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Blockchain Technology for Pay-For-Outcome Sustainable Agriculture Financing: Implications for Governance and Transaction Costs

Blockchain Technology for Pay-For-Outcome Sustainable Agriculture Financing: Implication for Governance and Transaction Costs

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Abstract

Pay-for-outcome financing mechanisms have been used to address agricultural runoffs to overcome the inefficiencies associated with push-based solutions, which are dependent on subsidies or philanthropic funding. As a market-based approach, pay-for-outcome platforms seek to incentivize sustainable practices, compensated by beneficiaries of the positive outcomes. Execution of pay-for-outcome financing mechanisms in an agriculture context is a complex transaction, involving investors, farmers, third party verifiers of outcomes, government and corporate beneficiaries, and thus requires a costly governance structure. Effective governance mechanisms are needed to meet the transaction costs identified in performance measurements. This study investigates the efficacy of blockchain technology to address transaction costs in pay-for-outcome financing for sustainable agriculture. Through a proof-of-concept, this study quantifies and explores the potential cost-saving benefits of utilizing blockchain. The proof-of-concept is an application of blockchain within a pay-for-outcome incentive model, namely the Soil and Water Outcomes Fund, for sustainable agriculture. Utilizing the Ethereum blockchain, transactions are facilitated through crypto wallets and a hybrid smart contract, while precipitation is used as a proxy for agricultural runoff measurements. Drawing from Transaction Cost Economics theory, a discussion is presented on how blockchains can reduce transaction costs, enhancing the governance and efficiency of pay-for-outcome mechanisms. Furthermore, the article presents blockchain transaction fees in the context of the scale of operations, considering the total number of participants in the Soil and Water Outcomes Fund. Our findings indicate that blockchain technology has the capacity to simplify intricate transactions, boost measurement accuracy, cut administrative expenses, and foster trust and transparency among stakeholders, thereby reducing the overall transaction costs associated with pay-for-outcome incentives. While blockchain has its limitations and is not a universally applicable solution for every type of transaction cost, we believe that blockchains are well-suited to facilitate pay-for-outcome financing such as the Soil and Water Outcomes Fund.

Keywords: Blockchain; Pay-for-outcome; Transaction cost; Smart contract; Sustainable agriculture; Chainlink oracle

1. Introduction

Excess nutrient input to natural waters can lead to eutrophication, the process by which algae blooms lead to hypoxia and degradation of water quality. Eutrophication has been shown to be a result of increased agriculture activities (Clune et al., 2020; Kerr et al., 2016). Due to the excess nutrient input and degradation of water quality from eutrophication, annual costs to drinking water quality, waterfront real estate value, and ecosystem restoration were estimated to be approximately $2.2 billion dollars (Dodds et al., 2009). End-of-pipe treatment strategies intended to manage eutrophication have been proposed, but they typically offer only short-term symptom relief, if any (Lürling et al., 2016). In contrast to end-of-pipe approaches, financial incentives for sustainable practices in agriculture that reduce excessive nutrient use have been introduced (Piñeiro et al., 2020). These incentives have historically relied on push-based programs, including “pay-for-practice” incentives or subsidies led by federal or local governments or philanthropic entities that pay agriculture producers to reduce fertilizer use and runoff by adopting low impact practices (Biffi et al., 2021). Examples include the Conservation Reserve Program Field Border Buffer Initiative, the Environmental Quality Incentives Program Organic Initiatives, and the Conservation Stewardship Program. In recent years, the Congressional Budget Office only allocated 6.8% of the total budget for the 2018 Farm Bill to the conservation programs (USDA Economic Research Service, 2023).

The long-term viability of such push-based programs is at risk due to potential budget cuts, and they may not deliver the intended water quality improvements (Shortle et al., 2012). It's projected that the Conservation Stewardship Program and the Environmental Quality Incentives Program will face a shortfall of $5 billion in the budget for the fiscal years 2024-2028 (National Sustainable Agriculture Coalition, 2019). Evidence suggests that the funds allocated from the U.S. Farm Bill for conservation payments is already short of what is needed to convert the required area of land to sustainable practices to see noticeable improvements in the water quality of Saginaw Bay, Michigan (Sowa et al., 2016). In the Plains and Prairie Pothole Region of the United States, only 8% of land area was enrolled in U.S. Farm Bill conservation programs, with farmers showing reluctance to participate due to financial considerations and a desire for autonomy (Sweikert & Gigliotti, 2019). Many other studies emphasize the need for greater conservation efforts (Piñeiro et al., 2020; Rehberger et al., 2023). This would require a significant increase in the conservation provisions within the Farm Bill (Sowa et al., 2016). However, many of the conservation programs are currently oversubscribed, with a backlog of farmer applications unfunded (Stubbs, 2022). The Institute for Agriculture and Trade Policy reported a similar phenomenon where the U.S. Department of Agriculture (USDA) rejects approximately three in four farmer applications to the Conservation Stewardship Program as well as the Environmental Quality Incentives Program (Happ, 2023). In addition to potential budget cuts and underfunding, there is strong evidence of misalignment of funds and environmental needs in conservation programs in the U.S. and E.U., limiting the effectiveness of such programs (Biffi et al., 2021). With the limitations of government funding, there is a growing inclination towards market-based approaches (Salzman et al., 2018; Shortle et al., 2012; US EPA, 2019).

The U.S. Environmental Protection Agency (EPA) issued a memorandum reiterating its "strong support for water quality trading and other market-based programs to maximize pollution reduction efforts and improve water quality" (US EPA, 2019). Water quality trading (WQT) involves transactions of 'credits' from a source that has reduced pollutants beyond mandatory levels to a buyer that leverages the credits to meet regulatory standards (US EPA, 2016). However, due to high transaction costs and limited participation, WQT has yet to deliver the anticipated efficacy

(Fisher-Vanden & Olmstead, 2013; Ribaudo & Nickerson, 2009). Payment for Ecosystem Services (PES) is another market-based incentive that has gained traction in recent years. Salzman et al. (2018) found considerable growth in the number of PES programs as well as transactions amounts across the watershed, biodiversity, and land-use carbon domains. Out of the three domains, watershed PES programs have experienced the most growth, with compliance confirmed through adoption of best management practices rather than actual improvements in water quality (i.e., performance-based). Prior literature suggests that using practice adoption as a determinant for compensation is less effective than performance-based models (Hanley & White, 2014; Lin et al., 2023; Weinberg & Claassen, 2006). In their 2006 study, Weinberg and Claassen compared the cost-effectiveness of the adoption approach to the performance-based approach. Results revealed that, for the same budget, performance-based programs could yield twice the environmental benefits of the adoption approach. Hanley and White (2014) showed that performance-based approaches are more advantageous when integrated with remote sensing to reduce the cost of monitoring. They also showed that performance-based approaches give farmers autonomy to innovate and choose their preferred implementation to achieve the desired outcomes. In a recent study, Lin et al. (2023) proposed an agent-based model that suggested pay-for-performance can reduce total suspended sediment loading with lower cost in the Susquehanna River Basin.

One on-going example of the performance-based approach is the Soil and Water Outcomes Fund. The Fund is implemented by the Iowa Soybean Association and Quantified Ventures (Washington, DC) to incentivize sustainable agriculture practices by measuring environmental outcomes. Investor capital is pooled in the fund for farmers to utilize for transitioning to more environmentally friendly practices, leading to reduced nitrogen and phosphorus concentrations in water, and more carbon retained in soils. The beneficiaries of the improved water quality and increased carbon sequestration pay out the fund investors. By considering multiple outcome metrics and identifying the corresponding beneficiaries, the fund is structured to pay out much more desirable per-acre payments than existing government programs to farmers. The mechanisms of the "pay-for-outcome" (PFO) performance management in the sustainable agriculture model are visualized in Figure 1. As of 2021, the fund has incentivized a 260% reduction in CO_2-equivalents, and a 28% and 27% reduction in nitrogen and phosphorus leakage, respectively, compared to the baseline "business-as-usual" practices (Soil and Water Outcomes Fund, 2021). The terms "performance-based approach," "pay-for-performance," and "pay-for-outcome" are used synonymously in this study.

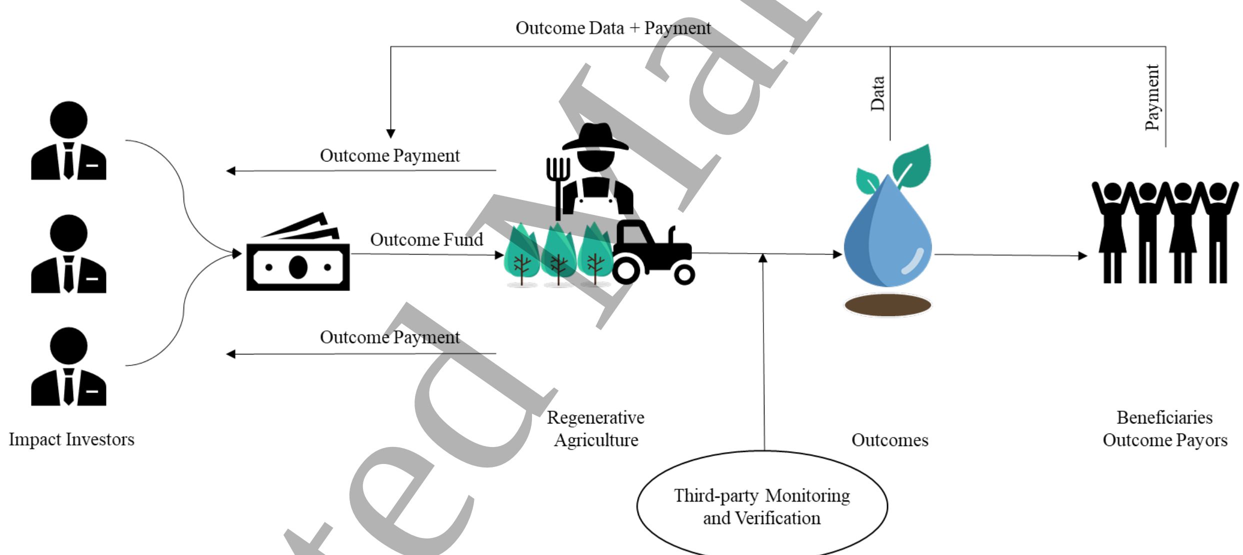

Figure 1. Outcome-based sustainable agriculture financing model (adapted from Quantified Ventures).

Costs associated with performance management can be assessed from three dimensions: transactional characteristics, governance features, and contextual factors (Musso & Weare, 2020). Relevant transactional characteristics include complexity and measurability. Measuring outcomes often requires considerable effort in data procurement and subsequent analysis. In addition, the validity of measurements is frequently disputed (de Olde et al., 2017; Gibon et al., 2020). Lack of consensus on the outcomes typically stems from the complexity of a project, uncertainties about the achievement of results, and ambiguity of the direct impact of the implemented changes. PFOs can also be costly and risky due to a lack of standardization while simultaneously being subject to unpredictable outcomes (Brand et al., 2021). The cost of developing financing structures presents an additional barrier for outcome-based financing to be adopted. Joffe (2015) as well as Strong and Preston (2017) have shown that the cost represents a large portion of the debt issued, leading to high transaction costs, illiquidity, and misalignment of risk-return expectations that create barriers for investments. Environmental impact bonds, a form of PFO, exhibit risks and uncertainty around performance metrics, costs in negotiations and structuring the contractual agreement as well as costs in forecasting and measuring (Brand et al., 2021). Additionally, governance structures are characterized by administrative costs and credibility of commitment. A range of contextual characteristics have also been considered, including accountability, stakeholder trust, and the quality of independent verifiers. Effective communication, coordination, and agreement from multiple entities are required (Ranjan et al., 2020). Considered a high-intensity incentive framework, PFO mechanisms can introduce gaming and issues of commitment that weaken the incentives, simultaneously increasing the administrative transaction cost (Musso & Weare, 2020). Musso and Weare (2020) theorized that (1) as incentive intensity increases, costs and benefits of performance management increase but the marginal cost increase is larger than the benefit accrued and (2) the difficulty of measurement or demands for accountability could limit the benefits of higher incentive intensities. With increasing incentive intensities, the legitimacy of the key performance indicators is likely to be called into question. In these cases, data tampering and manipulation can occur to achieve desired outcomes, and more resources will be required to corroborate the data veracity thereby increasing overall costs and expenses (Musso & Weare, 2020).

Innovations in technology, such as internet-of-things (IoT) and distributed ledger technology (DLT), show promise in lowering transaction costs (Chung et al., 2023; Dey & Shekhawat, 2021; Okpara et al., 2022; Ratliff et al., 2019). DLT, known more commonly as blockchain, has the potential to address the informational and transactional inefficiencies of firms and organizational models (Dey & Shekhawat, 2021; Figueiredo et al., 2022). The decentralized characteristic of blockchain in conjunction with trust generation through cryptographic algorithms, direct peer-to-peer interactions, and low counter-party risk have been argued to reduce transaction costs (Ahluwalia et al., 2020; Bakare et al., 2021; Schmidt & Wagner, 2019). Information asymmetry between transacting parties can be ameliorated by the blockchain's transparent nature and removing intermediaries (Ahluwalia et al., 2020). Schmidt and Wagner (2019) posit that blockchain helps to solve three governance problems in decision chains: safeguarding by limiting opportunistic behavior, transparency in performance measurement, and secure adaptation of parties in the information chain to uncertainty in outcomes. Bakare et al. (2021) proposed a blockchain-based framework for direct cash subsidy transfer to farmers in India to overcome payment corruption and delays that have hindered government agriculture subsidy programs. The authors argue that blockchain smart contracts technology ensures transparency, reduces delays and instances of fraud, and eliminates intermediaries in the current benefits distribution system. By examining several financial institutions that have applied blockchain technology to bonds issuances, Pana and Gangal (2021) concluded that blockchains effect cost reduction by shortening the length of the settlement processes as well by decreasing the number of intermediaries. Pufahl et al. (2021) uses blockchain technology to address trust and efficiency across the agriculture supply chain, where payment failure, insufficient visibility, and high costs of obtaining information frequently occurs. Chen (2022) suggested that blockchains can monitor dynamic changes in production lines to improve energy efficiency, thus reducing corporate carbon emission intensity. While there has been ample research on cryptocurrencies and specific applications of blockchain, the literature on environmental governance utilizing blockchains is wanting and largely aspirational (Kumar Singh et al., 2023; Rocha et al., 2021). Howson et al. (2019) echoed this sentiment and suggested that more case-specific demonstrations are required for future adoption blockchain-based solutions. The execution of such systems is limited by technical expertise, scalability, privacy and security, and regulatory standards (Mendling et al., 2018; Zhang et al., 2023).

There is a knowledge gap in real-world applications at the intersection of blockchain technology and pay-for-outcome incentive structures. The objective of this study is to evaluate the efficacy of blockchain technology in reducing transaction costs in sustainable agriculture PFOs. This research seeks to answer the question: Are blockchains a suitable technology to facilitate sustainable agriculture PFOs? A proof-of-concept (PoC) for pay-for-outcome financing in sustainable agriculture using a hybrid smart contract on the Ethereum blockchain is presented. The benefits of employing blockchains in a PFO incentive structure are explored through the perspective of transaction cost economics (TCE). Blockchain wallets, a Chainlink oracle between the hybrid smart contract and off-chain weather data, and the Accuweather application programming interface are employed to illustrate the potential benefits of blockchains for PFOs, using the Soil and Water Outcomes Fund as a case study. Then, an argument is made for transacting through hybrid smart contracts, suggesting potential reductions in transaction costs relative to incentive intensity. Finally, the scalability of the PoC as well as the limitations of this study are addressed.

To the best of the authors' knowledge, this is the first study to provide PoC for a blockchain-based PFO and examine transaction costs in integrating blockchain technology for outcomes-based incentives in sustainable agriculture. By utilizing the TCE framework, this study discusses how blockchains are the favorable platform to implement PFOs by reducing costs and efficiently managing PFOs and transactions. This paper is subsequently structured as follows: In Section 2, the Soil and Water Outcomes Fund is described and set up in the context of a blockchain-based PFO sustainable agriculture scheme. The methods and tools are also discussed. In Section 3, the results of the proof-of-concept are presented. Blockchain-based PFOs from a transaction cost economics perspective, the scalability of the PoC, and the limitations of this study are also discussed in Section 3. The last section concludes the results and implications of this study.

2. Use Case and Methods

The Soil and Water Outcomes Fund, using Dubuque County in Iowa as the proof-of-concept location. The method consists of three main components: (1) the Ethereum Kovan Testnet and Goerli Testnet as the underlying blockchains with three Ethereum wallet accounts representing a farmer, an investor, and a beneficiary, (2) a hybrid smart contract[1] and (3) precipitation data accessed through the Accuweather Chainlink oracle data provider.

2.1 Use Case – The Soil and Water Outcomes Fund

The use case depicts an investor in the Soil and Water Outcomes Fund being rewarded by beneficiaries for outcomes such as reduction in nutrient runoff when a farmer transitions to more sustainable practices. Upfront capital is made to the farmer from the Soil and Water Outcomes

[1] Hybrid smart contracts are defined as "code running on the blockchain (on-chain) with data and computation from outside the blockchain (off-chain) provided by decentralized oracle networks." Source: https://chain.link/education-hub/hybrid-smart-contracts

Fund to incentivize and sustain less fertilizer-intensive practices. The beneficiaries purchase the positive outcomes of better water quality due to the shift to more sustainable practices and the proceeds are distributed back to the investor via the fund (Figure 1).

The PoC location is Dubuque County, Iowa (Latitude: 42.46916479, Longitude: -90.873663172) where farmers have enrolled in the Soil and Water Outcomes Fund. In the PoC, rather than direct sensor measurements of nitrogen and phosphorus at the edge of a farm, precipitation data was used as a proxy for nutrient runoff since Dubuque County does not have a Chainlink oracle to provide real-time water quality data from the field. The use of precipitation data from the AccuWeather Data Oracle, is a reasonable proxy and predictor for nutrient input into water bodies (Elrashidi et al., 2013; Sinha et al., 2017). For example, Sinha et al. (2017) showed that due to climate-change induced precipitation increase, riverine total nitrogen loading will also increase by 19 ±14%. Fertilizer inputs would need to decrease by 33 ±24% to offset the increase. Elrashidi et al. (2013) found that total soil nutrient loss from agriculture nonpoint sources was greater in wet years than dry years.

2.2 Methods

2.2.1 The Ethereum Blockchain and Wallet Accounts

The Ethereum blockchain is programmable, and allows for decentralized applications to be written in the Turing-complete language, Solidity (Buterin, 2014). The PoC application is an Ethereum hybrid smart contract. The Solidity-based hybrid smart contract used in this study can be found on GitHub[2]. The Kovan and Goerli Testnets are independent networks that conform to the Ethereum Mainnet protocol where the hybrid smart contracts are deployed. These networks are production-

[2] https://github.com/Enveblockchain/Ag_payforoutcome

like environments used to test smart contracts before deployment to the Mainnet. Kovan is a public proof-of-authority (PoA) Ethereum Testnet that has deprecated since the Ethereum blockchain transition from proof-of-work to proof-of-stake in September 2022. Goerli is a proof-of-stake (PoS) Ethereum Testnet which client developers are maintaining post-transition. Goerli's state is closest to Mainnet and is the recommended Testnet by the Ethereum Foundation. The entities in the PoC are represented as wallet accounts on the Ethereum blockchain. The farm, investor, and beneficiary have private keys that give them rights to access their own externally-owned accounts (EOAs) and the hybrid smart contract have addresses themselves termed contract accounts. The contract account code executes when deployed on the blockchain and takes up network storage (Buterin, 2014). The EOAs or other contract accounts can call accessible functions on the smart contracts to initiated transactions (Smith, 2023). In the PoC, we created three EOAs with Metamask and one hybrid smart contract on the Ethereum blockchain. The hybrid smart contract facilitates the interactions in the PFO and was written and compiled in the Remix integrated development environment (Remix, 2022). Security considerations for the contract were minimal as the PoC is for demonstration purposes only, thus the hybrid smart contract was written in a straight-forward manner.

2.2.2 Hybrid Smart Contract

The hybrid smart contract used in this study modifies and adds to Accuweather's bare-bone consumer contract for PFO functionality. The variables in the hybrid smart contract are the payout incentive (outcome_Payment), the precipitation in the specified location over the past 24 hours (precip24), and the three addresses of the investor or capital provider (Financier), the farmer (ServiceProv), and the beneficiaries (Gov) defined as the payable hashes of their respective EOAs. The state variables also include a storage for the unique oracle request identifier (loccurcondition_RID) and the oracle job identifier (loccurcondition_jobId). An oracle job specifies a series of tasks that needs to be carried out to procure off-chain data and send the data back on-chain to the smart contract. The reserved function (receive) paired with the payable modifier allows Ether (ETH) to be deposited into the contract account. The first function (withdrawFromContractBalance) enables the PFO participants to withdraw capital held in the smart contract (e.g., the up-front capital to enable farmers to implement sustainable agriculture practices from the financier or benefit payments from the beneficiary to the financier). The next set of functions initiates and completes the request-and-receive cycle that retrieves off-chain outcome data through an oracle. The function requestLocationCurrentConditions sends the data query as well as the payment for oracle services. Next, fulfillLocationCurrentConditions is the receive function that can only be called by the oracle that executed the data query with the unique oracle request identifier, in this case, loccurcondition_RID. Upon the call-back, the off-chain data is stored in the functions storeLocationResults and storeCurrentConditionsResults. The outcome metric that informs who receives the PFO payment is stored in storeCurrentConditionResult (precip24). The last function (outcomePayment) transfers the PFO payment to the financier if the desired outcome is achieved. The function enables transfer to the financier's wallet if the precipitation amount, just received on-chain by the callback mechanism, remains lower than a specific threshold.

2.2.3 Chainlink Oracle and Accuweather Application Programming Interface

Chainlink oracles link off-chain Accuweather precipitation data to the Ethereum hybrid smart contract (Figure 2). The hybrid smart contract makes a request to the Chainlink oracle through a sendChainlinkRequest that sends the request and Chainlink token (LINK) amount to the specified oracle address. The transferAndCall function imported within the ChainlinkClient contract from the ERC677 protocol, enables transfer of LINK tokens to the governing oracle contract and simultaneously initiate actions based on data from the sendChainlinkRequest. The oracle contract communicates by emitting an OracleRequest event that has the request specifications from the client hybrid smart contract. The emitted event is monitored and recorded by the off-chain oracle node which initiates a job request to the Accuweather API. Once data is retrieved from Accuweather, the off-chain node calls the fulfillOracleRequest function in the oracle contract to move the requested data back on-chain. In fulfillOracleRequest, it uses the callback contract address initially defined in the hybrid smart contract to return the result to the ChainlinkClient.

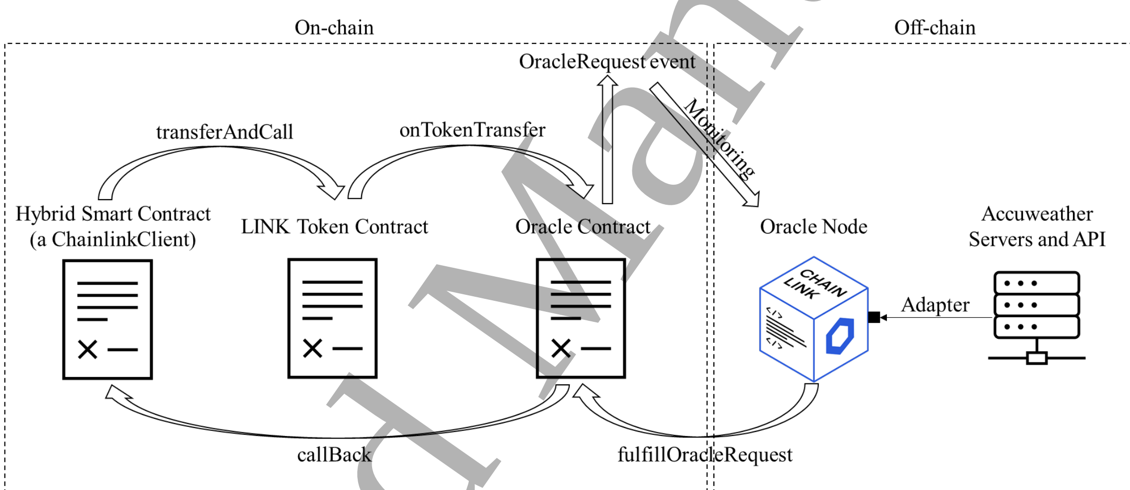

Figure 2. Data flow from on-chain request to off-chain fulfillment (Chainlink, 2023).

The AccuWeather Application Programming Interface (API) enables queries for weather data based on a given location through a web interface that follows REST architecture. REST, or REpresentational State Transfer, is an data access standard for applications on the web to communicate with one another (Codecademy, 2022). Given an API key, the user can search for a specific location with geographic coordinates, postal codes or city names using the Locations API, which responds with a location key. The location key that is returned can be used to access other API endpoints such as current conditions or daily forecasts weather data APIs.

3. Results and Discussion

The PoC applies a blockchain-enabled process to the Soil and Water Outcomes Fund (Figure 1). Three blockchain characteristics are suitable and applicable to the use case of sustainable agriculture incentives. First, smart contracts make payments tamper-proof. In hybrid smart contract presented in this study, the farmer who receives the incentive payment is defined as the state variable ServiceProv. The contract address cannot be modified once it is deployed on the blockchain. This means that any transaction initiated by the transfer function will be sent to the correctly designated recipient. While the smart contract in this proof-of-concept includes only one farmer, the number of participating farmers can be scaled to include an arbitrary number of recipient addresses. Second, an immutable record of all transactions occurring from the pay-for-outcome scheme is etched in Ethereum blockchain. These records are visible and can be queried by all stakeholders since the Ethereum blockchain is a public ledger. Third, the hybrid smart contract serves as a trusted monetary distribution escrow, ensuring payments are received by the correct recipients and timely settlement is achieved. It allows for flexible timing of transactions as long as the contract remains funded by the investors. The smart contract acts as an escrow from which farmers can withdraw a pre-specified amount. Payments cannot be voided or stopped by an individual authority thus the farmers in this case can depend on timely deliveries of funds. Outcomes for PFO scheme can be extended to other metrics and do not have to be limited to nutrient reduction as long as suitable metrics or proxies can be defined, particularly for conservation performance payments (Engel, 2016).

3.1 Proof-of-Concept Blockchain Payment

The PFO is comprised of five transactions executed on the Ethereum blockchain: (1) the deployment of the smart contract, (2) the initial investment from the financier that send and stores funds in the hybrid smart contract analogous to the Soil and Water Outcomes Fund, (3) the transfer of funds to the farmer's wallet via the smart contract, (4) the initiation of the request-and-receive cycle including LINK payment to the Accuweather Chainlink oracle, (5) the beneficiaries send funds to the smart contract for the financiers to withdraw based on the outcome of the data from Accuweather. For all these function calls and executions require Ether to run and LINK to access the oracle services. Transaction fees are not proportional to the amount of Ether being transferred. Function calls required gas fees in gwei, a denomination of Ether. Only when accessing the Accuweather oracle services are LINK tokens required. The results shown in Table 1 indicate that when testing the PoC on the Koven Testnet and Goerli Testnet, all transactions combined, totaled 0.00889559 ETH and 0.01935112 ETH, respectively. The US Dollar price of Ether ranged from $993.64 to $3522.83 between April 2022 and April 2023 (CoinMarketCap, 2023), the period during which this PoC was conducted. For the Kovan Testnet, the total transaction fees are thus equivalent to $8.84 - $31.34 USD to execute the pay-for-outcome transaction. Transaction fees registered on the Goerli Testnet were higher than those found on the Kovan Testnet, falling in the range of $19.23 - $68.17 USD. The Goerli Testnet transaction fees should closely resemble those on the Ethereum Mainnet as it uses the same consensus mechanism (i.e., proof-of-stake) and its state is closest to the Mainnet. The Kovan Testnet uses proof-of-authority consensus which has deprecated since the Ethereum upgrade from the proof-of-work mechanism to proof-of-stake.

Smart contract deployment is a one-time transaction and accounts for the bulk of the transaction fees. Once deployed on the blockchain, there are no subsequent fees to be incurred for this transaction. Given the total transaction fees in Table 1 include the accurate and timely transfer of funds, agnostic jurisdiction boundaries, a tamper-proof benefit distribution mechanism, and an immutable record of the process, the operational transaction costs of the PFO should be considered lower than the incentive being paid for sustainable agriculture adoption. Additionally, the PoC shows that PFOs can be executed on a blockchain in a series of streamlined trusted transactions. Capital providers are less hesitant to invest if they can be assured that funds are transparently delivered to the right entity and the return on investment is based on verifiable environmental outcomes.

Table 1. Blockchain transaction fees for the PFO smart contract in Ether and US dollars.

	Kovan Testnet		Goerli Testnet	
Transaction	**Ether**	**US Dollars**	**Ether**	**US Dollars**
Smart contract deployment	0.00818347	$8.13 - $28.83	0.01757218	$17.46 - $61.90
Outcomes Fund investment	0.00004737	$0.05 - $0.17	0.00009691	$0.10 - $0.34
Farmer incentive payment	0.00007878	$0.08 - $0.28	0.00017296	$0.17 - $0.61
Weather data procurement	0.00048011	$0.48 - $1.69	0.00122188	$1.21 - $4.30
Outcome payment	0.00010586	$0.11 - $0.37	0.00028719	$0.29 - $1.01
Total*	**0.00889559**	**$8.84 - $31.34**	**0.01935112**	**$19.23 - $68.17**

*Total may not be equal to the sum of all parts due to rounding errors.

3.2 Implications for blockchain-based PFO governance and TCE

The potential for cost reductions of blockchain-based PFOs has implications from a TCE perspective by discouraging fraud and gaming, providing transparency, reducing complexity, and ensuring accurate measurements. Following Musso and Weare (2020)'s qualitative graphical framework and discussion, Figure 3 illustrates blockchain-based PFOs' transactional characteristics, governance features, and contextual factors on the TCE cost and benefit curves. Let I be incentive intensity, C_0 to C_3 the total cost for implementing the incentives depending on transactional characteristics, governance features, and contextual factors, and B the benefits resulting from implementing incentives to reduce nutrient runoff. A theoretical benefit maximum exists at I = I*, where marginal costs equal the marginal benefits.

Increasing incentive intensity may improve performance and outcomes but very likely at the expense of higher governance and administrative costs, while simultaneously inducing malicious behavior such as gaming schemes (Musso & Weare, 2020). The cost curve may shift up from C_0 to C_1 for incentive mechanisms that require public accountability due to measurement ambiguity, leading to an increase in cost of monitoring, measuring, reporting, and auditing. Other costs include assessing the viability of performance-based setup, communication and coordination with willing farmers, engaging beneficiaries for incentive payout, and variable third-party verification costs. A third-party verifier would also be a potential single, centralized point of failure. Counter-party risk and low trust in centralized entities, such as evaluators and rating providers increase transaction costs further (deHaan, 2017; Gillespie & Hurley, 2013; Tomasic & Akinbami, 2011). Given the upward shift in cost, the net benefits of outcomes-based incentives would decrease. In cases where accountability issues are exacerbated or where participating actors work to game the performance metrics, the cost curve could increase to C_2, eliminating any net benefits.

The combination of blockchain properties including decentralization, transparency, and immutability, with smart contract functionalities such as enabling automation, has the capacity to shift the cost curve for PFOs from C_0 down to C_3 (Figure 3). Decentralization and transparency through consensus algorithms address costs associated with accountability and stakeholder trust (Ahluwalia et al., 2020; Bakare et al., 2021; Schmidt & Wagner, 2019). In addition, hybrid smart contracts, Chainlink oracles, and IoT sensors reduce the need for third-party monitoring, verification, and fund management, lowering transaction costs (C_0 to C_3). Conditional decision-making based on off-chain data such as those collected using IoT can be automated and streamlined, reducing friction in governance structures including administrative costs (Christidis & Devetsikiotis, 2016; Jiang et al., 2019). Hybrid smart contracts can enforce commitment through transparent, automated transaction execution based on performance outcomes read directly from IoT sensors, limiting opportunistic behavior and reducing uncertainties, which can further induce a shift from C_0 to C_3 (Schmidt & Wagner, 2019). The TCE implications apply in the context of the Soil and Water Outcomes Fund. Since the outcome incentives, farm participation and beneficiaries are well-defined, the benefits of facilitating the Fund on the blockchain can be realized.

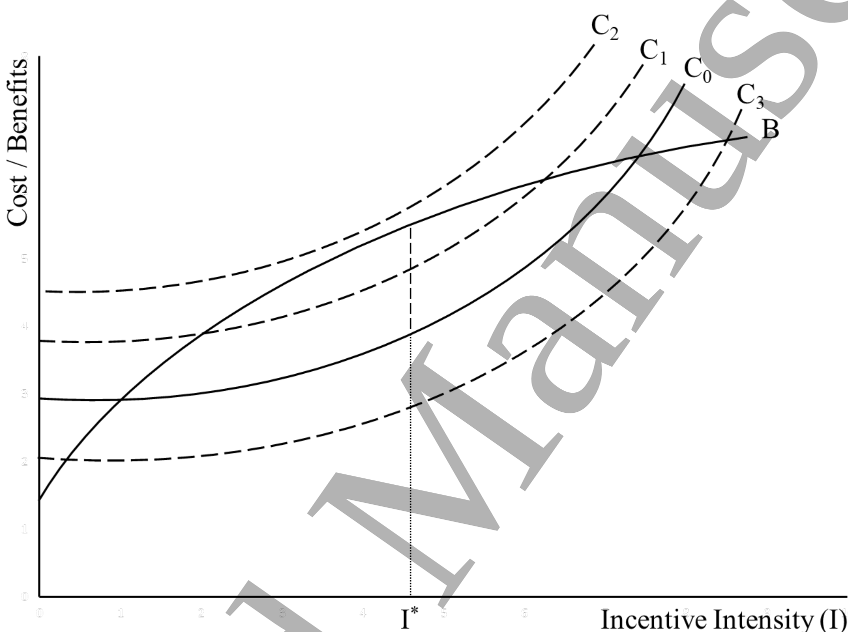

Figure 3. Effects of blockchain on the cost curve of outcomes-based incentives (adapted from Musso and Weare (2020)).

3.3 Scalability of blockchain-based PFO transactions: Soil and Water Outcome Fund Use Case

A PFO program for sustainable agriculture is typically deployed in a region, across a network of farmers covering large acreage of crops, and multiple beneficiaries. The Soil and Water Outcomes Fund added conservation practices such as cover crops and reduced tillage to more than 140,000 acres of cropland across multiple states in 2022. For farmers' reduction of nitrogen and phosphorus runoff and carbon sequestration, an average of $31 USD was paid per acre on an annual basis, totaling approximately $4.34 million USD[3]. The combination of hybrid smart contracts, oracles, and environmental data enables the PFO scheme to be self-enforcing and automated, and thus the scalability of this incentive mechanism is promising (Christidis & Devetsikiotis, 2016). The scalability of the blockchain-based PFO needs to consider the number of capital providers, participating farmers, and beneficiaries participating in the PFO. Earlier, presents transaction fees per investor, farmer, and beneficiary were presented (Table 1). In 2022, the Soil and Water Outcomes Fund has 3 primary investors, approximately 130 sustainable farming practices under contract, and 12 beneficiaries. Given that the smart contract deployment is a one-time transaction, we are only concerned with the scaling of transaction fees associated with Outcomes Fund investments, farmer incentive payments, weather data procurements, and outcome payments. Table 2 shows the range of transaction fees as a percentage of the total farmer incentive payments. The highest estimated transaction fee percentage is 0.0164% on the Goerli Testnet while the lowest is observed on the Kovan Testnet at 0.0019%. These transaction fees include deploying the smart contract, pooling funds from 3 investors to the smart contract, distributing the funds to 130 farming practices, measuring outcomes, and 12 beneficiaries sending funds back to the investors based on outcomes. For actively managed mutual funds, the typical expense ratio ranges from 0.5% to 1% (Maverick et al., 2021). While no comparable data are available for management and administrative costs of implementing a PFO, the proof-of-concept shows that blockchain-based PFOs are a promising alternative, reducing transaction fees that can lead to substantial differences in cost savings and returns over an extended period.

[3] Soil and Water Outcomes Fund: https://www.theoutcomesfund.com/impact

Table 2. Scaling of transaction fees as a percentage of the total farmer incentive payments

	Kovan Testnet	**Goerli Testnet**
Transaction	**US Dollars**	**US Dollars**
Smart contract deployment	\$8.13 - \$28.83	\$17.46 - \$61.90
Outcomes Fund investment	\$0.15 - \$0.51	\$0.30 - \$1.02
Farmer incentive payment	\$10.40 - \$36.40	\$22.10 - \$79.30
Weather data procurement	\$62.40 - \$219.70	\$157.30 - \$559.00
Outcome payment	\$1.32 - \$4.44	\$3.48 - \$12.12
Total	**\$82.40 - \$289.88**	**\$200.64 - \$713.34**
% of Total Incentive Payment	**0.0019% - 0.0067%**	**0.0046% - 0.0164%**

3.4 Study Limitations

While the results of the blockchain-enabled PFO are appealing, there are several limitations in this study and require further deliberation in future work. First, the cost of negotiating payout schemes for farmers was not considered and neither were the development costs, hence the focus was on execution of key operational elements. The purported cost savings require empirical validation. Second, the dependence on cryptocurrencies as the medium of exchange leads to additional barriers. An Ethereum smart contract can only transfer Ethereum Virtual Machine-compatible cryptocurrency such as ETH, LINK, and Polygon (Matic). All participating entities in the PoC would need to convert between fiat currency like the US dollar and ETH. Currently, the most straight-forward way to convert crypto to fiat, and vice versa, is through a crypto-exchange, which add to the barriers of setting up and scaling the PFO mechanism, that requires a bank account that complies with know-your-customer (KYC) and anti-money laundering (AML) procedures. In the conversion process, the crypto-exchanges charge fees as well. Factors such as the payment method, order amount, volatility of the market conditions and the exchange's liquidity determine the fees in the process, adding uncertainty to the process. The volatility of cryptocurrency values also remains a concern. This presents additional risks in blockchain-enabled PFOs. Lastly, contingency functions are not defined in the PoC smart contracts. Contingency functions that terminate the contract should be considered in case of any extreme weather conditions that may distort or affect monitoring outcomes. Such functions will only activate or trigger if certain abnormal (i.e., out of range) conditions occur. They could then be called by any participating entity after reaching an agreement on terminating the contract.

4. Conclusions

Excess nutrient runoff from conventional farming practices has led to degradation of surface water quality, and push-based incentives have limited results in inducing source reductions. This study explores a pay-for-outcome incentive structure on the blockchain for sustainable agriculture and discusses its potential cost reduction compared to non-blockchain solutions through the lens of Transaction Cost Economics. Previous literature has argued that "pay-for-outcome" approaches are associated with high transaction costs due to its high-intensity incentive nature. While pay-for-outcome structures are highly dependent on payment incentives, blockchain technology presents potential solutions to addressing the associated transaction costs. Blockchain's inherent decentralized characteristics, combined with consensus algorithms, direct peer-to-peer interactions, and programmable smart contracts, limit opportunistic behavior, increase transparency in outcome measurements, and reduce uncertainty in pay-for-outcome governance structures.

A proof-of-concept that simulates the Soil and Water Outcomes Fund on the Ethereum blockchain is present in this study. Three Ethereum wallet accounts were used to represent a farmer, an investor, and a beneficiary participating in the Soil and Water Outcomes Fund. The hybrid smart contract was deployed on two underlying blockchains: the Ethereum Kovan Testnet, employing proof-of-authority consensus, and the Goerli Testnet, utilizing proof-of-stake consensus. The hybrid smart contract governed transactions and was also used as an escrow to store value, representing the Soil and Water Outcomes Fund on the blockchain as a contract account. In lieu of water quality data for outcome measurements, the hybrid smart contract queries precipitation data from Accuweather Chainlink oracle data provider as a proxy. Five transactions constitute the blockchain-based pay-for-outcome setup: the deployment of the smart contract, the initial investment from the financier that send and stores funds in the hybrid smart contract analogous to the Soil and Water Outcomes Fund, the farmer transfer funds locked in the smart contract to their wallet, the initiation the request-and-receive cycle including LINK payment to the Accuweather Chainlink oracle, and the beneficiaries send funds to the smart contract for the financiers to withdraw based on the outcome of the data from Accuweather. The five transactions incurred transaction fees of \$8.84 - \$31.30 on the Kovan Testnet and \$19.23 - \$68.17 on the Goerli Testnet. A qualitative graphical analysis of transaction costs was subsequently discussed. Non-blockchain pay-for-outcome incentives can have higher governance and administrative costs, while simultaneously inducing malicious behavior such as gaming schemes. Blockchain-based pay-for-outcome setups are argued to lower costs through decentralization, increased transparency and data-informed transactions on hybrid smart contracts. Blockchain technology can reduce the need for third-party monitoring, verification, and fund management with a streamlined data feed from IoT sensors to a hybrid smart contract using Chainlink oracles. Hybrid smart contracts can also limit opportunistic behavior and reduce uncertainties by enforcing commitment through automated transaction execution based on off-chain data outcomes, which can further reduce costs. Scaling of the proof-of-concept to include the total number of participants in the Soil and Water Outcomes Fund showed transaction fees to be lower than actively managed mutual fund expense ratios.

Despite the limitations of this study, the proof-of-concept and transaction cost analyses show promising evidence that blockchain technology is well-positioned to support pay-for-outcome financing mechanisms such as the Soil and Water Outcomes Fund.

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