}
	(4,601.9)	(4,596.7)	(4,794.3)	(4,883.7)	(4,804.8)	(2.6×10^{4}, 1.8×10^{308})	(-1.8×10^{308}, 4.9×10^{4})
Year = 2014	44,745.7***	42,061.5***	50,092.4***	44,527.0***	46,378.6***	5.0×10^{4}	5.0×10^{4}

	(5,279.9)	(5,646.0)	(5,784.9)	(7,139.9)	(6,483.7)	(3.8×10^4, 1.8×10^{308})	(-1.8×10^{308}, 5.7×10^4)
Constant	119,486.9***	118,638.6***	119,009.2***	117,373.8***	117,917.9***	1.1	1.2×10^5
	(4,114.2)	(4,144.6)	(4,285.1)	(4,503.2)	(4,366.6)	(-1.8×10^{308}, 1.2×10^5)	(1.2×10^5, 1.8×10^{308})
N	72	72	72	72	72		
R^2	0.8	0.8	0.8	0.8	0.8		
Adjusted R^2	0.8	0.8	0.8	0.8	0.8		
F Statistic	47.1*** (df = 7; 64)	41.8*** (df = 8; 63)					

Notes*:*

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

Table S2. Annual and dry-season enhanced sponge effects (ESE) for 2009-2013 and 2015 water years. 2014 was excluded as an outlier.

Water year	Wet season start date in May	Annual sponge effect (%)	Dry-season sponge effect (%)
2009	13	11.3	27.2
2010	15	-18.3	4.4
2011	10	16.6	17.6
2012	24	2.3	11.5
2013	10	-17.6	0.3
2015	21	-3.1	9.2
Average		-1.5	11.7

Table S3. Baseline cumulative dry-season discharge by sub-watershed.

Sub-watershed	Hectares	Baseline cumulative dry-season discharge (Million m^3)	Baseline cumulative dry-season discharge (m^3 ha^{-1})	Contribution (%) to total baseline cumulative dry-season discharge in the Panama Canal Watershed
Alajuela	99,115	305.8	3,085.3	51
Gatun	87,982	114.3	1,299.1	19
Cirí Grande-Trinidad	45,044	92.6	2,055.8	16
Caño Quebrado	71,614	83.4	1,164.6	14
Total PCW	303,755	596.1	1,962.4	100

Table S4. Difference in annual sediment yield for non-forested and forested lands, by hectare, within the Panama Canal Watersheds, calculated using measured and equilibrium sediment yields for six major river basins (6, 7).

River Basin	River Basin Area ha	Forested Area ha	Non-forested Area ha	Measured Sediment Yield Mg ha^{-1} yr^{-1}	Equilibrium (Forested) Sediment Yield Mg ha^{-1} yr^{-1}	Non-forested Sediment Yield (measured yield – equilibrium yield) × basin area / non-forested area Mg ha^{-1} yr^{-1}
Chagres	41,400	40,600	800	2.89	1.26	81.5
Boquerón	9,100	7,600	1,500	8.87	1.36	46.6
Pequení	13,500	12,800	700	6.58	1.49	94.3
Gatún	11,700	7,300	4,400	3.05	1.07	5.3
Trinidad	17,400	3,200	14,200	1.12	0.86	0.3
Cirí Grande	18,600	3,800	14,800	1.95	0.98	1.2

Table S5. Estimated annual reduction in sediment volume and avoided Lake Gatun dredging costs per hectare from agroforestry adoption by sub-watershed.

Sub-watershed	Area-Weighted Sediment Yield Mg ha^{-1} yr^{-1}	Sediment Volume m^3 ha^{-1} yr^{-1}	Annual avoided Dredging Costs \$ ha^{-1} yr^{-1}
Alajuela	79.2	66.0	59*
Gatun	5.3	4.4	39
Cirí Grande-Trinidad	0.8	0.7	6
Caño Quebrado	0.8	0.7	6

*Assumes 90% of sediment settles in Alajuela Lake and does not reach Gatun Lake where dredging operations take place.

Table S6. The hectares of land by sub-watershed within each step used to define the physical and social extent of the market.

Sub-watershed	All land	Convertible land (all)	Convertible Chagres National Park land	Private convertible land	Potentially enrollable convertible land	Enrollable convertible land
Alajuela	99,115	12,486	9,669	2,476	2,105	448
Gatun	87,982	32,180		25,048	20,214	3,376
Cirí Grande-Trinidad	45,044	33,594		28,845	22,730	8,819
Caño Quebrado	71,614	38,260		33,461	26,701	3,418
Total PCW	303,755	116,520	9,669	89,830	71,750	16,061

Table S7. Conversion factors used to adjust private convertible land to reflect lands that are potentially enrollable and actually enrollable by sub-watershed.

Sub-watershed	Percent of sampled convertible lands that are potentially enrollable	Percent of sampled in the market convertible land that is actually enrollable
Alajuela	85	21
Gatun	81	17
Cirí Grande-Trinidad	79	39
Caño Quebrado	80	13
Total PCW	80	22

Table S8. Area, increase in lake levels, net benefits, and benefit-cost ratio for the physical and social extent of the market with an 11.7% (31.1%) ESE with a 7-year lag in development for extractive water management.

Market extent assumption	Area (1000 ha)		Increase in cumulative dry-season lake levels (cm)		Total net benefit ($1,000)		Benefit-cost ratio	
	Convertible Land							
Full market extent	116.52		1.66	(4.42)	-45,149	(-44,464)	0.01	(0.02)
Voluntary participation assuming uniform marginal benefits across sub-watersheds	10.74	(11.65)	0.18	(0.51)	215	(218)	5.7	(5.0)
Voluntary participation assuming uniform marginal benefits but differentiated marginal costs by sub-watershed	8.58	(9.18)	0.12	(0.34)	48	(91)	2.4	(2.8)
	Enrollable Convertible Land							
Full market extent	16.06		0.23	(0.62)	-6,221	(-6,122)	0.01	(0.03)
Voluntary participation assuming uniform marginal benefits across sub-watersheds and undifferentiated marginal costs	1.35	(1.48)	0.02	(0.06)	21	(30)	7.0	(5.7)
Voluntary participation assuming uniform marginal benefits but differentiated marginal costs by sub-watershed	1.42	(1.53)	0.02	(0.06)	11	(20)	4.6	(4.6)
Marginal benefits equal marginal cost by sub-watershed	1.26	(1.38)	0.02	(0.06)	12	(21)	13.9	(9.2)
	Convertible Land in Chagres National Park							
All Convertible Land in Chagres National Park	9.67		0.24	(0.63)				

Table S9. The cost, by water management strategy, of increasing average monthly lake levels using the Rio Indio Dam project.

				In Situ Use		Extractive Use	
	Annual water supply (Million m^3)	Maximum cumulative lake level rise (cm)	Annual cost ($M yr^{-1})	Average increase in monthly lake levels (cm)	Cost of lake level increase ($ cm^{-1})	Average increase in monthly lake levels (cm)	Cost of lake level increase ($ cm^{-1})
Increase in Gatun Lake Operational Level	200	45	1.9	45	42,000	3.75	505,000
Rio Indio Dam	1200	300	38.5	74	521,000	24	1,605,000

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