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Environmental Impact Bonds: a common framework and looking ahead

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Abstract

A frequent barrier to addressing some of our world's most pressing environmental challenges is a lack of funding. Currently, environmental project funding largely comes from philanthropic and public sources, but this does not meet current needs. Increased coordination and collaboration between multiple levels and sectors of government, in addition to private sector funding, can help address the environmental funding challenge. New financial tools and strategies can enable this transition and facilitate uptake of innovative solutions. One such mechanism, the Environmental Impact Bond (EIB), is an emerging financial tool with the potential to transform the environmental funding landscape. However, these financial instruments are not well understood or recognized beyond those actively involved in EIB projects or in the field of conservation finance. As EIBs gain momentum, there is a clear need for a common framework, including definitions and nomenclature, research needs, and outlook for the future. In this paper, we define EIB mechanics, elucidate the difference between EIBs and Green Bonds, and propose a common vocabulary for the field. Drawing on first-hand experience with the few EIBs which have been deployed, we review and assess lessons learned, trends, and paths for the future. Finally, we propose a set of future targets and discuss research goals for the field to unify around. Through this work, we identify a concrete set of research gaps and objectives, providing evidence for EIBs as one important tool in the environmental finance toolbox.

1. Introduction

While many obstacles impede solving our greatest environmental challenges, perhaps the greatest barrier is a lack of funding. Contemporary estimates suggest that globally, $722 to $967 billion is needed annually for environmental conservation alone, but this need is not met by the current allocation of $124 billion a year (Deutz *et al* 2020), which largely comes from government and philanthropic sources (Hamrick 2016). This unmet demand is unlikely to be filled only through increases in traditional public and philanthropic capital deployments, necessitating new approaches to environmental project finance and implementation. Plus, the structure in which these funds are deployed, through competitive applications and reimbursable grants, presents challenges of future funding uncertainty and can delay work on the ground.

The environmental funding challenge is exacerbated by a series of governance constraints (Hess *et al* 2016, Chazdon *et al* 2017, Cousins 2018). First, environmental resources are considered shared goods. They seldom fall within political boundaries, which can result in their over-use by multiple independent parties who act entirely within self-interest (Hardin 1968, Ostrom 2009). Correspondingly, environmental problems are dispersed over a disparate set of geographical and political boundaries, resulting in the lack of a clear single financial and/or government entity to take the lead on raising funds and implementing a project, even when there are clear net benefits (Dallimer and Strange 2015, Lonsdorf *et al* 2020, Keenan *et al* 2019).

In addition, individual agencies, landowners, or interest groups are unlikely to have the available capital to perform large scale conservation projects needed to produce tangible changes. Many environmental systems exhibit substantial threshold effects, i.e., meaningful benefits are only realized with a change of significant magnitude (Groffman *et al* 2006). For example, if a system is at great risk of wildfire, thinning in one small part of the fireshed has minimal impact on reducing wildfire risk (North *et al* 2012). However, because of the environmental funding deficit, restoration, natural infrastructure, and conservation projects are not being implemented at the scale required to generate substantial environmental change, despite many studies showing the opportunities and benefits of doing so (Deutz *et al* 2020, Strassburg *et al* 2020). Addressing these challenges through new financing approaches has the potential to flip the current planning paradigm such that money is not the limiting factor in achieving environmental management goals.

There is an opportunity to turn environmental funding shortfalls into financing opportunities. While often conflated, there is a distinct difference between funding and financing (Keenan *et al* 2019)—funding is the actual money that is used for the stated purpose, whereas financing is the process of setting up a financial relationship between counterparties for some stated purpose. Novel financial tools, which simultaneously tap new funding sources while using financing principles to overcome cash-flow issues, offer a set of solutions that may increase capital flows into environmental protection and restoration while ensuring that project capital requirements are addressed. A simple example of project financing would be where entities who are receiving flood risk reduction benefits from shared infrastructure pay premiums through cost sharing. Financial vehicles can attract outside investors, whose investments are repaid by those implementing and benefitting from the project. This structure allows for flexible repayment (mitigating the need to have all the capital upfront from implementers), integrates cost-sharing opportunities, and includes non-conventional parties to expand the funding available for a project.

In the environmental sector, conservation finance has emerged as a powerful approach to deploy private capital for environmental projects (Meyers *et al* 2020). Conservation finance is defined by the Conservation Finance Alliance as the 'mechanisms and strategies that generate, manage, and deploy financial resources and align incentives to achieve nature conservation outcomes' (Meyers *et al* 2020, p 10). Private investors are increasingly interested in conservation finance opportunities. A 2016 worldwide survey of corporations, banks, philanthropies, NGO's and governmental organizations estimated that there were over $3.1 billion earmarked for conservation but undeployed due to a lack of market-rate, investment ready opportunities (Hamrick 2016). Despite this significant demand, there are few investable projects, resulting in a significant market mismatch. New investment vehicles are needed to increase supply of projects for investment opportunities. Simultaneously, these developments would train a new set of environmental financial product managers to establish a proven track record (Hamrick 2016).

To enable the engagement of private parties and novel financing instruments, the risk and return expectations, long term cash flows, and financial risk mitigation strategies need to be well understood. The transition of institutional investment into conservation opportunities has thus far been hampered by the following barriers, many of which apply to project implementation across the environmental sector:

(a) The absence of benchmarks to evaluate project success and investment return (Huwyler *et al* 2016)

(b) Lack of project development, managerial track record, and previous success with which to model future work (Huwyler *et al* 2016)

(c) The unpredictability of the underlying cash flow, and ability to connect risk to an adequate return (Brandstetter and Lehner 2018)
(d) Lack of large-scale projects which increase capital allocation (Hamrick 2016)
(e) Limited environmental-financial modeling research to inform development (Adriaens and Ajami 2021)
(f) Difficulties in establishing cause and effect relationships between projects and measuring improved environmental outcomes (Hone *et al* 2017)
(g) Benefits are often broadly enjoyed, but paid for by just a few beneficiaries (Hardin and Cullity 2020).

To overcome these barriers, multiple types of public–private partnership financing vehicles have been developed (Allen and Yago 2011). A fundamental aspect of many conservation finance mechanisms is that they can be integrated with new governance structures, for example collaborative decision-making or inclusion of new payors, thereby enabling innovative solutions to be developed (Hebb and Sharma 2014, Quesnel *et al* 2017). In this paper, we focus on one specific mechanism, Environmental Impact Bonds (EIBs).

2. Defining EIBs and state of the art

2.1. Impact investment through Environmental Impact Bonds

EIBs are a financing mechanism to raise capital for environmental projects which repay the principal and interest using financial benefits stemming from the environmental benefits of a project. EIBs are structured similarly to traditional bonds where principal is borrowed by stakeholders/beneficiaries with the promise of repayment to investors, with interest, over time. However, the main difference between EIBs and traditional bonds is that traditional bonds are often repaid with general revenues from the issuer, not necessarily related to the financing activity, whereas EIBs specifically tie financial return on investment to the success of the intervention and revenue generated and/or cost savings related to that success (Nicola 2013, Hall *et al* 2017). Sometimes, this financial model is referred to as 'outcomes-based financing,' a concept that originated in the social services sector with Social Impact Bonds.

EIBs address the critical environmental funding gap by (1) providing one financial vehicle for multiple stakeholders/beneficiaries to rally around and serve as an unbiased intermediary; (2) allowing stakeholders and beneficiaries to quickly raise large volumes of up-front capital to realize more immediate environmental benefits; and (3) providing an opportunity to aggregate projects and/or funds.

EIBs are often compared to Green Bonds given their similar nomenclature and both can be core Environmental, Social, and Corporate Governance (ESG) investments (Saha and d'Almeida 2017, Hyun *et al* 2019). Green Bonds are traditional fixed-income products for which the proceeds are earmarked specifically for projects that focus on environmental sustainability or combating climate change. Conversely, EIBs are based on the principle that repayment is indexed to forecasted and/or realized environmental benefits of which financial cash flow stems from. If payment is based on realized measured benefits, the EIB is pay-for-performance. Indeed, a distinct difference between EIBs and Green Bonds is the direct linkage of environmental to financial benefits in EIB projects whereas Green Bonds fund a project based on planned actions.

The first Green Bond was issued in 2008 through a Swedish pension fund, and since then the market has grown to a cumulative issuance of $269.5 billion in 2020 (Taylor 2021). While only three EIBs have been issued to date (cumulatively worth $43 million), many EIBs are currently proposed, with at least five projects under development [at the time of writing, table S1 (https://stacks.iop.org/ERIS/1/023001/mmedia)]. These proposed projects are cumulatively worth almost $100 million USD, and all projects are listed and described in the supplemental information T1 and table S1. While it is difficult to make a direct comparison between Green Bonds and EIBs, the growth of Green Bonds in recent years shows there is significant investor appetite for environmentally focused ESG focused investments.

While various features of EIBs have attracted considerable attention, including the use of pay-for-performance repayment mechanisms, the fact that EIBs may help finance interventions that not only produce positive environmental outcomes but make economic sense (independent of any environmental benefits) has attracted less attention. There are many systems in which short-term management interventions are likely to generate substantial long-term cost savings that are not currently being financed, either because the governmental agencies responsible for such interventions do not have the budget (or political capital) available or because the interventions are novel or untested. By bringing in private, return-seeking risk capital that may not have to be repaid unless the expected future cost savings are realized, EIBs may open up a substantial new source of capital for important environmental expenditures. As long as these expected cost savings are identifiable, ascertainable, and quantifiable and the need to incur those costs is inescapable, then a prima facie case for using private capital to finance these short-term interventions exists if public financing is unavailable. In this way, EIBs may create the incentives needed for public agencies and private investors to identify

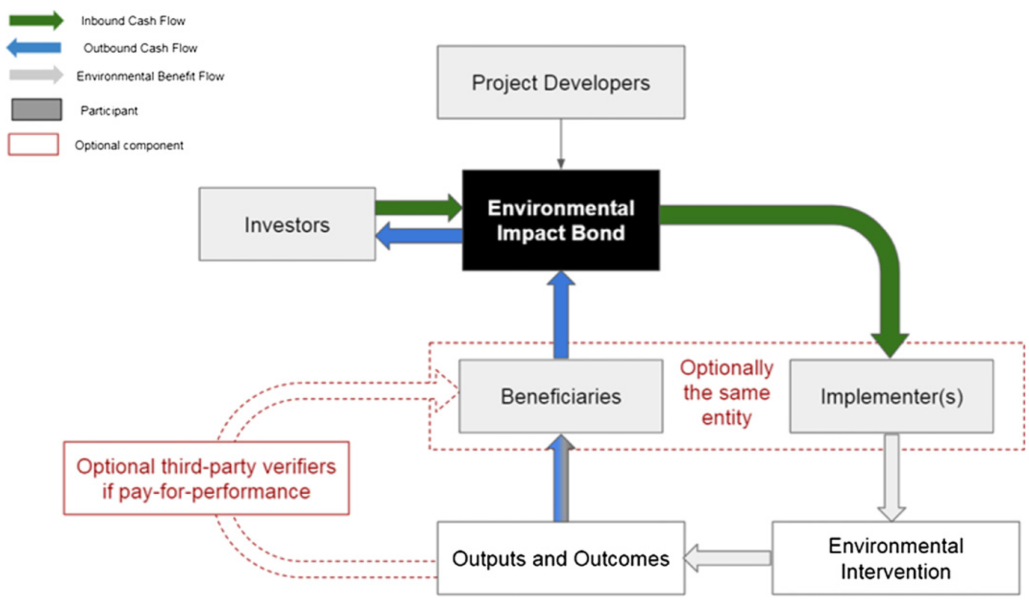

Figure 1. Overview of EIB structure, including cash flow (blue and green arrows) and environmental benefits (gray arrows). The EIB is designed by project developers, and implemented by stakeholders and others to fund restoration activities that yield quantifiable environmental benefits. These environmental benefits are converted by the beneficiaries into financial benefits that influence the return on investment.

overlooked systems in which short-term interventions may generate both substantial long-term costs savings and environmental returns.

A central goal of this paper is to propose a standardized set of vocabulary for EIBs to create a more consistent description. We adopt the term EIB to describe a variety of environmentally focused financial instruments, specifically any financial instrument (bond, loan, or pay-for-performance contract) that funds a project which generates environmental and financial benefits and is repaid based on performance, forecasted and/or realized cost savings or other financial benefits. Having a common language for EIB academics and practitioners reduces potential confusion both within and outside the field and represents an important first step for EIBs to mature into an established investment. A second goal of this paper is to propose a set of expanding (in need of a wider viewpoint) and refining (in need of further focus) research questions to further develop the field for widespread use.

2.2. EIB mechanics

EIBs function in the following manner: investors provide the upfront capital to a project-specific (or aggregation of projects) financial vehicle (figure 1). These up-front funds are then passed to the project implementer responsible for carrying out the work on the ground, which can optionally also be the entity benefitting from the project. As the environmental intervention leads to specific outcomes and outputs, a consortium of public and/or private entities benefitting from the project repay the cost of the project, plus interest, to the EIB (the financial vehicle) which is then sent to the investors. The interest rate can be predetermined, or performance based as various environmental benefits are realized for the project beneficiaries. Aggregation of public and private entities can be facilitated by a project developer who develops the contracts and terms of repayment for each entity.

A cornerstone feature of EIBs is that they are repaid by beneficiaries of the project outputs and outcomes. Two value streams for these beneficiaries are cost savings and financial benefits, many of which are linked to ecosystem services associated with natural infrastructure.

Cost savings can be either: (1) reduced costs, for example, reductions in sediment generation (Gudino-Elizondo *et al* 2019) or riverine trash flows and downstream cleanup (Brand *et al* 2020); or (2) more efficient ways to fulfill regulatory obligations, for example meeting total maximum daily load requirements for surface water discharge (Davidsen *et al* 2015, Wolfand *et al* 2018), habitat requirements for hydropower generators (Jager and Smith 2008), environmental baseflow challenges (Yarnell *et al* 2015, Poff 2018), or carbon offsets (Van Kooten *et al* 2009). Beneficiaries contribute to the project based on money saved by not paying fines for not meeting their regulatory goals or by not having to continue or pursue more expensive projects alone.

Financial benefits encapsulate all other positive outcomes, including (1) reduced expected losses, for example, reducing losses from wildfires through forest restoration, (Fried *et al* 1999, Thompson *et al* 2013), or reducing flooding through expanded green space (Narayan *et al* 2017); or (2) enhanced revenue, for example

Table 1. Mathematical definitions of EIB elements adapted from Brand *et al* (2020).

Term	Symbol or equation	Notes
Cost savings: contemporaneous	$F^{(1)}(x) = C_0(x) - C_1(x)$	$C_0(x)$ is the management cost post-intervention using the pre-intervention financial-environmental conditions (estimated through model runs), $C_1(x)$ is the measured cost post-intervention
Cost savings: mean	$F^{(2)}(x) = n\overline{C}_0(x) - C_1(x)$	$\overline{C}_0(x)$ is the average management cost pre-intervention (calculated from historical data), $C_1(x)$ is the measured cost post-intervention and n is the issue length of the bond
Intervention cost	C_{int}	Cost of the intervention, which becomes the EIB principal
Cost savings PDF	f	Probability distribution function of future cost savings over time frame n, where n is the issue length of the bond
Cost savings CDF	F	Cumulative distribution function of future cost savings over time-frame n, where n is the issue length of the bond. Mathematically defined as $F_{\Delta C}(x) = \int_{-\text{inf}}^{x} f_{\Delta C}(u)\,\text{d}u$
Probability of underperformance	$P_{\text{u}} = F(C_{\text{int}})$	Estimated likelihood that the EIB outcomes generate less than cost of the intervention
Probability of overperformance	$P_{\text{o}} = 1 - F(C_{\text{int}})$	Estimated likelihood that the EIB outcomes generate an excess of cost savings or revenue generation from interventions
Environmental risk premium	Risk premium $= P_{\text{u}} \times$ principal	Amount paid on the condition that cost savings, enhanced revenue, and/or regulatory compliance savings are generated for stakeholders. Interpreted as the expected loss multiplied by the probability of occurrence
Environmental interest rate	a. $i_{\text{env}} = (1 + P_{\text{u}})^{(1/n)} - 1$ b. $i_{\text{env}} = (1 + F(C_{\text{int}}))^{(1/n)} - 1$	a. Function of probability of underperformance b. Function of intervention cost (C_{int}) and the cdf of cost savings. Interpreted as the cost of financing for beneficiaries to reward investors for taking on additional risks

from improved recreation opportunities (Quantified Ventures 2020), improvements in property values from urban greening (Bolitzer and Netusil 2000, Crompton 2001), enhanced streamflow from forest restoration (Saksa *et al* 2017), or trading of carbon or nutrient credits (Letsinger 2020). Beneficiaries can then use a portion (or all) of that additional revenue to pay back project costs.

Once environmental outcomes have been identified and projected, the financial benefits and a corresponding cash flow of the outcomes (cost savings, other financial benefits, or both) can be calculated using Monte Carlo or Monte Carlo Markov Chain modeling (Brand *et al* 2020). This analysis can develop a projection of benefits from the project (and the difference between the counterfactual world where the project was not completed) and be used by beneficiaries to support repayment of some portion of benefits to investors to provide an investment return. Additionally, the stochastic nature of the modeling analysis can be used to determine risk that the accumulated benefits cannot repay the EIB investors (Brand *et al* 2020, D.C. Water 2016).

2.3. EIB elements

The following section provides qualitative descriptions of the proposed EIB vocabulary, with the associated quantitative mathematical descriptions outlined in table 1.

2.3.1. Environmental Impact Bond (EIB)

A financial instrument issued by stakeholders or a third party whereby investors provide capital for environmental interventions that is repaid with interest by beneficiaries who experience reductions in management costs (savings) or enhanced revenue streams (Geobey *et al* 2012). Can be structured as either a bond or a loan, with either regular payments (as a coupon or otherwise) or sold at a discount to its face value, which is paid upon maturity.

2.3.2. Participants

Investors—interested parties who invest in environmental projects and are seeking to be repaid the original investment with interest. Parties can be both traditional investors looking primarily for financial outcomes and/or investors focused primarily on environmental outcomes. Returns can be both market rate and/or below market rate depending on investor appetite and environmental benefits accrued.

Paying beneficiaries—an entity who receives benefits from the project enabled by the EIB and repays EIB principal and interest as those benefits accrue. An example of a beneficiary could be a property owner whose flood risk is reduced by environmental benefits, and repays the EIB using that benefit. EIBs can have one or multiple paying beneficiaries.

Project developers—consultants, researchers, or academics who perform the enviro-financial modeling needed to develop estimates of environmental benefits and structure EIB repayment. This category also includes the non-profits and private companies that structure the deals and administer the contracts.

Implementers—groups implementing the environmental interventions on the ground. Could be the beneficiary or landowner themselves, but could also be a nonprofit, tribal, or local government partner.

2.3.3. Environmental benefits

Cost savings—principal and interest of the bond are paid using environmental management cost savings resulting from work performed using EIB principal. Savings for beneficiaries come in the form of reduced management costs due to regulatory compliance and/or reduced management needs. Contemporaneous cost savings are defined as the difference between the two cumulative cost distribution functions (CDFs, F) over the EIB duration (table 1), which requires model reruns post EIB/interventions to estimate what costs would be without the intervention. The advantage of this method is that it controls for environmental conditions between pre- and post-intervention periods. There are two potential downsides: (1) it relies on the accuracy of the model's prediction of what costs would be without the intervention and (2) model runs could be expensive to re-run, depending on the project.

Conversely, mean cost savings estimate the difference between average costs incurred before and actual costs after the project was implemented (table 1). This approach benefits from ease of use, as there is no requirement for potentially expensive model reruns after interventions are implemented. The downside to this approach is that there may be confounding variables that influence the management costs and therefore make the difference between average costs incurred before and actual costs after the project was implemented not representative of the actual benefits delivered by the project itself.

Other financial benefits—other financial benefits which accrue to beneficiaries. Examples include increased profits from tourism, greater tax revenue, and increased revenues for hydropower generators due to enhanced riverine flows.

2.3.4. Repayment structure

Variable environmental benefit repayment—repayment of the EIB occurs as environmental benefits are realized according to the pay-for-performance structure outlined in the contract by market participants.

Fixed environmental benefit repayment—repayment of the EIB occurs on a regular, fixed schedule with payment pre-defined according to expected environmental benefits.

Mixed environmental benefit repayment—the EIB is repaid with a mixture of both fixed and variable environmental benefits. For example, the principal of the EIB could be repaid using a by assuming a fixed environmental benefit source such as carbon sequestration or recreation-based tax revenue, while the interest of the EIB could be repaid using variable environmental benefits. The principal and interest could also be fixed payments with an additional pay-for-performance bonus or clawback.

2.3.5. Quantifying risk and success

Probability of underperformance—estimated likelihood that the EIB outcomes will lead to financial benefits realized by beneficiaries which are unable to pay back the bond principal and/or interest from the environmental benefits of the interventions.

Probability of overperformance—estimated likelihood that the EIB outcomes generate an excess of cost savings or revenue generation from interventions.

Environmental risk premium—amount paid on the condition that cost savings, enhanced revenue, and/or regulatory compliance savings are generated for stakeholders. Interpreted as the expected loss multiplied by the probability of occurrence.

Environmental interest rate—used in interpreting the cost of financing an EIB.

2.4. Funded EIBs through the lens of the proposed definitions

2.4.1. D.C. Water Bond (2016)

The D.C. Water Bond was the first issued EIB (table 2). The bond was used to pay for green stormwater infrastructure in the Washington D.C. area, with the goal of reducing the volume and frequency of stormwater flows into the region's combined sanitary sewer system, thereby reducing sewer overflows that send raw sewage into the Potomac River and downstream to the Chesapeake Bay. Cost savings associated with reducing the flow of

Table 2. Current EIBs.

Name	Issue year	Principal (10^6 USD $)	Location	Project developer	Paying beneficiaries	Environmental focus	Interest rate and repayment structure	Issue length (years)
D.C. Water bond	2016	25	Washington, D.C	Quantified Ventures	D.C. Water	CSO	3.43% with pay-for-performance add-on; mixed environmental repayment structure	30
Yuba forest resilience bond	2018	4	California	Blue Forest, World Resources Institute	Yuba Water Agency, State of California, U.S. Forest Service	Wildfire and water supply	2.5% (blended 4% and 1%); fixed environmental repayment	5
Atlanta flood bond	2020	14	Atlanta, GA	Quantified Ventures	Atlanta Department of Watershed Management	Flood control	3.55%–4.67%; mixed environmental repayment structure	10

stormwater into the sanitary sewer system are used to repay the bond. This EIB was issued at $25 million by project developers Quantified Ventures and was structured within an overall bond package of over $300 million to address combined sewer overflow (CSO) events. This bond was not publicly issued but rather privately sold to the investors (Goldman Sachs and Calvert Impact Capital) who assumed the bond's risk. The paying beneficiary is D.C. Water (the water and sewer agency), and consequently the ratepayers/consumers of water in Washington, D.C.

The bond is structured as pay-for-performance, with the success metric being volume of stormwater reduction. The core interest rate was set at 3.43% for 30 years with a mixed environmental benefit repayment structure with a pay-for-performance component. The probability of over/underperformance was calculated at 2.5% for each respectively, with the contract stipulating an 'over-performance' payment to bondholders to increase the effective interest rate in the case that the environmental interventions are more successful than anticipated. Conversely, if the interventions underperform, the contract has a 'clawback' clause to reduce the effective interest rate (D.C. Water 2016).

2.4.2. Forest Resilience Bond: Yuba project I (2018)

The Yuba Project Forest Resilience Bond (FRB) was the first opportunity for private investors to support public land management and the first to focus on forest restoration and associated wildfire risk reduction (Madeira and Gartner 2018). The FRB raised $4 million in private capital to fund ecological restoration across 15 000 acres in the Yuba River Watershed by project developers Blue Forest Conservation. The paying beneficiaries are the US Forest Service, State of California and the Yuba Water Agency who are responsible for repaying investors (AAA Insurance of California, Calvert Impact Capital, the Rockefeller Foundation, and the Gordon and Betty Moore Foundation) for meeting the project outcomes. The positive economic benefits stem from: (1) reduced wildfire and corresponding infrastructure risk throughout the watershed, (2) protected downstream water quality, and in particular decreased risk of post-wildfire woody debris flow for the Yuba Water Agency, and (3) increased water flows due to reduced uptake/evapotranspiration by underlying brush and small diameter trees. The FRB was a private loan offering with a relatively short-term length at 5 years, having a blended interest rate of 2.5%, with 1% being paid to foundation investors through program related investments and 4% being paid to market rate investors with a fixed environmental benefit repayment.

2.4.3. Atlanta Flood EIB (2020)

The Atlanta Flood EIB is a $14 million dollar bond in the Proctor Creek Watershed designed by project developer Quantified Ventures which results in cost savings resulting from a reduction in stormwater runoff, improved water quality, and decreased flood flows by replacing impervious surfaces with green infrastructure (Office of Communications and Community Relations 2019). These cost savings are in turn paid with a mixed environmental benefit repayment by paying beneficiary Atlanta Department of Watershed Management. Similar to the D.C. Water Bond structures, the interest rate varies between 3.55% and 4.67% depending on the success of the interventions. The bond is notable because it is the first time an EIB is available to public investors, meaning residents in the Proctor Creek Watershed will be able to invest in their own community and bond. The probability of overperformance is calculated at 27.7%, which would trigger a higher interest rate payment to investors.

Table 3. Estimates of potential future value of EIBs within the United States for three categories: flooding, fires, and water quality. All estimates have been rounded to the nearest tens of billions of dollars.

EIB Type	EIB subtype	Approximate Value (billions of $USD)	Source(s):
Flood mitigation		**$510–880**	
	Wetland conservation (coastal flooding)	$360–480	Costanza *et al* (2008)
	Floodplain conservation (fluvial flooding)	$150–400	Johnson *et al* (2020)
Wildfires		**$100–130**	Lynch and Mackes (2003), North *et al* (2012)
Water quality		**$60**	
	CSO treatment for urban stormwater	$50	Environmental protection Agency (2000)
	Wetland conservation for water quality	$10	Day *et al* (2014)
Total		**$670–$1070**	

3. Future research needs: expansion

3.1. What is the potential future market size for EIBs?

EIBs will only become a significant financial instrument if the potential future market is of sufficient size to attract institutional support and capital. Here we speculate the future market capitalization of EIBs using contemporary estimates of conservation and environmental needs for three different types of EIBs: flooding, wildfires, and water quality. While there are other environmental issues which are suitable for EIBs, these environmental challenges have been the focus of EIBs to date. Estimates are provided for the United States only due to a lack of data and examples of EIBs in other countries. To date, the only EIBs proposed and released have been in the United States (tables 1 and S1). Our calculations aim to serve as a jumping off point for future researchers to develop more concise, tailored estimates across multiple fields.

We calculated upper limit market estimates under the assumption that EIBs are the primary vehicle for investments in each major environmental category. While the assumption that EIBs are the primary investments in these fields is violated due to governmental, private, and philanthropic investments in each of these areas, the previously discussed funding gaps in all of these fields (Hamrick 2016) demonstrates that there is plenty of room for private capital.

EIB estimates were derived by adding the total estimated capital requirements and accumulated benefits, if possible. Otherwise, in the absence of appropriate model data and/or model output, we estimated only the total capital requirements (i.e., the cost of land acquisition), without estimating the accumulated benefits as well. Specific details on the methodology for deriving these estimates are described below and in the supplemental text (T2). Table 3 shows that the upper limit of the EIB market capitalization in the US (assuming full market penetration) has the ability to rival the size of the $4 trillion-dollar municipal bond market (Cestau *et al* 2019). A key future research question which emerges from this analysis is then: what percentage of the estimate of capital requirements for each environmental problem will be filled by EIBs will be considering the multitude of options available to investors (Green Bonds, municipal bonds)? And when would the structure of an EIB be preferred compared to more standard methods of financing (e.g. general obligation municipal bonds)?

3.1.1. Flood mitigation

Flooding is the costliest natural disaster globally and has been significantly increasing over the past decades (Diaz *et al* 2008, Smith and Katz 2013). Floodplain (Johnson *et al* 2020) and wetland conservation, such as purchasing property within a floodway, (Narayan *et al* 2017) is a proven and increasingly popular tool to reduce the impacts of major flooding. Estimates of the total value of floodplain and wetland conservation for the United States are placed at $510–$880 billion $USD (Costanza *et al* 2008, Johnson *et al* 2020).

3.1.2. Wildfire risk reduction

The US Forest Service, the largest US federal agency forestland manager at 193 M acres, estimates that 65–82 M acres of forest are in need of restoration (USDA 2015), forest thinning through either mechanical means or prescribed fires (Lynch and Mackes 2003), to decrease the risk of severe wildfire. In addition, there are 16.3 M acres of non-commercial private forestland (USDA 2015) and assuming a similar proportion is in need of restoration, an additional 5.5–6.9 M acres require investment. This is likely to be a conservative estimate, as many private forests are lower in elevation with drier conditions and have a higher risk of wildfire exposure. The total value of a wildfire risk reduction EIB for the United States is estimated at $100–$130 billion USD, which includes the initial restoration costs ($71–$90 billion) and recurring costs ($25–$41 billion).

3.1.3. Urban stormwater management and improved water quality

CSOs occur when drainage systems for stormwater runoff and sewage are combined due to high loads from rainfall and there is insufficient overall capacity to contain or treat the flows during storm events. CSOs are a leading cause of water quality impairments and non-attainment of EPA water quality standards (DeBell 2004). Water quality has been a focus for previous and future EIBs (tables 2 and S1). In particular, water quality EIBs have focused on using green infrastructure to reduce the impact of CSOs and stormwater pollution. Estimates for control costs have been as high as $50.6 billion USD (Environmental Protection Agency 2000). These estimates were used to formulate the basis of the estimates for EIB size in table 3 (rounded to $50 billion), recognizing that this represents capital costs only, and not the total expected economic benefits, which would likely be higher. Additionally, wetlands play a role in improving water quality. Contemporary estimates for the value of wetlands in improving water quality in the Mississippi River Delta alone is $2.5–$10.8 billion, which was also incorporated into the estimates listed in table 3.

3.2. How can scale and standardization reduce development costs?

A major impediment to widespread adoption of EIBs is that development costs (cost of scientific investigation plus developing the financing structure) oftentimes represent a significant percentage of the bond issuance, resulting in high fees and potentially a major barrier to investment (Strong and Preston 2017). This has been a significant challenge for the Social Impact Bond field and is true for the current state of the EIB market—with little experience to go on, the cost of forecasting and measuring success, in addition to simply developing and structuring the deal, hampers EIB issuance. Currently, many EIBs/SIBs have addressed this issue by offsetting costs through interested third party grants (Olson and Phillips 2013). Many EIBs are structured as pay-for-performance, meaning that measuring success (which has its own costs) is a significant ongoing component of EIB costs. This issue can be addressed within the EIB field through scale and standardization.

3.2.1. Scale

Currently, few EIBs have been issued, but an increase in scale, in terms of both number of deals and volume of dollars invested, will naturally lead to a reduction in the relative cost of measurement. Smaller EIBs will likely have a higher percentage of their issue value dedicated to development, monitoring, and assessment. Furthermore, insofar as EIBs enable much larger projects, the environmental outcomes will be easier to measure relative to the natural variability of systems that can overwhelm the signal of smaller projects.

For example, imagine a hypothetical EIB developed to address excessive nutrient loading in a smaller watershed, say 10 km^2. Say the cost of monitoring is relatively fixed at $20 000 for a 5 years monitoring program, which includes installation of a stream gauge and field sampling of storm events for nutrients to compare pre-vs-post EIB implementation. The total value of the EIB issued to install green infrastructure is $1 million, yielding a monitoring cost of 2%, which would likely be unpalatable to investors and stakeholders. Now, imagine the same bond and green infrastructure is implemented in a 1000 km^2 watershed for $100 million. The technology for monitoring that site with stream gauges and field sampling is going to be more expensive, but will scale more efficiently compared to the 10 km^2 watershed. Say this cost is ∼$40 000—which translates to a monitoring cost of 0.04%, which would be much more digestible for participants. Additionally, a $100 million dollar investment will have much lower management costs per dollar invested compared to a $1 million dollar investment, yielding additional savings.

However, bonds of this scale will require numerous smaller scale/pilot test sites to prove EIB effectiveness. Development costs will likely have similar efficiency gains with larger scales. Investors should not be dismayed at initially high development and monitoring costs for EIBs given the opportunities for economies of scale. Indeed, most new technologies and industries require a 'breaking in' period and only become profitable after many years of trial and error and a 'scaling up' period to achieve efficiency through volume. It is expected that EIBs are currently going through a similar period.

3.2.2. Standardization

Efficiency gains will come from standardizing the field of EIBs. Currently, EIBs are developed on a piecemeal basis, with differing versions of development, monitoring, and assessment. This learning process, while necessary, is expensive compared to more established financial products. An apt metaphor would be to compare the nascent market for EIBs to Green Bonds. The first issued Green Bond had to be developed in conjunction with the World Bank and had a prohibitively high individual development cost. Compare this to today, with billions in Green Bonds issued and certified by the World Bank under a relatively cheap and standardized framework for billions of dollars' worth of bonds.

Standardization is likely to come in many forms. First, we propose research into standardizing EIB structure as outlined in section 4.1. Second, research into a standardized framework for development, implementation and evaluation could be developed for each type of EIB. This work can leverage existing impact bonds as a starting framework. A critical piece of this framework is to find replicable ways to connect environmental outcomes to financial benefits in a manner which beneficiaries are bought-in and willing to repay. We anticipate this will be accomplished through additional deals, research, and finally, trial and error.

3.3. Who will be the main purchasers of EIBs?

To date, the main purchasers of EIBs have largely been philanthropic organizations, impact investors, development finance institutions, large banks or insurance agencies. Additionally, large banks and philanthropic organizations have assumed much of the risk of EIBs to date. In the case of the FRB, four different investors, two concessional and two market rate, provided the loan, and the D.C. Water Bond was backstopped by Goldman Sachs before being put up for sale. The Atlanta Flood Bond is notable for being the first bond which is available for sale to the general public. We outline both barriers and opportunities for institutional (large) and retail (individual) investors in the following sections.

3.3.1. Barriers and opportunities for institutional investors

Institutional investors can take on risk, but it must be appropriately quantified so they can build portfolios according to the risk/reward goals (Brandstetter and Lehner 2018). Brand *et al* (2020) provided a basic framework to quantify risk and reward for zero-coupon EIBs, however, additional work is needed to diversify the repayment and risk allocation structures available for EIBs.

The dearth of EIBs and the relatively small sizes of current deals also prohibit investment by some large institutional investors who require investments of a certain size. The due diligence and development costs are generally similar and independent of the dollar amount invested. Therefore, for many institutional investors, there is a strong interest in developing bigger deals, in which they can receive a greater absolute dollar return net of fixed costs and 'get money out the door'.

Finally, a lack of managerial experience and examples of successful EIBs is another major issue for large investors. Many institutional investors are bound to their stakeholders to attempt to produce certain returns on their investments and place their money in products with a proven track record. Without a trained cohort of experienced EIB managers along with successful examples, large investors will have difficulties investing large volumes of capital into EIBs.

3.3.2. Barriers and opportunities for retail investors

Thus far, retail investors have largely not participated in purchasing EIBs. One reason is lack of a well-defined track record, along with higher purchase prices ($1 million USD+) than a single individual may be able to pursue. Further research is needed on quantifying risks to EIBs and developing multiple tranches/ability to purchase as small as a single $1000 bond to allow smaller investors to participate in the EIB market, similar to the Quantified Ventures Atlanta EIB. Another reason stems from the lack of securities law surrounding EIBs and the inability to market certain financial products to non-institutional investors.

However, there is an opportunity for retail investors to participate not by individually investing but by instead pooling resources into one aggregated investment. This financial aggregation can provide an avenue for smaller investors wanting to invest in environmentally sustainable projects, but that may not have the resources, knowledge or legal authority to invest individually (Quesnel *et al* 2017). This configuration would likely require an intermediary to make the project logistically possible, and this middleman aggregator often assumes some project risk (Hussain 2013). While this crowdfunding approach is new to the environmental finance sector, there is an emerging demand and potential for large investments in the future (Hörisch 2015, Hörisch and Tenner 2020).

3.4. How can co-benefits be included in EIBs to expand funding streams?

Many environmental projects are planned for one specific benefit. Thus far, EIBs have largely leveraged that one benefit, experienced by one paying beneficiary, for funding. However, many environmental projects are inherently multi-benefit (Gordon *et al* 2018, Everard and McInnes 2013). Stacking multiple benefits, and potentially multiple paying beneficiaries, into one EIB can enable broader adoption and increase the scale at which EIBs are developed.

The Yuba Forest Resilience Bond took this approach, where the project was planned for fire risk reduction, but both of the water resources and fire risk reduction benefits were leveraged for financing. However, there are many more benefits of forest restoration, such as increased biodiversity, that were not included in the EIB development process. Future work should examine all of the benefits that come from different environmental interventions and how they can be leveraged for future EIBs. Additionally, there are many non-financial benefits that result from environmental projects, for example non-use (i.e. option, bequest, existence) values and including these values is a major goal for EIB development.

3.5. How do EIBs influence environmental equity?

A final expansion question entails understanding the equity implications of EIBs relative to other financing options. Both infrastructure provisioning and environmental restoration—the two common aims of EIBs—have long histories of unequal impacts on different socioeconomic and ethnic groups (Mohai *et al*

2009, Moran 2010, Palamar 2010, Banzhaf *et al* 2019). Thus far EIBs have addressed some equity aspects into their structures, but there is room for greater emphasis. For example, the Yuba Project Forest Resilience Bond was located in a disadvantaged county and aims to provide jobs through restoration activities. In the case of the Atlanta Flood, the water manager is committed to including equitable water policies and practices into the project (Hallauer *et al* 2019).

As EIBs expand in their use, researchers and practitioners should be attuned to potential equity impacts. First, understanding effects on procedural equity entails understanding how different financing structures shape who has a say in what projects are implemented (McDermott *et al* 2013). In many settings, government decisions are subject to substantial requirements for transparency and public participation (Woods 2015, Marantz and Ulibarri 2019), while business trade secrets are protected from public view and they only sometimes provide opportunities for public input. Thus, shifting financing responsibility from governments to businesses could limit opportunities for public input. Second, understanding distributional equity entails understanding how different financing mechanisms shape where projects are built and who they benefit versus harm (McDermott *et al* 2013). On one hand, opening up new sources of capital could enable provisioning of environmental benefits in underserved areas. On the other hand, without adequate attention to distributional impacts, EIBs could reinforce trends where wealthy, predominately white locations receive environmental amenities while low income, pollution-burdened locations do not.

At the same time, the literature suggests that when structured appropriately, public–private partnerships could bring the best of public and private, merging the social equity and long-term vision of the government sector with the innovation and efficiency of the private sector (Jensen 2017, Nizkorodov 2021). EIBs, which often include a mixture of public and private entities, may provide a similar benefit.

4. Future research needs: refinement

4.1. How can EIB repayment be structured?

Additional research is needed to assess the appropriate EIB financial structures for different types of environmental projects. For example, some environmental projects will have a steady stream of environmental benefits which might make them more amenable to the financial structure of a bond with a regular coupon payment. Others might have highly variable environmental benefits which might require a catastrophe bond structure (where benefits are only paid out in the case of event/no-event), or a loan. A hybrid structure could also be envisioned for projects which have variable and fixed benefits, where the variable benefits are repaid via a pay-for-performance mechanism. There is also an opportunity for below market or negative interest rates if the investor can receive an external return from an outside source for participating in the project. For example, an investor participating in a forest restoration project may be willing to take a negative interest rate if there are carbon credit dollars available to supplement their initial investment. Indeed, carbon credits have become a significant portion of many companies' bottom line and contribute significant returns (Ruffo 2020).

4.2. How can uncertainty and risk be better incorporated within EIB development and models?

All models, including both environmental and financial, have uncertainty. While further reducing uncertainty is certainly a worthwhile goal, it will be impossible to completely eliminate uncertainty in environmental models. Rather, the goal of researchers should be to quantify those uncertainties and ensure that investors are adequately rewarded for taking on additional risks. There are few published examples of models which explicitly incorporate financial and environmental risks for the purposes of repaying an EIB. One notable and recent example is the work of Brand *et al* (2020), who developed a methodology for quantifying the probability of inability to repay the principal on a zero-coupon using downstream cost savings for an EIB for addressing cross-border pollution between the US and Mexico. This model characterized uncertainty in future cash flows by incorporating both financial (inflation and cost of trash disposal uncertainties) and environmental (future rainfall and channel erosion) uncertainties.

Two EIBs issued to date have been structured as pay-for-performance and backstopped by one or more philanthropic organizations. Maturation of the field will force EIBs to stand on their own and require different risk sharing structures. There are multiple ways to share and define risk with financial instruments—the two most common are principal at risk (PaR) and return at risk (RaR). Calculating PaR and RaR results in different risk profiles, which could result in markedly different interest rates needed to reward investors.

EIBs must exist as diverse financial instrument offerings to meet the needs of differing investors and stakeholders. More work is needed to investigate the financial and environmental impacts of different types of bonds and loans. So far, EIBs interest rates have been set by stakeholders and developers. However, most financial instruments' interest rates are actually set by market dynamics. This mismatch can be solved with increasing scale and volume of EIBs offered and through mathematical modeling. Instead of deriving an interest rate, a series of interest rates could be tested to evaluate their impact on ability for repayment using environmental benefits. This information could then be provided to investors who can make an informed decision about what interest rate they require from the EIB and the effect of that interest on probability of repayment.

4.2.1. Integration within standardized risk models

Research into environmental-financial modeling which underpins EIBs is lacking and in need of development (Adriaens and Ajami 2021). However, the financial services industry has spent many years and millions of dollars developing standardized models of financial risk for quantifiably evaluating bonds and loans, including around climate (Keenan 2019). The EIB field should leverage this exhaustive body of work. For example, JP Morgan Chase and Credit Suisse have developed software (Credit Risk + and Credit Metrics) which use financial services concepts such as value at risk, expected loss, and probability of default to rigorously estimate the risks certain financial instruments pose to bank stability (Crouhy *et al* 2000). EIBs should ideally utilize the same vocabulary and adopt the same methodologies so they can be easily integrated into the mainstream financial system.

4.2.2. Modeling multivariate risk: the relationship between environmental and credit risk

Investors are becoming increasingly aware of the impacts of environmental variability and climate change on credit risk (Link and Risk 2016). The current structure of EIBs assumes that a paying beneficiary's broader financial conditions do not impact the probability of EIB repayment. In order to account for all the potential risks to the financial security of an EIB, the structure should consider and incorporate credit risks and broader financial conditions, and their interactions with environmental risks within the risk assessment.

For example, imagine a situation with an EIB dedicated to reducing the risk of wildfires, benefitting a local utility. Despite the best efforts of a forest restoration and thinning project, a wildfire breaks out which is large enough to bankrupt the utility due to litigation and massive infrastructure damage. To avoid this, for example, the Forest Resilience Bond includes a force majeure clause whereby the contract can be broken to prevent a corresponding financial obligation for a project that no longer makes sense. The potential bankruptcy would be partly due to environmental conditions, but the environmental conditions correspondingly could also lead to a deterioration of broader financial conditions which end in bankruptcy.

As environmental and financial conditions are often closely intertwined and positively correlated, especially in cases with low-probability extreme events, new tools are needed to assess the amplified risk. Copulas (Trivedi and Zimmer 2007) are one statistical tool that could be used to address multivariate and interdependent environmental and financial risks (Keef *et al* 2013, Quinn *et al* 2019, Schoelzel and Friederichs 2008, Cherubini *et al* 2004), but more research is needed on the applications of these and other methods to EIB development.

4.2.3. Stochastic modeling of intervention costs

The current methods developed for evaluating EIB project outcomes and benefits have all assumed constant intervention costs—the planning and permitting, construction, restoration, land acquisition, maintenance, monitoring, operating, and technology costs to implement a project. However, these costs can be highly variable and extremely difficult to predict (Ballesteros-Perez *et al* 2020). This variability could lead to significantly higher risks of not yielding anticipated benefits compared to using a static estimate. Future work should focus on developing methodologies for incorporating variable costs into the cost-benefit metrics, analyses and decision making.

4.3. How can improved measurement facilitate EIB development?

4.3.1. Measuring success through outputs and outcomes

One current trend is that EIBs to date have contained rigorous measurement standards and performance metrics to evaluate project success. In some cases, success is simply defined as project outputs or advancement (in essence, 'getting work done on the ground'). For example, Herrera *et al* 2019 used the output metric of acreage of wetland restored in designing their proposed EIB (table S1), to be used as the basis for repayment. Conversely, success in the case of the D.C. Water Bond is measured through project outcomes, by tracking the volume of stormwater reduced. Predicting, measuring, and monitoring environmental outcomes is challenging, and developing metrics which are easily and efficiently measured will aid in EIB development. While a robust modeling approach to quantifying risk and return is preferred, in reality, many investments have thus far been structured based on the specific constraints and realities of the different parties to the deal.

It may be impossible to develop a set of universal risk metrics and measurement standards for every EIB issue. However, that does not mean that developing standardized risk and measurement criteria for subcategories of EIBs is impossible. Undoubtedly, creating a set of measurement and risk metrics should be a goal for the field as it matures.

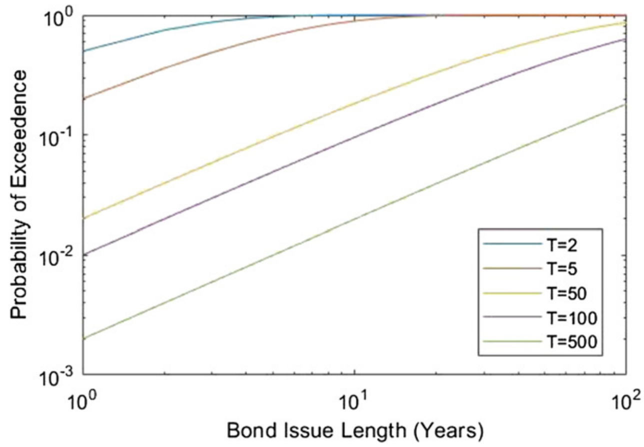

Figure 2. Probability of exceedance over bond issue length for return periods (T) of 2, 5, 50, 100, and 500 years return intervals. Note that both scales are in logarithmic format.

4.3.2. Measuring success with low-probability extreme events

Measuring success of pay-for-performance EIBs designed to reduce the risk due to wildfire, flooding and other natural disasters will prove to be challenging. The main issue is that large floods and wildfires are inherently rare and (are modeled as) stochastic events. An EIB designed to reduce the risk and impact of these events (such as the Atlanta Flood Bond, Forest Resilience Bond, and proposed Coastal Resilience Bond) will require data to prove the project's success. However, the probability of a '100 years event' is, by definition, 1% each year—meaning that it is unlikely for the project to experience an event of significant magnitude within 5–10 years of the project's completion. This fundamental fact means that it will be very difficult to measure an EIBs success for extreme events (>50 years return period) using empirical data.

There are multiple ways to address this issue. The easiest way is through a longer EIB repayment timeline, or reducing the return period of the event. Figure 2 provides an example for an EIB. The curves for each return period ($T =$ years) shows the probability of witnessing the extreme event (probability of exceedance) in a given timeframe (bond issue length). While the likelihood of a 100 years event is only 9.5% over a 10 year period, it becomes 26% over a 30 years period (the length of long-term US Treasury Bonds), and 63% over a 100 year period. While it may be unlikely investors would have an appetite for a 100 years EIB, recent examples of 'century bonds' provide an interesting counter-example (Morgan Chase 2019). Additionally, long-term bonds will be susceptible to non-stationary statistical variables driven by climatic change which could significantly impact risk, and have less liquidity for investors, which would require higher interest rates (Bailey 2005, Mudd *et al* 2014, Swain *et al* 2020).

Another method for addressing the issue of improbable events could be accomplished through geographic diversification. For example, an EIB including projects over multiple geographic regions of interest increases the likelihood of experiencing an extreme event as one adds more independent places of interest (Towe *et al* 2018). However, given the locality of EIBs, where those who benefit from a project are often located near or downstream of the intervention, while at the same time many investors are interested in local projects, research is needed to understand how geographic bundling could be integrated into EIB structuring. Correspondingly, EIBs could be packaged for multiple extreme events, such as fires, flooding, and/or wind damages, which increases the likelihood of observing any event (similar to catastrophe bonds), and therefore increases the likelihood of realizing cost savings. These aggregation strategies, similar to those used by insurance/reinsurance companies, have the potential to overcome many challenges facing the EIB market to date. Interventions would need to be carefully constructed and diversified to ensure that success is not dependent on just one or two interventions (unless empirically proven to be successful). Correspondingly, too much diversity in interventions could yield difficulties in attribution and measuring success, and the added complexity could yield hidden risks resulting in a higher required interest rate by investors to account for the uncertainty.

4.3.3. Measuring success in systems with hysteresis and environmental memory

Another potential and parallel issue with including pay-for-performance in EIBs is that many environmental systems exhibit hysteresis and memory. Hysteresis is when systems exhibit path dependency where exceeding a certain environmental threshold or travel down a certain path yields one outcome in one direction, but exhibit different behavior when the direction (or 'path') is changed. In the context of environmental management, hysteresis becomes important because many environmental problems, while reversible, are much more expensive to manage after the event occurs or if certain thresholds are exceeded (Ranjan and Shortle 2007).

For example, a forest may be able to withstand minor damages, but with enough tree cutting, regrowth may be impossible due to insufficient initial stock, soil loss and changes in soil moisture (Cramer and Hobbs 2002). In that case, the forest must be completely replanted to regain normal function.

Environmental memory occurs when changes in inputs do not yield anticipated outcomes due to accumulated pollutant levels within the system of interest. For example, recent studies have estimated that even if ambitious goals in reducing nutrient loads from agricultural runoff into the Gulf of Mexico are met through aggressive infrastructure and best management practices, it could take 30 years to see a corresponding downstream response due to legacy nutrient contamination (Van Meter *et al* 2018). In the context of EIB development, this means that any EIB with a pay-for-performance characteristic would likely need at a minimum of 30 years, if not longer, to be evaluated and have a payout.

The hysteresis and environmental memory effects present both opportunities and pitfalls for EIBs. The major opportunity is that EIBs can overcome the initial capital hurdle for systems which have exceeded environmental loss thresholds, whereby piecemeal efforts by well-meaning stakeholders will have little to no effect on overall environmental outcomes. The pitfall is that the system must be well understood, so that modelers, beneficiaries, and investors know that the system needs a certain threshold of investment before any returns of environmental benefits are seen.

4.4. What is the impact of model uncertainty on EIBs?

Model uncertainty could be a significant barrier to the further market development of EIBs. Environmental models are fraught with uncertainty due to data quality, parametric uncertainty, and model structural uncertainties. Uncertainty associated with climate change further complicates model prediction. Once financial model uncertainty is incorporated into the models, the uncertainties could become large enough to pose a significant risk to an EIB's financial viability.

Models to inform EIBs will ultimately be a mixing pot of uncertainties, producing an imprecise figure with which to price certain elements of the bond (Brand *et al* 2020). The uncertainty bounds themselves will be difficult to quantify, owing to constraints on data, computing power, and process understanding—and reasonable error approximations would likely be so large that they could repel potential investors (Chatfield 1996). Existing model capabilities should instead be interpreted with a full appraisal and understanding of their constraints:

First, uncertainty is part of the risk. Incorporating uncertainty into all facets of environmental predictions is critical, including uncertainty in model formulation, model parameters, future climate and initial and boundary conditions (Refsgaard *et al* 2007). Pricing can therefore explicitly account for bonds underpinned by uncertain models, rewarding investors for funding uncertain bonds. Second, confidence increases at scale. Generally, as you aggregate your field of view, uncertainties tend to cancel and so error bars narrow—imprecise models, if unbiased, can provide accurate answers (Wing *et al* 2020). Uncertainly priced bonds could therefore be more reliably implemented at large spatial scales.

Another possibility for reducing uncertainty in EIB outcomes is to focus on implementing EIB projects that are dynamic and adaptive. For example, smart stormwater systems are controlled automatically in real time with a network of sensors and actuators, and can be optimized to achieve multiple benefits, such as CSO prevention, flood reduction, water supply resilience and water quality improvement (Kerkez *et al* 2016, Xu *et al* 2021). Real-time control technology allows systems to dynamically adapt to changing environmental conditions such as climate change and urbanization, thus limiting their uncertainty relative to passive systems.

5. Conclusions

EIBs are promising financial instruments for deploying private capital to solve environmental problems on a larger scale than public and philanthropic sources alone.

A key outcome of this work was the development of a standardized vocabulary to reduce confusion surrounding the diversity of management and financial structures which currently exist within the EIB field. 'Environmental Impact Bond' is chosen as a catchall term to describe financial structures of both bonds and loans; and while many previous EIBs have pay-for-performance characteristics, it is noted that pay-for-performance need not be required for EIBs. Payment structures (fixed, variable, and mixed) were identified, along with participants within the EIB creation process (paying vs non-paying beneficiaries). Risk is briefly defined, and methods for measuring risk and connection to reward for investors are discussed.

The three EIBs released to date in the US have taken on a diversity of both environmental problems (wildfires, flooding and stormwater quality) and financial structures. Many of the environmental benefits were cross-cutting within the different EIBs. For example, the Yuba Project Forest Resilience Bond reduces the probability of wildfires through best management practices for forest management. These forest health interventions also improve downstream water quality by reducing ash, enhance hydropower revenue generation through increased streamflow and contribute to biodiversity gains. Leveraging multiple benefits of EIB projects expands the potential pool of paying beneficiaries and can lead to the scaling required to move the needle on many environmental problems.

EIBs are a promising financial structure, but impact and accountability must be carefully accounted for as the field expands (Dey and Gibbon 2018, Balboa 2016). These challenges can be partially quelled by additional research which supports development, standardization, and scaling. As the EIB field expands and the deals themselves are refined, EIBs will become increasingly powerful tools for effectively addressing large, costly, and urgent environmental challenges. Addressing these environmental and financial research questions will also help attract diverse investors who are increasingly focused on sustainable investments. Given the potential for environmental, social, and economic benefits to be unlocked by EIBs, additional funding is needed for researchers to answer the objectives outlined above, and our results can be used to drive funding opportunities in EIB research. This research will not only answer practical questions concerning financial instruments, but also deeper, more challenging scientific questions impacting many disciplines and industries.

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Data availability statement

No new data were created or analysed in this study.

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References

Adriaens P and Ajami N 2021 Infrastructure and the digital economy: reinventing our role in the design, financing, and governance of essential services for society *J. Environ. Eng.* **147** 02521001

Allen F and Yago G 2011 Environmental finance: innovating to save the planet* *J. Appl. Corp. Finance* **23** 99–111

Bailey R E 2005 *The Economics of Financial Markets* (Cambridge: Cambridge University Press)

Balboa C M 2016 Accountability of Environmental Impact Bonds: the future of global environmental governance? *Global Environ. Polit.* **16** 33

Ballesteros-Pérez P, Sanz-Ablanedo E, Soetanto R, González-Cruz M C, Larsen G D and Cerezo-Narváez A 2020 Duration and cost variability of construction activities: an empirical study *J. Constr. Eng. Manage.* **146** 04019093

Banzhaf H S, Ma L and Timmins C 2019 Environmental justice: establishing causal relationships *Annu. Rev. Resour. Econ.* **11** 377–98

Bolitzer B and Netusil N R 2000 The impact of open spaces on property values in Portland, Oregon *J. Environ. Manage.* **59** 185–93

Brand M W, Gudiño-Elizondo N, Allaire M, Wright S, Matson W, Saksa P and Sanders B F 2020 Stochastic hydro-financial watershed modeling for Environmental Impact Bonds *Water Resour. Res.* **56** e2020WR027328

Brandstetter L and Lehner O M 2018 Opening the market for impact investments: the need for adapted portfolio tools *Enterpren. Res. J.* **5** 87–107

Cestau D, Hollifield B, Li D and Schürhoff N 2019 Municipal bond markets *Annu. Rev. Finance Econ.* **11** 65–84

Chatfield C 1996 Model uncertainty and forecast accuracy *J. Forecast.* **15** 495–508

Chazdon R L, Brancalion P H S, Lamb D, Laestadius L, Calmon M and Kumar C 2017 A policy-driven knowledge agenda for global forest and landscape restoration *Conserv. Lett.* **10** 125–32

Cherubini U, Luciano E and Vecchiato W 2004 *Copula Methods in Finance* (New York: Wiley)

Costanza R, Pérez-Maqueo O, Martinez M L, Sutton P, Anderson S J and Mulder K 2008 The value of coastal wetlands for hurricane protection *AMBIO A J. Hum. Environ.* **37** 241–8

Cousins J 2018 Remaking stormwater as a resource: technology, law, and citizenship *Wiley Interdiscip. Rev. Water* **5** e1300

Cramer V A and Hobbs R J 2002 Ecological consequences of altered hydrological regimes in fragmented ecosystems in Southern Australia: impacts and possible management responses *Austral Ecol.* **27** 546–64
Crompton J L 2001 The impact of parks on property values: a review of the empirical evidence *J. Leisure Res.* **33** 1–31
Crouhy M, Galai D and Mark R 2000 A comparative analysis of current credit risk models *J. Bank. Finance* **24** 59–117
D.C. Water 2016 *D.C. Water, Goldman Sachs and Calvert Foundation Pioneer Environmental Impact Bond*
Dallimer M and Strange N 2015 Why socio-political borders and boundaries matter in conservation *Trends Ecol. Evol.* **30** 132–9
Davidsen C, Liu S, Mo X, Holm P E, Trapp S, Rosbjerg D and Bauer-Gottwein P 2015 Hydroeconomic optimization of reservoir management under downstream water quality constraints *J. Hydrol.* **529** 1679–89
Day J W *et al* 2014 *Perspectives on the Restoration of the Mississippi Delta: The Once and Future Delta* (Dordrecht: Springer)
DeBell K M 2004 U.S. EPA's report to congress on the impacts and control of combined sewer overflows and sanitary sewer overflows *Proc. Water Environ. Federation* pp 783–9
Deutz A *et al* 2020 *Financing Nature: Closing the Global Biodiversity Financing Gap* The Paulson Institute The Nature Conservancy, and the Cornell Atkinson Center for Sustainability https://nature.org/enus/what-we-do/our-insights/reports/financing-nature-biodiversity-report
Dey C and Gibbon J 2018 New development: private finance over public good? Questioning the value of impact bonds *Publ. Money Manage.* **38** 375
Diaz H F *et al* 2008 *Climate Extremes and Society* (Cambridge: Cambridge University Press)
Environmental Protection Agency 2000 Clean watersheds needs survey 2000 report to congress available at: epa.gov
Everard M and McInnes R 2013 Systemic solutions for multi-benefit water and environmental management *Sci. Total Environ.* **461–462** 170–9
Fried J S, Winter G J and Gilless J K 1999 Assessing the benefits of reducing fire risk in the wildland–urban interface: a contingent valuation approach *Int. J. Wildland Fire* **9** 9–20
Geobey S, Westley F R and Weber O 2012 Enabling social innovation through developmental social finance *J. Soc. Enterpren.* **3** 151–65
Gordon B L, Quesnel K J, Abs R and Ajami N K 2018 A case-study based framework for assessing the multi-sector performance of green infrastructure *J. Environ. Manage.* **223** 371–84
Groffman P M *et al* 2006 Ecological thresholds: the key to successful environmental management or an important concept with no practical application? *Ecosystems* **9** 1–13
Gudino-Elizondo N, Biggs T W, Bingner R L, Langendoen E J, Kretzschmar T, Taguas E V, Taniguchi-Quan K T, Liden D and Yuan Y 2019 Modelling runoff and sediment loads in a developing coastal watershed of the US-Mexico border *Water* **11** 1024
Hall D, Lindsay S and Judd S 2017 Permanent forest bonds: a pioneering Environmental Impact Bond for Aotearoa New Zealand available at: http://researcharchive.vuw.ac.nz/handle/10063/8141
Hallauer A M, Tyagi A, Glen B, Bell D and Cohen B 2019 Environmental Impact Bond: an innovative financing mechanism for enhancing resilience in the city of Atlanta through green infrastructure *World Environmental and Water Resources Congress 2019*
Hamrick K 2016 *State of Private Investment in Conservation 2016: A Landscape Assessment of an Emerging Market* Forest Trends
Hardin G 1968 The tragedy of the commons *Science* **162** 1243–8
Hardin R and Cullity G 2020 *The Free Rider Problem, the Stanford Encyclopedia of Philosophy. Winter 2020* E N Zalta Metaphysics Research Lab, Stanford University available at: https://plato.stanford.edu/archives/win2020/entries/free-rider/
Hebb T and Sharma R 2014 New finance for America's cities *Reg. Stud.* **48** 485–500
Herrera D *et al* 2019 Designing an Environmental Impact Bond for wetland restoration in Louisiana *Ecosyst. Serv.* **35** 260–76
Hess D J, Wold C A, Hunter E, Nay J, Worland S, Gilligan J and Hornberger G M 2016 Drought, risk, and institutional politics in the American Southwest *Socio. Forum* **31** 807–27
Hone J, Drake V A and Krebs C J 2017 The effort–outcomes relationship in applied ecology: evaluation and implications *Bioscience* **67** 845–52
Hörisch J 2015 Crowdfunding for environmental ventures: an empirical analysis of the influence of environmental orientation on the success of crowdfunding initiatives *J. Clean. Prod.* **107** 636–45
Hörisch J and Tenner I 2020 How environmental and social orientations influence the funding success of investment-based crowdfunding: the mediating role of the number of funders and the average funding amount *Technol. Forecast. Soc. Change* **161** 120311
Hussain M 2013 *Financing Renewable Energy Options for Developing Financing Instruments Using Public Funds* The World Bank
Huwyler F, Käppeli J and Tobin J 2016 *Conservation Finance from Niche to Mainstream: The Building of an Institutional Asset Class* (Zürich: Credit Suisse Group AG and McKinsey Center for Business and Environment)
Hyun S, Park D and Tian S 2019 Differences between Green Bonds versus conventional bonds *Handbook of Green Finance* (Singapore: Springer) pp 127–54
Jager H I and Smith B T 2008 Sustainable reservoir operation: can we generate hydropower and preserve ecosystem values? *River Res. Appl.* **24** 340–52
Jensen O 2017 Public–private partnerships for water in Asia: a review of two decades of experience *Int. J. Water Resour. Dev.* **33** 4–30
Johnson K A, Wing O E J, Bates P D, Fargione J, Kroeger T, Larson W D, Sampson C C and Smith A M 2020 A benefit-cost analysis of floodplain land acquisition for US flood damage reduction *Nat. Sustain.* **3** 56–62
Keef C, Tawn J A and Lamb R 2013 Estimating the probability of widespread flood events *Environmetrics* **24** 13–21
Keenan J M 2019 A climate intelligence arms race in financial markets *Science* **365** 1240–3
Keenan J M, Chu E and Peterson J 2019 From funding to financing: perspectives shaping a research agenda for investment in urban climate adaptation *Int. J. Urban Sustain. Dev.* **11** 297
Kerkez B *et al* 2016 Smarter stormwater systems *Environ. Sci. Technol.* **50** 7267–73
Letsinger E 2020 https://quantifiedventures.com/blog/introducing-reharvest-partners Introducing reharvest partners: quantified ventures' first subsidiary company available at: https://quantifiedventures.com/blog/introducing-reharvest-partners
Link H F P and Risk T O S C 2016 ERISC phase II available at: http://footprintfinance.org/content/uploads/2016/05/ERISC-2-AW-PAGES-WEB.pdf
Lonsdorf E V, Koh I and Ricketts T 2020 Partitioning private and external benefits of crop pollination services *People Nat.* **2** 811–20
Lynch D L and Mackes K 2003 Costs for reducing fuels in Colorado forest restoration projects, fire, fuel treatments, and ecological restoration *Proc. RMRS-P-29* (Ft. Collins, CO: USDA Forest Service) pp 167–75
Madeira L and Gartner T 2018 Forest resilience bond sparks innovative collaborations between water utilities and wide-ranging stakeholders *J. Am. Water Works Assoc.* **110** 42–9
Marantz N J and Ulibarri N 2019 The tensions of transparency in urban and environmental planning *J. Plann. Educ. Res.*

McDermott M, Mahanty S and Schreckenberg K 2013 Examining equity: a multidimensional framework for assessing equity in payments for ecosystem services *Environ. Sci. Policy* **33** 416–27

Meyers D *et al* 2020 Conservation finance: a framework available at: https://static1.squarespace.com/static/57e1f17b37c58156a98f1ee4/t/5e728a4e1e6cc747e7cdbdc2/1584564815888/Conservation+Finance+Framework+March+2020.pdf

Mohai P, Pellow D and Roberts J T 2009 Environmental justice *Annu. Rev. Environ. Resour.* **34** 405–30

Moran S 2010 Cities, creeks, and erasure: stream restoration and environmental justice *Environ. Justice* **3** 61–9

Morgan Chase J P 2019 Return of the century bond available at: https://jpmorgan.com/country/US/en/detail/1320574730728 (accessed 28 September 2020)

Mudd L, Wang Y, Letchford C and Rosowsky D 2014 Hurricane wind hazard assessment for a rapidly warming climate scenario *J. Wind Eng. Ind. Aerod.* **133** 242–9

Narayan S *et al* 2017 The value of coastal wetlands for flood damage reduction in the Northeastern USA *Sci. Rep.* **7** 9463

Nicola D J 2013 *Environmental Impact Bonds Case I3 Working Paper# 1* (Durham, NC: Duke University)

Nizkorodov E 2021 Evaluating risk allocation and project impacts of sustainability-oriented water public–private partnerships in Southern California: a comparative case analysis *World Dev.* **140** 105232

North M, Collins B M and Stephens S 2012 Using fire to increase the scale, benefits, and future maintenance of fuels treatments *J. For.* **110** 392

Office of Communications and Community Relations 2019 City of Atlanta Department of Watershed Management announces first publically issued Environmental Impact Bond, city of Atlanta available at: https://atlantawatershed.org/first-publicly-issued-environmental-impact-bond/ (accessed 28 September 2020)

Olson J and Phillips A 2013 Rikers Island: the first Social Impact Bond in the United States *Community Development Investment Review* 097–101

Ostrom E 2009 *Understanding Institutional Diversity* (Princeton, NJ: Princeton University Press)

Palamar C 2010 From the ground up: why urban ecological restoration needs environmental justice *Nat. Cult.* **5** 277–98

Poff N L 2018 Beyond the natural flow regime? Broadening the hydro-ecological foundation to meet environmental flows challenges in a non-stationary world *Freshw. Biol.* **63** 1011–21

Quantified Ventures 2020 Outdoor recreation Environmental Impact Bond, quantified ventures available at: https://quantifiedventures.com/outdoor-recreation-environmental-impact-bond (accessed 13 October 2020)

Quesnel K J, Ajami N K and Wyss N 2017 Accelerating the integration of distributed water solutions: a conceptual financing model from the electricity sector *Environ. Manage.* **60** 867–81

Quinn N, Bates P D, Neal J, Smith A, Wing O, Sampson C, Smith J and Heffernan J 2019 The spatial dependence of flood hazard and risk in the United States *Water Resour. Res.* **55** 1890–911

Ranjan R and Shortle J 2007 The environmental Kuznets curve when the environment exhibits hysteresis *Ecol. Econ.* **64** 204–15

Refsgaard J C, van der Sluijs J P, Højberg A L and Vanrolleghem P A 2007 Uncertainty in the environmental modelling process—a framework and guidance *Environ. Model. Software* **22** 1543–56

Ruffo G H 2020 Tesla earned $428 million with carbon credits in Q2 2020, inside EVs available at: https://insideevs.com/news/438345/tesla-428-million-carbon-credits-q2-2020/#:~:text=In%202019%2C%20Tesla%20got%20%24593,million%20to%20these%20carbon%20regulations (accessed 14 December 2020)

Saha D and d'Almeida S 2017 Green Municiple Bonds *Finance for City Leaders Handbook* 2nd 5 M KamiyaZ Le-Yin Nairobi: United Nations Human Settlements Programme

Saksa P C, Conklin M H, Battles J J, Tague C L and Bales R C 2017 Forest thinning impacts on the water balance of Sierra Nevada mixed-conifer headwater basins *Water Resour. Res.* **53** 5364–81

Schoelzel C and Friederichs P 2008 Multivariate non-normally distributed random variables in climate research—introduction to the copula approach available at: https://hal-cea.archives-ouvertes.fr/cea-00440431/

Smith A B and Katz R W 2013 US billion-dollar weather and climate disasters: data sources, trends, accuracy and biases *Nat. Hazards* **67** 387–410

Strassburg B B N *et al* 2020 Global priority areas for ecosystem restoration *Nature* **586** 724–9

Strong A and Preston B L 2017 Environmental Impact Bonds may not bear fruit for green investors available at: https://rand.org/blog/2017/11/environmental-impact-bonds-may-not-bear-fruit-for-green.html (accessed 1 October 2020)

Swain D L, Wing O E J, Bates P D, Done J M, Johnson K A and Cameron D R 2020 Increased flood exposure due to climate change and population growth in the United States *Earth Future* **8** e2020EF001778

Taylor M 2021 *Green Bond Issuance on Track to Almost Double in 2021, Market Estimates Suggest* Institutional Asset Manager

Thompson M P, Vaillant N M, Haas J R, Gebert K M and Stockmann K D 2013 Quantifying the potential impacts of fuel treatments on wildfire suppression costs *J. For.* **111** 49–58

Towe R, Tawn J and Lamb R 2018 Why extreme floods are more common than you might think *Significance* **15** 16–21

Trivedi P K and Zimmer D M 2007 *Copula Modeling: An Introduction for Practitioners* (Hanover, MA: Now Publishers Inc)

USDA 2015 Who owns America's trees, woods, and forests? USDA forest service available at: https://fs.fed.us/nrs/pubs/inf/nrs_inf_31_15-NWOS-whoowns.pdf

Van Kooten G C, Laaksonen-Craig S and Wang Y 2009 A meta-regression analysis of forest carbon offset costs *Can. J. For. Res.* **39** 2153–67

Van Meter K J, Van Cappellen P and Basu N B 2018 Legacy nitrogen may prevent achievement of water quality goals in the Gulf of Mexico *Science* **360** 427–30

Wing O E, Quinn N, Bates P D, Neal J C, Smith A M, Sampson C C and Alfieri L 2020 Toward global stochastic river flood modeling *Water Resour. Res.* **56** e2020WR027692

Wolfand J M, Bell C D, Boehm A B, Hogue T S and Luthy R G 2018 Multiple pathways to bacterial load reduction by stormwater best management practices: trade-offs in performance, volume, and treated area *Environ. Sci. Technol.* **52** 6370–9

Woods N D 2015 Regulatory democracy reconsidered: the policy impact of public participation requirements *J. Publ. Adm. Res. Theor.* **25** 571–96

Xu W D, Burns M J, Cherqui F and Fletcher T D 2021 Enhancing stormwater control measures using real-time control technology: a review *Urban Water J.* **18** 101–14

Yarnell S M, Petts G E, Schmidt J C, Whipple A A, Beller E E, Dahm C N, Goodwin P and Viers J H 2015 Functional flows in modified riverscapes: hydrographs, habitats and opportunities *Bioscience* **65** 963–72