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Modeling multiple ecosystem services and beneficiaries of riparian reforestation in Costa Rica

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ABSTRACT

Riparian buffers—forests along rivers—generate many essential ecosystem services, and their protection and restoration are the focus of many policy efforts. Costa Rica is a global leader in this regard, where legislative and executive frameworks work in concert to conserve forests that deliver public benefits such as water quality and carbon storage both locally and globally. Yet implementation and enforcement is an urgent challenge, and could benefit from high-resolution targeting with a quantitative understanding of expected benefits. Here, we undertake such an analysis, focusing on the benefits of implementing Forest Law 7575, which specifies the amount of forest to be preserved along rivers. We model changes in sediment retention, nutrient retention, and carbon sequestration from a baseline scenario based on current land use that is in partial compliance with the law. We contrast this with a simulated reforestation scenario, where riparian forest cover is increased to at least a minimum level of compliance (10 m buffers) everywhere. We find that targeted riparian reforestation—increasing national forest cover by 1.9 %—would substantially increase ecosystem services. Water quality regulation would be improved via an increase of 3.9 % in sediment retention (1.4 Mt/year), 81.4 % in nitrogen retention (0.012 Mt/year), and 85.9 % in phosphorus retention (0.0022 Mt/year). Moreover, riparian reforestation would increase the national carbon stock 1.4 % above current levels (7.0 Mt). Our analysis shows where riparian buffers are most beneficial—generally in steep, erosion-prone, and intensively fertilized landscapes. Through a canton-level analysis comparing potential increases in sediment and nutrient retention with demographic information, we find that these benefits would flow to communities that depend on rivers for

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drinking water and that are otherwise vulnerable. Small increases in riparian reforestation in Costa Rica, implemented via an existing law, could confer large benefits to rivers and all who depend on them.

1. Introduction

Globally, biodiversity and natural ecosystems are declining at rapid rates, with 75 % of terrestrial land area significantly altered by human activity (Brondizio et al. 2019), and associated losses of vital services (Brauman et al. 2020). In response, governments, multilateral development banks, and other institutions are beginning to consider ecosystem services explicitly in major decisions (Mandle et al. 2019). Many countries are committing to ecosystem restoration, with new plans, policies, and financing (BenDor et al. 2015, Ouyang et al. 2016, Salzman et al. 2018), setting aside large areas of land for global agreements such as the Bonn Challenge and New York Declaration on Forests (Suding et al. 2015, Chazdon et al. 2017, Holl 2017) or corporate-led efforts like the Trillion Trees platform (Seymour 2020). Given limited resources to achieve ecosystem protection, however, it is crucial to evaluate the benefits and tradeoffs of different restoration options. As we enter the UN's Decade on Ecosystem Restoration, new science is crucial to help guide restoration efforts to achieve maximum benefit for people and the natural world.

Riparian buffers, those vegetated areas adjacent to rivers and streams, generate disproportionately high levels of services relative to their spatial extent (Capon et al. 2013), because of their blend of terrestrial and aquatic habitats, microclimates, and both lateral and longitudinal connectivity to adjacent hillslopes and upstream rivers. Much work has been done to quantify the services riparian buffers provide, focused especially on particular streams and watersheds (Sweeney et al. 2004, Gray et al. 2014), and on water and habitat provision and connectivity (e.g., Naiman et al. 1993, Sabo et al. 2005, Marczak et al. 2010 [biodiversity]; Osborne and Kovacic 1993, Lee et al. 2003, Mayer et al. 2007 [water]; Stutter et al., 2012; Luke et al., 2019; Riis et al., 2020 [all services]). These studies demonstrate the importance of riparian buffers and highlight the potential impact of their restoration on more local scales.

A major challenge that remains is creating effective policy mechanisms to safeguard and restore riparian buffers and the key services that they provide. While several studies have explored the potential outcomes of large-scale riparian reforestation (Townsend and Masters 2015, Fremier et al. 2015, Krosby et al. 2018), they did not examine specific policies. A further gap remains in quantifying the impact of riparian restoration across multiple scenarios, services, and regions, the results of which could present policymakers with a clear case for restoration and conservation, outlining where to prioritize implementation. Zheng et al. (2016) took first steps to illustrate this, evaluating multiple restoration scenarios, including riparian buffer reforestation, and multiple services in a watershed in China. Daigneault et al. (2017) went even further, modeling the effects of varying riparian buffer widths on multiple services across all of New Zealand to inform future policy. However, both of these studies concern hypothetical future policies, and it may be far easier to implement an existent policy than create and implement a new one.

A key opportunity lies in enforcing existing frameworks for protecting riparian habitats and water resources. Because of the importance of natural vegetation to water quality and quantity, many countries have laws protecting riparian buffers (Lee et al. 2003, Lees and Peres 2008, Luke et al. 2019). However, these regulations are often not strongly enforced (Ducros and Watson 2002, Meli et al. 2019, Biggs et al. 2019), and the costs of weak enforcement – to rivers, water resources, and people – are, with few exceptions (Daigneault et al. 2017) little known. Quantitative analysis of the benefits of policy-relevant riparian reforestation could encourage stronger implementation of existing and future policies, especially by making tradeoffs between different objectives more transparent (e.g., maintaining water quality vs maximizing agricultural production). Far too many ecosystem service asessments remain at the level of biophysical supply rather than connecting to social and economic information that is needed to delineate the beneficiaries of the service, which is especially important for addressing equity concerns (Mandle et al., 2020; Thierry et al., 2021; Villarreal-Rosas et al., 2020; Wieland et al., 2016). Given the heterogeneity in socio-economic status of people who live in proximity to riparian areas, it is critical to examine to what extent vulnerable populations (e.g., impoverished households, single parent families, or Indigenous peoples) depend on riparian buffers or would benefit from riparian reforestation programs. Such information could be instrumental in defining priority areas for investing limited resources in implementing riparian buffers.

Here, we modeled the benefits of implementing an existing riparian buffer policy across multiple ecosystem services, to different groups of beneficiaries, for the case of Costa Rica. Costa Rica, a tropical Central American country, is part of the Mesoamerican Biodiversity Hotspot (Myers et al. 2000). The country has experienced rapid deforestation in the 20th Century, declining from an estimated 70 % forest cover in 1950 to 21 % forest cover in 1987. Since then, there has been net reforestation to 52 % forest cover in 2013, thanks to a suite of innovative conservation policies and financial mechanisms (Banco Central de Costa Rica 2016, Daniels et al. 2010, Umaña Quesada 2019). The national government has a strong ongoing commitment to conservation and carbon neutrality, supporting a vision of inclusive, green growth (Instituto Costariccense de Turismo, 2017). Costa Rica depends on ecosystem services to support its large ecotourism industry (Valverde Sanchez 2018), as well as for hydropower, which accounts for over half of its energy supply (Ministerio de Ambiente y Energía 2015). In 1996, Costa Rica also pioneered the first national Payments for Ecosystem Services (PES) scheme, which incentivizes landowners to protect and restore forests on their property (*Ley* Forestal 1996, Pagiola 2008). While Costa Rica is a regional leader in access to clean water, there is still a significant portion of the country's population, particularly amongst rural, poor, and Indigenous groups, that lacks access to clean water (Cuadrado-Quesada 2020, de Albuquerque 2009, Avila 2019, Contraloría General de la República de Costa Rica 2018, Instituto Nacional de Estadística y Censos 2011, World Health Organization 2018).

Herein, we quantified the ecosystem service implications of national compliance with Costa Rica's Forest Law 7575 of 1996, which mandates protection of forest corridors along rivers. To model the impact of relatively small buffer strips on country-wide ecosystem services provision, we employed novel methods for high resolution ecosystem modeling. We did this based on two scenarios: one baseline scenario with current land use/land cover, and one reforestation scenario in which riparian buffers have been implemented as per Costa Rican law. For both scenarios, we evaluated three services, whose benefits ranged from local to global: nutrient retention, sediment retention, and carbon sequestration. Riparian buffers are mostly implemented in order to prevent sediment and nutrients from entering streams because they are located at the hillslope channel interface. Therefore, the main benefit we expected to see from riparian reforestation was decreased nutrient and sediment export to streams. For this reason, in this study we focused on modeling sediment and nutrient retention, and treated carbon sequestration as a co-benefit of implementing riparian buffers. Based on the analysis of differences between these two scenarios, we explored three questions:

1. How could enacting Costa Rica's Forest Law 7575 influence ecosystem service provision countrywide?

2. How are the ecosystem service benefits of riparian reforestation distributed spatially?
3. Who benefits most from riparian restoration, specifically for services related to drinking water quality?

Through answering these questions, we hope to help prioritize restoration in the places where riparian buffers could provide the greatest benefits, improving the quality of life of people depending directly and indirectly on clean rivers, especially the most vulnerable populations.

2. Methods

2.1. Scenario generation

We generated two main scenarios: one baseline scenario, and one reforestation scenario where riparian buffers were increased to meet the provisions of the law. Specifically, Articles 33 and 34 of Forest Law 7575 call for protection of 10 m buffers on both sides of a river in flat urban areas, 15 m buffers in flat rural areas, and 50 m buffers in any steep (greater than 40 % grade) areas (*Ley* Forestal 1996, Torres 2013). Costa Rica's historical natural landcover was almost entirely forest, although just over 50 % is currently forested. The law therefore calls for maintenance of that natural landcover in buffer zones across the entire country. It is important to note that Forest Law 7575 mandates protection, not restoration, of riparian buffer zones. Therefore, our reforestation scenario, while relevant to extant policy, would require new policy or financial mechanisms to become a reality.

To create the baseline scenario, we began with a 2012 land cover raster with 17 classes generated by the Costa Rican National Meteorological Institute (IMN) at a 10 m resolution. We performed multiple steps to ensure quality control for this baseline raster, including filling in missing data, and adjusting stream locations to match the locations of streams extracted from a digital elevation model (DEM) that drives the hydrological modeling (see Appendix B Sections 1 and 2 for full details). Streams were derived from a 10 m DEM created by down sampling a 90 m HydroSHEDS DEM. The down sampling was undertaken to match the resolution of the DEM to the resolution of the land cover data. Streams were extracted using the InVEST tool RouteDEM with a threshold flow accumulation value of 1000 cells (100,000 m^2) using a multiple flow direction algorithm for flow routing.

To create the reforestation scenario, we first determined which land use classes from the baseline scenario must be reforested to meet the provisions of the law through consultation with experts from the Costa Rican government (Table A.1). We then created a land cover raster representing the reforestation scenario map by adding buffers of forest alongside DEM-derived rivers to meet the minimum provisions of the law: 10 m on both sides of a river, regardless of river size, in all appropriate land use classes (Fig. 1). We chose 10 m buffers because they were much more feasible to model, and they represent a conservative estimate of the effects of full compliance. We performed additional analyses to approximate how much this scenario underestimates the effects

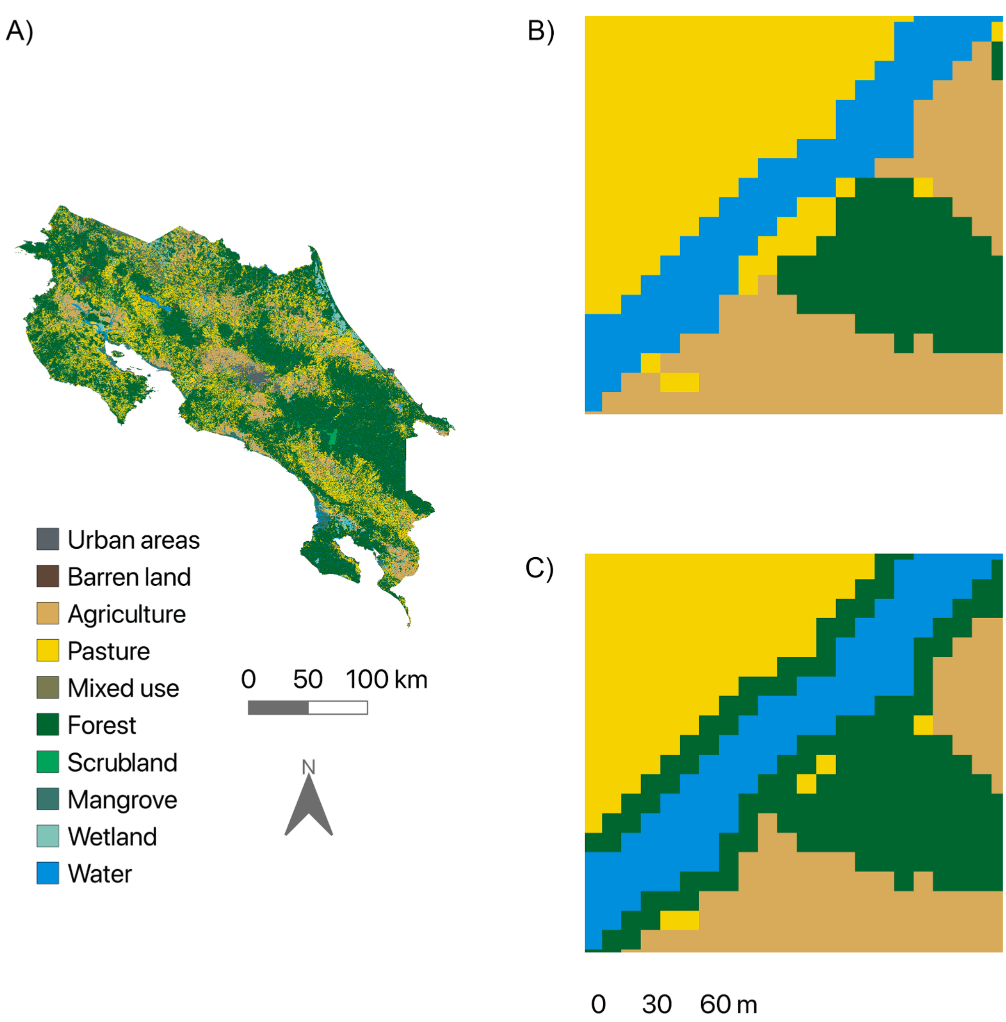

Fig. 1. We created two different land cover scenarios to model the effects of complying with Forest Law 7575 in Costa Rica. Our baseline scenario was based on a current land use map, shown A) for the country and B) around a single river, with a 10 m resolution and compiled from multiple sources, including the Costa Rican National Meteorological Institute, the Costa Rican Coffee Institute, the Costa Rican Airborne Research Program in Remote and In Situ Sensing, and the European Space Agency. C) We generated our reforestation scenario by adding a 10 m forest buffer on either side of rivers in appropriate land use classes, in this case pasture and agriculture. This amount of buffer matches the minimum provisions of the Forest Law, and represents a conservative estimate of the effects of full compliance.

of full compliance (Appendix B Section 1.4). We generated all scenarios in Python 3.8 and ArcGIS 10.7.1 (python script available at https://github.com/kelley-langhans/CostaRica-river-reforestation; see Appendix B for full details).

2.2. Ecosystem service modeling

We quantified ecosystem service provision using InVEST 3.7.0, an open-source software produced by The Natural Capital Project (Sharp et al. 2020). InVEST creates spatially explicit maps of ecosystem services based on different scenarios and allows for evaluation of tradeoffs and synergies between different services. We ran three InVEST models on both baseline and reforestation scenarios: Sediment Delivery Ratio, Nutrient Delivery Ratio, and Carbon Storage and Sequestration. Ecosystem services were modeled for the entire country at a 10 m resolution (all InVEST input and output data available at https://osf.io/srjwx/). While we use established InVEST models, we introduce novel methods to perform modeling at a very fine scale across a large spatial extent, to create policy-relevant scenarios, and to utilize local data.

2.2.1. Sediment retention

The InVEST Sediment Delivery Ratio (SDR) model assesses annual soil loss (calculated by the revised universal soil loss equation, RUSLE) from hillslope pixels, connectivity between those pixels and a downslope drainage (e.g., a river channel) and the resulting sediment export to that drainage. It requires a digital elevation model (DEM), rainfall erosivity (R), soil erodibility (K), watersheds, a biophysical table with estimates of cover-management factor (usle_c or C factor) and support practice factor (usle_p or P factor) for each land use class (Table A.2), along with an optional drainage layer. Sediment retention is calculated as the difference between sediment export in the two scenarios (baseline and reforestation).

To ensure that the SDR model routed all sediment flow to the water bodies in our land use map, we used a drainage layer made from all water in our land use map (see Appendix B Section 2). We set kb and IC0, calibration parameters that determine the relationship between hydrological connectivity and SDR, to the default values of 2 and 0.5, respectively. We set SDRmax to 0.8, i.e., no more than 80 % of the sediment eroded on a hillslope pixel can be delivered to a stream. We performed a literature review on C factor values for the biophysical table, using Costa Rican values wherever possible, Latin American values where we could not find Costa Rican values, and finally global values when neither of the other two were available (Table A.2). We used global erosivity and erodibility layers from Borrelli et al. (2017) with data gaps filled in using Focal Statistics in ArcGIS.

2.2.2. Nutrient retention

The InVEST Nutrient Delivery Ratio (NDR) model estimates export of nutrients from hillslope pixels, retention by downslope vegetation, and export to waterbodies. The model can assess both nitrogen (N) and phosphorous (P) retention. It requires a DEM, nutrient runoff proxy (precipitation), watersheds, and a biophysical table with estimates of nutrient load and retention parameters for each land use class (Table A.3). As for sediment retention, N and P retention are calculated as the difference in export between scenarios.

As in SDR modeling, we set threshold flow accumulation to 1000 and kb to 2. We performed a literature review on N and P load and retention in each land use class for the biophysical table, using values from studies conducted in Costa Rica wherever possible, from studies conducted in Latin America where we could not find values from Costa Rica, and finally values from global studies or studies in other regions when neither of the other two were available (Table A.3). When we were unable to find values for P, we estimated based on values for N. We did not include subsurface flow because we lacked sufficient information to parameterize our model.

2.2.3. Carbon sequestration

The InVEST Carbon Storage and Sequestration model estimates carbon stored in a landscape and sequestered over time in four carbon pools: aboveground living biomass, belowground living biomass, dead organic matter, and soil. Here we considered only aboveground living biomass, for which we were able to get the most accurate and fine-scale data from global maps in Costa Rica. The InVEST model requires as input a biophysical table with estimates of carbon stock in each land cover class (Table A.4).

There is significant variation in carbon stock within land use categories in different regions of the country. To capture this, we divided our map into Costa Rica's four Global Ecological Zones (FAO 2001) as per IPCC (Intergovernmental Panel on Climate Change) carbon sequestration guidelines, which estimate aboveground biomass for each land cover class differently for each ecological zone (Aalde et al. 2006). We then estimated aboveground carbon stock in each land use/ecological zone combination using two different methods. For all classes that were primarily trees (i.e., forests, forest plantation, coffee, and oil palm), we estimated carbon stock using a map of aboveground carbon for pantropical ecosystems from Baccini et al. (2017). This map, generated from a combination of field and earth observation data and optimized to detect live woody vegetation, represented the best data we had on tree carbon stock. We used zonal statistics on this map to estimate average carbon stock for each tree land use class. For all non-tree land use classes, we used an IPCC lookup table that estimated carbon stock for different land use class within each ecological zone (Gibbs and Ruesch 2008, as applied in Suh et al. 2020) (see Appendix B Section 3.3 for more details).

2.2.4. Uncertainty analyses

For both the SDR and NDR models, we found a range of values in the literature to parameterize forested buffers that would determine how effective they were at blocking sediment and nutrient pollution from reaching streams. In order to explore the uncertainty around how well forested buffers can protect water quality, we ran models on low, average, and high values from these ranges.

For the SDR model, we adjusted the C factor, a measure of how much sediment each land cover type retains and produces, for forest buffers using a range of values from our literature review from Costa Rica (Mora Cordero 1987, FAO 1989, Lianes et al. 2009) (see Table A.2 for full SDR biophysical table and exact calculations). We found both a low and high C factor value for each primary and secondary forest. We assumed that forested buffers are planted to represent the composition of natural primary forests, but would still remain structurally altered and similar to secondary forests for a considerable amount of time. We thus estimated an upper C factor value (0.02) as an average of the highest values reported for primary and secondary forests. We applied the same reasoning to estimate a lower C factor value (0.004) for forested buffer and estimated the average C factor (0.012) to be the mean of those four values.

For the NDR model, we adjusted the N and P retention efficiency of forest buffers using values from a review of N retention efficiency in riparian buffers in the United States (Mayer et al. 2005). We took the highest of all the values for retention efficiency in forested buffers (N = 22) to estimate the high end of retention efficiency (1.0), the lowest to estimate the low end of retention efficiency (0.58), and used the median (0.95) as a central estimate. These values may represent an underestimate of retention efficiency, as N and P retention have been shown to be higher in tropical than temperate forests (Templer et al. 2008, Dalling et al. 2016).

For the Carbon Storage and Sequestration model, although we did not have the same range of values for forest buffers, we explored uncertainty by running models where we chose carbon stock values for woody vegetation from different data sources (see Appendix B Section 4.3 and Appendix C Section 3 for further details).

2.2.5. Analysis

We explored countrywide changes in ecosystem services due to reforestation by subtracting results from the riparian reforestation scenario from outputs for the baseline scenario. We then summarized results across relevant administrative boundaries (canton or nation-wide). To determine increases in forest cover with restoration, we added up all forest pixels (primary forest, secondary forest, and general forest, but not forest plantations or mangroves) in our baseline and scenario land cover rasters and subtracted the scenario total from the baseline total (code available at https://github.com/kelley-langhans/CostaRica-river-reforestation).

2.3. Beneficiaries analysis

In order to examine who would benefit from reforestation, we compared modeled changes in ecosystem services to spatially explicit demographic groups. We considered only water quality benefits from increased sediment and nutrient retention, as the benefits of carbon sequestration are not localized, nor are they the main focus of this study. We focused our analysis on the distribution of ecosystem services benefits, not the distribution of overall costs and benefits from reforestation.

We obtained information at the canton level about drinking water sources, poverty, women-led households, and racial make-up from the 2011 Costa Rican census (Instituto Nacional de Estadística y Censos 2011), the most recent year available and cited in Costa Rican policy documents about water quality (Instituto Costarricense de Acueductos y Alcantarillados 2016, Avila 2019). The Costa Rican census is a de jure census, where people are censused in their home, and both household and individual demographic data are collected (Instituto Nacional de Estadísticas y Censos 2018). Specifically, we analyzed information about the number of people who obtain their household water from rivers or creeks (as opposed to other sources), the percent of households below the poverty line, the percent of women-led households, and the percent of the population that identified as Indigenous (data available at: https://www.inec.cr/censos/censos-2011; for more information about census data collection, see Appendix B Section 5.1).

We identified "hotspot" cantons where a high demand for services coincided with a high potential for increase in water quality with reforestation as potential places to prioritize riparian reforestation. We then compared distributions of vulnerable populations—poor households, women-led households, and Indigenous populations—between hotspot and other cantons to explore how prioritizing reforestation in this way would affect vulnerable populations (for more details on beneficiaries analysis, see Appendix B Section 5.1; for descriptive maps of how these demographic data differ between cantons, see Figure A.1; code available at https://github.com/kelley-langhans/CostaRica-river-reforestation and data at https://osf.io/srjwx/). To further investigate potential impacts on Indigenous communities, we also calculated projected increases in service per area in each Indigenous territory in Costa Rica (Observatorio del Desarollo, 2008) and compared those values to the average increase in service per area nationwide.

3. Results & Discussion

3.1. Countrywide increases in ecosystem services

Reforesting riparian buffers in compliance with the minimum provisions of Costa Rican law adds 522 km^2 of forest, an increase in forest cover of 1.9 % above the current baseline and accounting for 1 % of Costa Rica's total land area. Implementation of buffers to meet the minimum provisions of Forest Law 7575 increases annual sediment retention by 3.9 % (1.4 Mt) compared to the current baseline export to waterbodies, nitrogen retention by 81.4 % (0.012 Mt), and phosphorus retention by 85.9 % (0.0022 Mt), and increases carbon stock by 1.4 % (7.0 Mt) (Fig. 2). These increases are comparable to those found in other riparian reforestation modeling studies across tropical, subtropical, and temperate regions (Betrie et al., 2011; Daigneault et al., 2017; Olley et al., 2015; Ouyang et al., 2013, 2015; Zheng et al., 2016). While the magnitude of increases in ecosystem services depends on the landscape context and the precise reforestation scenario modeled, these studies show that riparian reforestation has large ecosystem services benefits across systems.

Of the land converted to forested buffers in the reforestation scenario, 54.2 % was previously pasture (representing a decrease of 2.9 % of Costa Rica's total pasture cover), 14.2 % was non-coffee/oil palm permanent crops (a decrease of 3.2 % of Costa Rica's total), and 8.1 % was non-pineapple annual crops (a decrease of 3.6 % of Costa Rica's total) (Table A.5).

Our models actually underestimate the effects of reforesting to meet the provisions of Costa Rican law, as we model only the effects of reforesting 10 m buffers, while the law calls for protection of up to 50 m of buffers in steep areas (greater than 40 % slope). We estimate that 7 % of all stream reaches in Costa Rica are steep, 2 % are flat and urban, and 91 % are flat and rural. However, 89 % of the area within 50 m of steep streams is already forested (Appendix C Section 1). This means that excluding 50 m forest buffers around steep streams from our modeling does not have a large impact on our results; instead, most of our underestimation comes from modeling 10 m buffers in flat rural areas

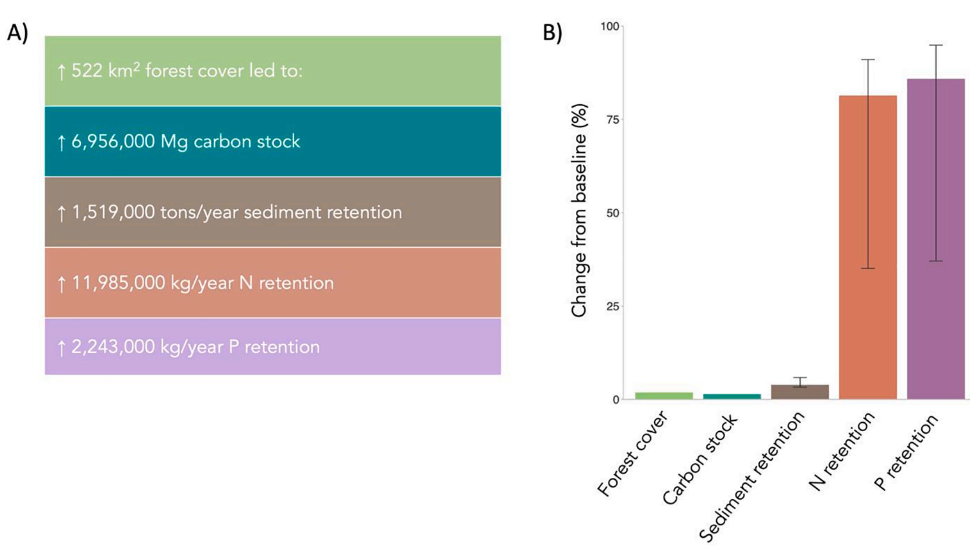

Fig. 2. A relatively small increase in forest cover from riparian reforestation to be compliant with Costa Rican law could lead to large increases in ecosystem services nationwide. A) An increase in forest cover of 522 km^2 with riparian reforestation would increase carbon stock and sediment, N, and P retention. B) A 1.9 % increase in nationwide forest cover would lead to increases of a similar scale in carbon stock (1.4 %) and sediment retention (3.9 %), and disproportionately large increases in N and P retention (81.4 % and 85.9 %) as compared to current levels. Error bars on sediment, N, and P retention represent the upper and lower bounds of our uncertainty analyses.

where the law calls for 15 m buffers. In fact, recent field studies in Costa Rica suggest that riparian buffer length (Brumberg et al. 2021) and canopy cover (de Jesús Crespo et al. 2020) may have a larger impact on water quality than buffer width, so modeling or implementing 10 m instead of 15 m buffers may not create much of a difference in sediment and nutrient retention services.

3.2. Spatial patterns in ecosystem services hotspots

On a small spatial scale, reforesting around rivers has different impacts on ecosystem services depending on land use and gradient of the adjacent hillslopes. Riparian reforestation has the largest potential sediment and nutrient retention benefits below steep slopes with erosion-prone land uses (e.g., bare ground, pasture, and farming), high levels of fertilizer application (i.e., highly-fertilized crops like pineapple and oil palm), and low levels of nutrient retention (e.g., urban areas) (Fig. 3). Our analysis pinpoints such areas where reforestation could have a large impact on ecosystem services at a spatial scale of 10 m.

Costa Rican cantons stand to benefit through different ecosystem services (Fig. 4, Table A.6). Alvarado, a steep, agriculture-dominated canton, is projected to see the greatest increase in sediment retention per unit area with reforestation, followed by Sarchí, Poás, Asserí, and León Cortés Castro, all of which are also agriculture-dominated and located in the Cordillera Central or Talamanca Mountains around the Central Valley. Palmares, an urban and coffee-dominated canton, would experience the greatest increase in N retention per unit area, followed by Naranjo, León Cortés Castro, Poás, and Grecia, which are also primarily urban/coffee mixes or coffee-dominated. P retention follows a very similar pattern, where the cantons with the greatest increase would be Palmares, Naranjo, Corredores, León Cortés Castro, and Poás. All of these are coffee-dominated or urban/coffee-dominated, with the exception of Corredores, which is dominated by oil palm.

Many of the same cantons also have the largest return on investment, or increase in services per amount of forest added, from riparian reforestation (Fig. A.2). The main difference is that cantons that currently have large areas of forest would also experience large returns on investment. Alvarado, Sarchí, Oreamuno, Asserí, and Paraíso would experience the greatest increase in sediment retention per unit forest added. Like the other cantons, Oreamuno and Paraiso are agriculture-dominated and in the mountains around the Central Valley, but they also have large forested areas. León Cortés Castro would experience the largest increase in N retention per unit forest, followed by Palmares, Naranjo, Tarrazú, and Desamparados, the last two of which have large forested areas as well as coffee. P retention again follows a similar pattern, where the cantons with the greatest increase would be León Cortés Castro, Palmares, Naranjo, Corredores, and finally Quepos, which is dominated by oil palm and forest.

3.3. Uncertainty analyses

Sediment retention is moderately sensitive to uncertainty in C factor values. Assigning a high C factor value of 0.02 (a less effective buffer) results in an increase in sediment retention of 1.3 Mt/yr, or 3.3 % of the current total export, with reforestation. Assigning a low C factor value of 0.00355 increases sediment retention in riparian buffers by 2.3 Mt/yr, or 5.8 % of the current total export.

Adjusting the retention efficiencies of forested buffers has a much larger impact on nutrient retention. Assigning low retention efficiencies of 0.58 (a less effective buffer) leads to increases in N retention of 0.0052 Mt/yr and P retention of 0.00097 Mt/yr. These represent only 35.1 and 37.1 % of the current export, respectively. However, assigning high retention efficiencies of 1.0 increases N retention by 0.013 Mt/yr and P retention by 0.0025 Mt/yr, or 91.0 % and 94.9 %, respectively.

Despite these large uncertainty ranges, we have found that our spatial prioritization of cantons based on increases in services with reforestation is robust. Using high, medium, or low C factor or retention efficiencies can lead to large differences in absolute, or even relative, increases in ecosystem services between scenarios. However, regardless

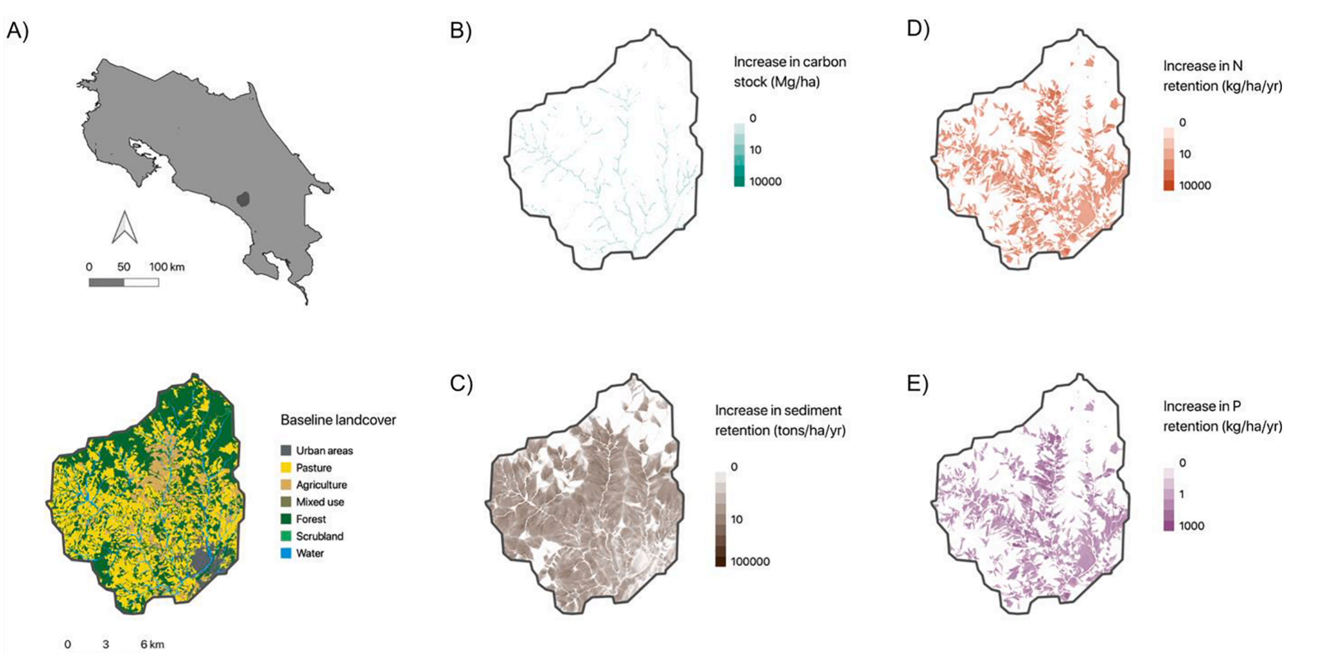

Fig. 3. The results of our country-wide fine-scale ecosystem modeling in a single sample watershed. Riparian reforestation has a high potential to reduce nutrient and sediment export when implemented in areas prone to erosion, with high levels of fertilization, and with low levels of nutrient retention. A) Baseline land use in a watershed around San Isidro de El General in Costa Rica containing the rivers Pacuar, Pedregoso, and Quebradas. While increases in B) carbon stock occur everywhere that forest buffer is added along rivers, C) sediment retention increases when reforestation takes place downstream of areas that are prone to erosion, such as pasture and agriculture. Similarly, D) N and E) P retention increase in areas with high levels of fertilization or low capacities to retain nutrients, including agriculture, pasture, and urban areas.

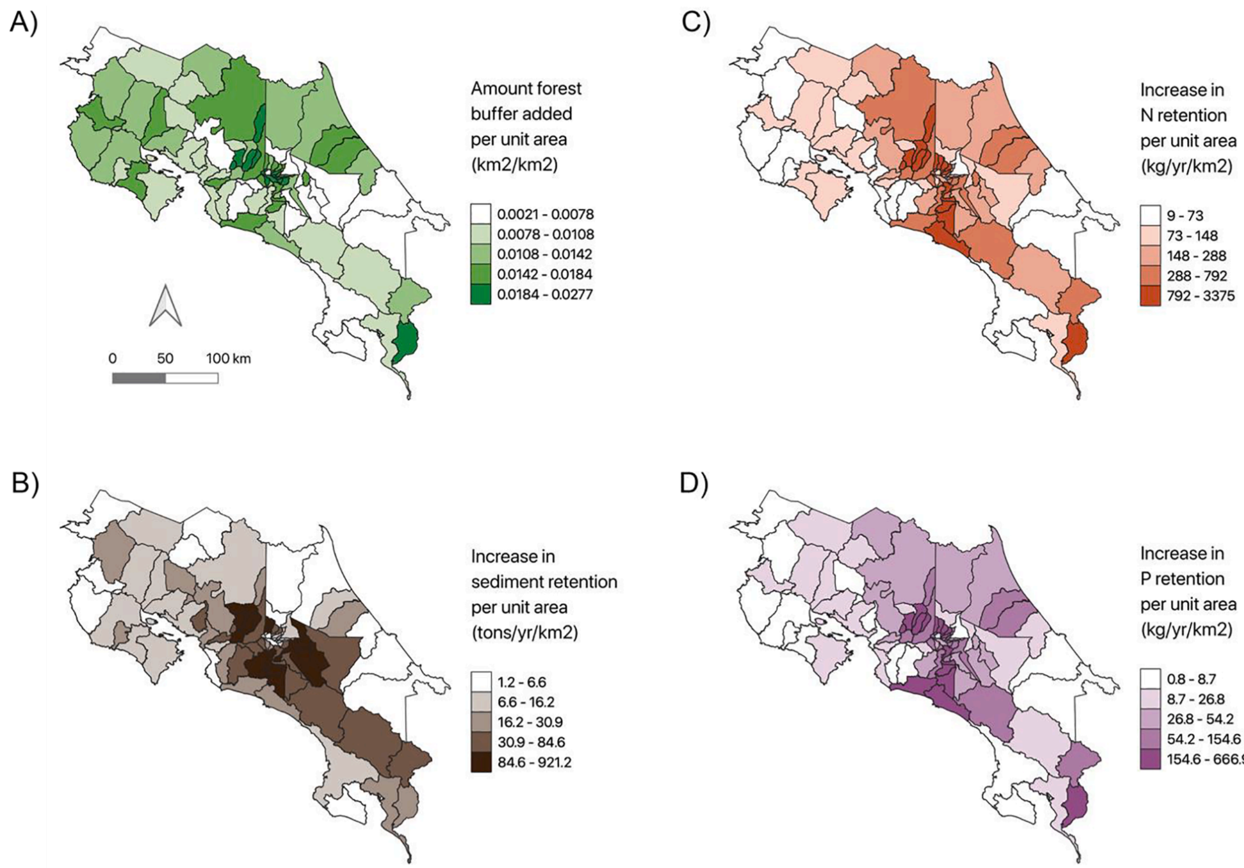

Fig. 4. Increases in hydrological services per canton do not necessarily scale with A) the amount of forest added by buffering around rivers which were previously unforested. Instead, B) sediment retention increases the most with riparian reforestation in steep, erosion-prone cantons. C) N and D) P retention increase the most in urban cantons with low nutrient retention and agriculture-dominated cantons with high levels of fertilization. All results are normalized by canton area.

of the way these values are parameterized, our models are fairly consistent in ranking cantons by increase in service (Fig. A.3) or identifying the cantons with the highest potential increase (Table A.6). For example, regardless of the uncertainty scenario, the top five cantons for increase in sediment, N, and P retention remain the same. Therefore, our approach can be used to identify areas of greatest impact for reforestation, even if the exact magnitude of that impact is uncertain. Our results are best interpreted in terms of spatial prioritization than absolute amounts of change in ecosystem services.

These uncertainty analyses also have a practical application. By comparing differences in ecosystem service increases achieved by planting more and less effective buffers, we can identify areas where more effective buffers are necessary to increase ecosystem services, as well as places where less effective buffers are sufficient (Appendix C Section 3). Despite remaining uncertainty in the biophysical models (see Appendix C Section 3 for more details), practitioners can use these results to pinpoint places where extra resources should be expended to make the buffers as efficient as possible.

In addition to the uncertainties in model parameterization that we have discussed above, the Sediment Retention, Nutrient Retention, and Carbon Sequestration InVEST models have structural limitations that should be taken into account when interpreting these results. The Sediment Retention model relies on USLE (the Universal Soil Loss Equation, Renard et al. 1997), which does not take into account all sources of erosion and tends to overestimate erosion in steep and subtropical settings; the Nutrient Retention model is very sensitive to input parameters that may change over space and time; and the Carbon Sequestration model does not take into account dynamic sequestration (for more details, see Appendix C Section 3).

3.4. Beneficiaries

Our analysis shows that a majority of cantons with large numbers of people dependent directly on rivers for drinking water could benefit greatly from ecosystem service increases from reforestation. Twenty out of 81 cantons are hotspot cantons, cantons with a high need for good surface water quality (based on population per area dependent on untreated river water) that could see large increases in water quality via increased retention of sediment, N, and P per unit area with reforestation (Fig. 5 & Fig. A.8, dark purple cantons). Reforesting these 20 hotspot cantons could provide large increases in water quality for 50,679 people dependent on rivers, 47 % of the country's river-dependent population. Conversely, there are only four cantons that have a high need for good surface water quality that would see only small increases in water quality via increased sediment and nutrient retention (Fig. 5 & Fig. A.8, bright red cantons), and all four already have low baseline pollution and extensive riparian buffers. These cantons are key places to focus riparian forest protection efforts, along with others that currently have high water quality and a large population dependent on rivers. Running deforestation scenarios with our models could further illuminate the current conservation value of these cantons and reveal areas within them for prioritizing riparian forest protection.

Overall, our analysis shows that implementing the minimum provisions of Forest Law 7575 in hotspot cantons would not lead to an inequitable distribution of ecosystem service benefits between vulnerable and non-vulnerable populations (Fig. 6) (For a more detailed exploration of beneficiaries and equity, also see Table A.6 for a full list of demographic data and ecosystem services data for each canton; and Fig A.4 & Appendix C Section 4.1 for maps and discussion of baseline pollutant export and river-dependent population, which highlights areas

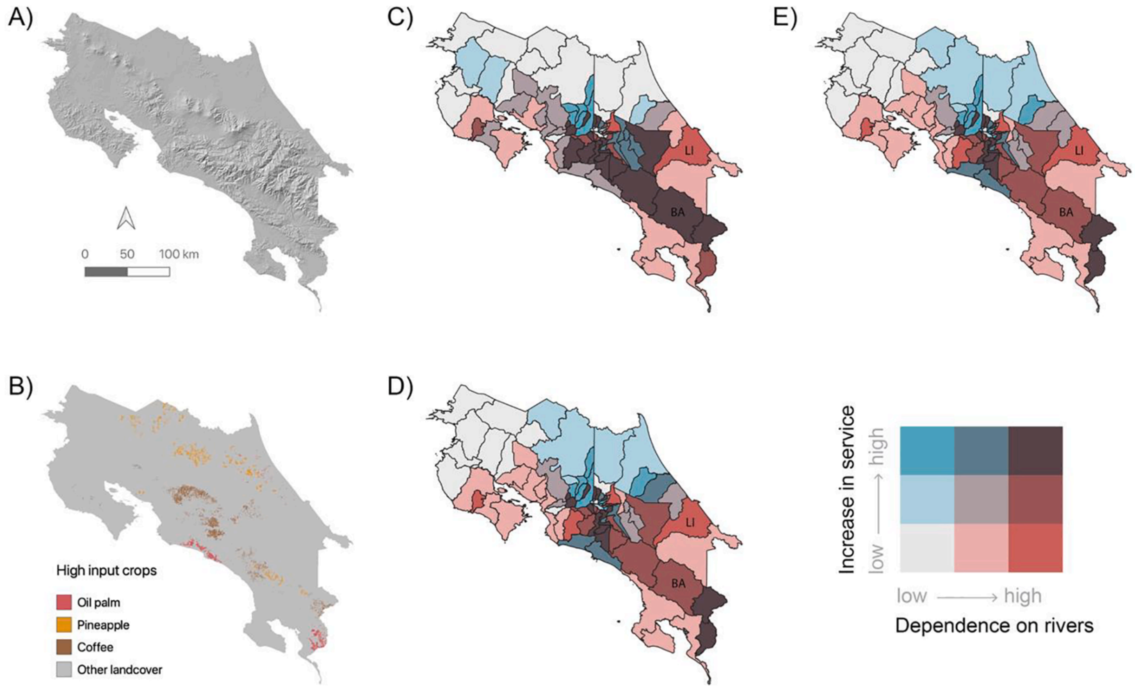

Fig. 5. Elevation, land cover, ecosystem services increases, and beneficiaries mapped across cantons in Costa Rica. A) A topographic map of Costa Rica, along with B) a map of the most intensively-fertilized crops can predict which regions of the country will see the highest increases in sediment and nutrient retention, respectively. Increases in hydrological services with reforestation—C) sediment retention, D) N retention, and E) P retention—in each canton in Costa Rica are mapped along with the number of people dependent on rivers for drinking water. All values are normalized by canton area. Increases in services are plotted in blue, and people dependent on rivers in red, and values have been binned into terciles (lightest color = 0–33.33 %, medium color = 33.33–66.66 %, darkest color = 66.66 %-100 %). Dark purple "hotspot" cantons represent those with the highest need for good water quality where reforestation has the highest potential to increase water quality. Case study cantons have been marked on C), D), and E), BA = Buenos Aires, LI = Limón. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

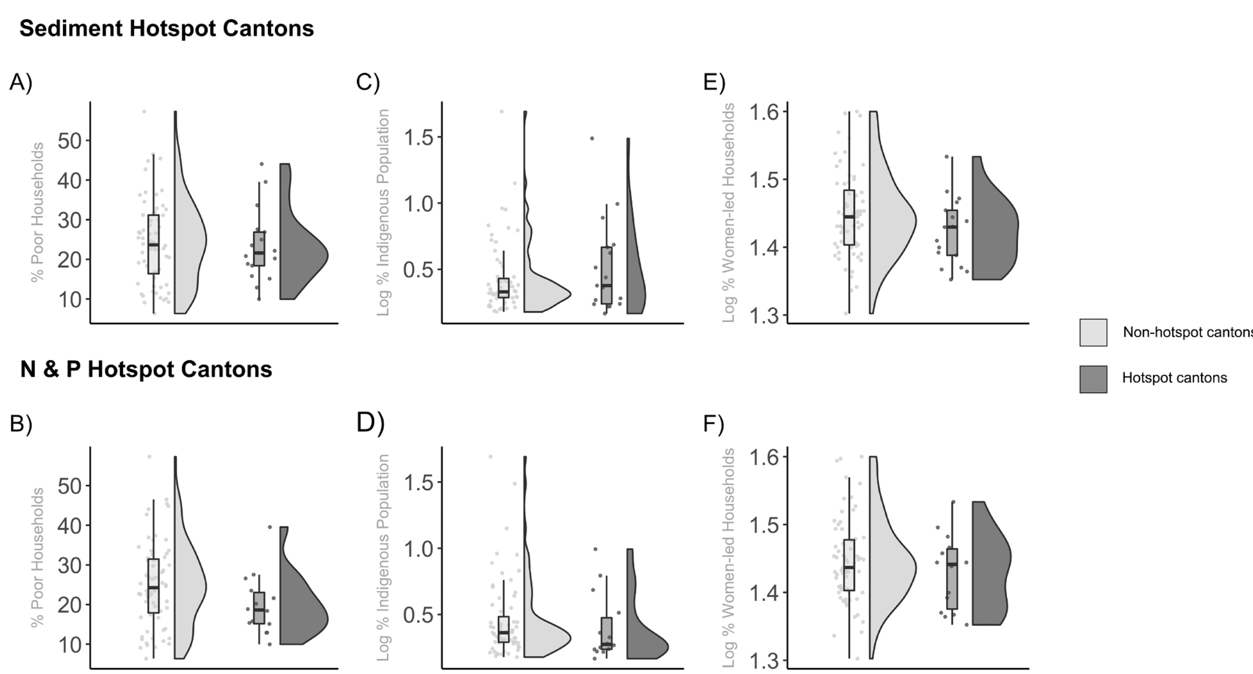

Fig. 6. Reforesting hotspot cantons would not disproportionately confer ecosystem services benefits to vulnerable populations, but would also not leave them out. We compare distributions of A-B) percent poor households, C-D) percent Indigenous population, and E-F) percent women-led households between hotspot cantons (in purple) and non-hotspot cantons (in gray), where hotspot cantons are based on increased sediment retention with reforestation and high demand for water quality (top row; A, C, E) or increased nutrient retention with reforestation and high demand for water quality (bottom row; B, D, F). Distributions of all three vulnerable groups overlap between hotspot cantons and non-hotspot cantons, showing that there are not more vulnerable populations in hotspot as opposed to non-hotspot cantons.

where riparian forests are currently playing an important role and should be conserved). Reforesting hotspot cantons would not disproportionately confer water quality benefits to vulnerable populations, but would also not disproportionately exclude them. Distributions of the percent poor households, Indigenous population, and women-led households between hotspot cantons and all other cantons were very similar. However, some individual hotspot cantons had very high percentages of vulnerable populations. Policymakers could pinpoint restoration efforts in these cantons to deliver ecosystem service benefits to the most vulnerable.

To explore further how vulnerable populations could be impacted by prioritizing hotspot cantons for reforestation, we present two case studies. These case studies are not the cantons with the highest increase in ecosystem services with reforestation; rather they illustrate how all the above analyses could be combined to guide reforestation and conservation policies.

Buenos Aires is a rural canton in southern Costa Rica, with the Talamanca Mountains running through its northern edge. The canton is primarily a mosaic of pasture and forest with some farming. A quarter of its population (some 11,600 people) depends directly on rivers for drinking water. It is also home to a large number of Indigenous people (30 % of the population) and poor households (44 % lie below the poverty line). Buenos Aires has a high baseline level of sediment and a medium level of nutrient export per area. Our analysis indicates that full implementation Forest Law 7575 would lead to a large increase in sediment retention and a medium increase in nutrient retention per area. Reforesting around rivers would not only increase ecosystem services, but would also deliver those increased services to especially vulnerable populations.

Limón runs from the forested La Amistad International Peace Park down to the lowlands of the Caribbean coast, where it transitions to pasture and farmland. Ten percent of its population (some 9,300 people, on par with the population per area of Buenos Aires even though it is a smaller percentage) depend directly on rivers for drinking water, and it has high levels of vulnerability—30 % of households lie below the poverty line, 32 % are women-led, and the population is 8 % Indigenous. The canton is projected to see a very low increase in water quality with reforestation because it has very low baseline levels of pollutant export and most of it is already forested—only 0.5 % of the canton's total area would have to be reforested to meet the provisions of the Forest Law. Thus, Limón is an example where maintaining existing forest along streams, rather than restoring them, would be effective.

3.4.1. Indigenous territories

Indigenous territories have low potential increases in ecosystem services with reforestation compared to the rest of Costa Rica, but also much higher riparian forest cover and baseline water quality (See Table A.7 and Figs. A.5–7 for service levels and baseline pollutant export in Indigenous territories; for more detailed results, see Appendix C Section 4.3). Indigenous territories have particularly low baseline levels of N and P and low potential for increases in N and P retention. Only one territory is an exception: Reserva Indígena Ngäbe-Buglé de Altos de San Antonio has baseline N export per kilometer that is about 30 % higher than the national average and P export per kilometer that is more than twice the nationwide average. Reforesting in this territory could provide large advantages.

3.4.2. Improving beneficiaries analyses

Taking beneficiaries into account is critical in prioritizing restoration efforts. Availability of spatially disaggregated demographic data is rapidly improving (Rasolofoson et al. 2018), so future work could replicate this approach at a finer resolution, identifying more precise locations to prioritize restoration based on water usage by vulnerable populations within cantons. Investigating the intersection between the demand for and increase in ecosystem services with restoration has been identified as a key component of conservation (Chazdon et al. 2017), and if a goal of restoration is improving people's quality of life, it is crucial to explicitly take people into account. In addition, when considering justice in reforestation efforts, it is also important to ensure that vulnerable populations are not the ones bearing the cost of reforestation on their land.

3.5. Policy implications

In this study, we model the impacts of reforestation to match the provisions of Costa Rican Forest Law 7575 to achieve two goals: 1. To outline a set of methods that can be used in policy-relevant scenario evaluation across contexts and 2. To provide relevant data to support decision-making and prioritization around riparian reforestation in Costa Rica, under consideration of multiple ecosystem services and their respective beneficiaries. In this section, we discuss the implications of implementing riparian reforestation in the Costa Rican context: the benefits of increasing ecosystem services in Costa Rica, the potential challenges and costs of reforestation on the ground, and what policy mechanisms could be leveraged to achieve reforestation.

3.5.1. Benefits of increasing ecosystem services in Costa Rica

Increasing water quality in Costa Rica is a high priority for human health, hydropower, and aquatic biodiversity. Increasing sediment and nutrient retention is not the same as increasing surface drinking water quality; however, sediment and nutrients in the water both decrease surface drinking water quality. Although Costa Rican surface water law may provide information about chemical analyses necessary to determine drinking water quality, 6.5 % of the population still lacked access to potable water in 2020 (Mora Alvarado and Portuguez 2021), and in some cantons as few as 10 % of people have access (Instituto Nacional de Estadística y Censos, 2011). While the quality of most water sources in Costa Rica are monitored, some of them do not receive rigorous treatment (Instituto Costarricense de Acueductos y Alcantarillados 2016, Mora Alvarado and Portuguez 2021). Recent studies have shown that some areas still draw their water directly from streams that do not meet water quality standards (Mena-Rivera and Quirós-Vega 2018). In addition, Costa Rican water infrastructure is particularly vulnerable to hurricanes and earthquakes (Bower 2014, Instituto Costarricense de Acueductos y Alcantarillados 2016), and as recently as 2020 120,000 people lost access to water service for several days after Tropical Storm Eta and Hurricane Iota (Programa Estado de la Nación 2021). These natural disasters force people to temporarily rely on other water sources, including streams (Instituto Costarricense de Acueductos y Alcantarillados 2016). Finally, even for people who do not draw their water directly from streams, surface water quality may be linked to drinking water quality. This can happen in two ways. Firstly, some water services draw their water directly from untreated surface water (Avila 2019), although this is technically illegal: a 2020 survey of sources found that 7 % of them were surface water (Mora Alvarado and Portuguez 2021). Secondly, infiltration links surface and groundwater, and contamination in rivers can spread to the aquifers that most of the country relies on (Shahady and Boniface 2018). Thus, while the small fraction of people who still get water directly from rivers are vulnerable to contamination by sediment and nutrients, it also remains a concern for others who rely on untreated or under-treated surface water directly, and those who rely on untreated or under-treated groundwater.

Improving surface water quality could therefore have a larger impact on drinking water quality in the country than what we are able to quantify by measuring river-dependent population. Surface water quality in Costa Rica is known to be poor, polluted by sewage, industrial chemicals, and agrochemicals (Bower 2014), and some rivers have been found to have very high levels of N and P (Mena-Rivera et al. 2018). Nitrates, in particular, can pose serious human health concerns when present in drinking water (Ward et al. 2018). While typical water treatment methods remove sediment, they do not remove nitrates, which are especially susceptible to leaching into groundwater due to their high solubility (Rezvani et al. 2019). This is a special concern in Costa Rica, which in 2018 was one of the top 10 countries in the world for *N*-based fertilizer application per area of arable land (FAO 2020). The influx of nutrients into aquatic ecosystems has devastating consequences for vulnerable freshwater biodiversity (Dudgeon et al. 2006, Vörösmarty et al. 2010, Ardón et al. 2021). Preventing excess sediment export to dams is also important for securing the efficacy of Costa Rica's hydropower facilities, which account for over half of its energy supply (Ministerio de Ambiente y Energía 2015), because excess sedimentation can reduce storage volumes and damage equipment (Morris and Fan 1998).

Riparian reforestation could be a key strategy to help Costa Rica meet carbon neutrality and sequestration goals, especially if reforestation efforts are tailored to increase the amount of carbon stored. Even if carbon sequestered per area is not higher in riparian than non-riparian forest, carbon per money invested in restoration could be. River banks provide a naturally moist habitat, making irrigation unnecessary for tree seedlings and thus potentially reducing the cost of reforestation.

Although we explore the effects of forest restoration on sediment and nutrient retention and carbon sequestration only, reforestation may have other benefits. Riparian buffers may aid in reducing bacteria from sewage and manure in rivers (Wenger 1999, Collins 2005). Only 16 % of sewage in Costa Rica receives treatment; consequently, sewage pollution is the country's top water quality issue and a huge policy priority (Gobierno de Costa Rica, 2020a). Riparian buffers can also prevent pesticides from reaching rivers (Wenger 1999), a key concern in Costa Rica, which had the highest average annual pesticide use per area of cropland of any country in the world from 2008 to 2018 (FAO 2018). Reforesting could benefit terrestrial and aquatic biodiversity via both adding habitat and increasing landscape connectivity (Lorion and Kennedy, 2009a, 2009b; Krosby et al., 2018).

3.5.2. *Achieving reforestation on the ground*

To achieve reforestation on the ground it is important to combine top-down approaches, such as policies and incentive programs, with bottom-up approaches that center on local communities, like education and participatory restoration (Hagger et al. 2017, Holl 2017, Bonilla Villalobos 2018, Meli et al. 2019). Landowner values around trees and restoration, which have been extensively studied in Costa Rica (Albertin and Nair 2004, Solano 2017, Sibelet et al. 2017, Leary et al. 2021), should be taken into account to envision restoration projects that benefit local people. However, many Costa Rican landowners perceive there to be a tradeoff between restoration and agricultural production and their livelihoods. Although they may be interested in increasing tree cover, smallholder farmers feel they cannot afford the foregone income from not farming or raising cattle on their land (Solano 2017, Vignola et al. 2017, Cascante 2018, Leary et al. 2021). In regards to Articles 33 and 34 of the Forest Law 7575 in particular, farmers believe the amount of land they are required to give up from production to be economically unjust (Vignola et al. 2017, Sibelet et al. 2017).

Our analysis has shown that pasture composes the majority of the land that would need to be reforested to create 10 m forest buffers. Riparian reforestation on pasture land incurs costs to individual farmers—fencing materials to keep out livestock, construction of alternative watering sources, lost grazing land, and obtaining trees and labor (Platts and Wagstaff 1984, Daigneault et al. 2017, Kilgarriff et al. 2020). These costs are borne by individuals, while the water quality benefits of reforestation accrue to downstream users, and the carbon sequestration benefits to the global community. However, studies on riparian fencing in pastureland have demonstrated benefits to herd owners, including increased beef cow weight and dairy cow production, decreased animal disease, and improved herd management (Zeckoski et al. 2007). For the smaller percentage of riparian buffer land that is currently in crop production, reforesting that land may present greater costs even than giving up other land as alluvial soils deposited by rivers are highly fertile (Boettinger 2005).

Costa Rican case studies suggest that a combination of financial incentives, such as the country's Payments for Ecosystem Services (PES) program or cost-sharing programs, and supporting existing values could be most effective in motivating landowners to conserve despite their concerns (Louman et al. 2016, Sibelet et al. 2017, Leary et al. 2021). In the case of reforesting cattle pasture, it may be more important for the government to pay for fencing and costs of physical reforestation than the smaller opportunity cost of lost forage, especially given the potential benefits to herds. Regardless of the underlying land use, financial incentives should offset opportunity costs of reforesting land, particularly for small-scale, economically vulnerable farmers who are least able to give up land for cultivation or pay the costs of reforestation.

3.5.3. *Policy mechanisms*

Legal mechanisms that specifically mandate reforestation of the areas protected by Forest Law 7575 could be instrumental in increasing riparian buffers. Articles 33 and 34 of Forest Law 7575 only mandate forest protection within riparian buffers and not reforestation (*Ley* Forestal 1996), although Water Law 276 Article 148 mandates waterways be reforested to at least 5 m on either side (*Ley* de Aguas 1942).

Many extant policy measures in Costa Rica could support riparian buffer reforestation. Costa Rica has stated intentions to reduce annual emissions to zero by 2050, with an intermediate goal of capping emissions from 2021 to 2030 at 106.5 Mt CO_2e (Gobierno de Costa Rica, 2020b). Our models estimate that reforesting around rivers would sequester around 25.9 Mt of CO_2e, about a quarter of this goal. Meanwhile, Costa Rica's National Decarbonization Plan includes the goal of increasing nationwide forest cover to 60 %, from the current level of just above 50 %, by 2030 (Ministerio de Ambiente y Energía, 2019). Of that 10 % of land area dedicated to reforestation, dedicating 1 % to the riparian buffers we identify would achieve outsized benefits. The country also has policy goals focused on riparian reforestation—for example, the Estrategia Nacional para la Recuperación de Cuencas Urbanas, which aims to restore urban creeks and address problems stemming from sewage pollution (Gobierno de Costa Rica, 2020a). Costa Rica's well-developed PES program (*Ley* Forestal 1996, Daniels et al. 2010) could be a key mechanism for financing restoration projects, especially if PES-funded riparian reforestation could address the common challenges for PES programs that especially affect the rural poor, such as unclear ownership of land (Lansing 2014) and the inability of payments to compete with monetary returns from intensive agriculture (Meneses 2010).

4. Conclusions

Our analyses show that riparian reforestation in Costa Rica would lead to large ecosystem service benefits. As we enter the Decade of Ecosystem Restoration, countries must seek restoration opportunities that can stem our ongoing biodiversity and climate crises without resulting in too great of an impediment to productive lands. Riparian buffers present an outstanding opportunity to increase biodiversity and ecosystem services with a relative small change in productive land, and should be at the forefront of our efforts (Naiman et al. 1993). Conservation and restoration of riparian forests will play a major role in maintaining biodiversity in fragmented tropical landscapes, where they serve as corridors connecting forest patches (Luke et al. 2019). Although riparian reforestation does come with costs to individual landowners, careful implementation of incentive systems aimed especially at the most vulnerable could offset costs to the most cost-sensitive individuals and provide ecosystem services benefits to the larger community. Already, people are envisioning bold reforestation plans in Costa Rica, where restored riparian corridors could provide socio-ecological resilience in the face of climate change (Townsend and Masters 2015). These results have implications beyond Costa Rica—countries across the world should consider riparian restoration, and can implement similar policy-relevant models to design restoration plans that incorporate multiple ecosystem services. The novel methods that we introduce here can be replicated in other locations to design relevant scenarios and perform location-specific modeling. Through reforesting rivers, we can safeguard the health of ecosystems and the people that live in them.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Code is available on Github (https://github.com/kelley-langhans/CostaRica-river-reforestation) and all data (including InVEST modeling inputs and outputs, beneficiaries analysis, other post-modeling analyses) are available on OSF (https://osf.io/srjwx/).

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Appendices A, B and C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2022.101470.

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