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From Trails to Tokens: FinTech Frontiers for Sustainable Stewardship and Transparent Governance in Protected Recreation Landscapes

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Abstract: Protected recreation landscapes grapple with a chronic trust deficit driven by financial opacity, operational leakage, and social inequity as challenges largely sustained by traditional cash-based revenue systems. This paper introduces the Trails-to-Tokens (T2T) model, a novel governance architecture designed to bridge the gap between physical stewardship interactions (Trails) and transparent, digital financial instruments (Tokens). Synthesizing Socio-Ecological Systems and Institutional Trust theories, the T2T framework utilizes blockchain-enabled smart contracts to automate revenue sharing and reward stewardship based on verifiable ecological and social outcomes. A key contribution of this paper is the transition from purely conceptual discourse to a data-informed architectural roadmap. The study internalizes empirical findings from African protected areas, where revenue accountability often shows significant downward trends and community trust remains low. The T2T model addresses these failures by providing an operationalization matrix and a four-phase pilot protocol intended for future empirical validation. By replacing discretionary human intermediaries with immutable digital ledgers, the model establishes a performance-linked social contract that is hypothesized to restore trust and foster financial resilience, provided the initial rule-setting is transparent. This paper offers a replicable methodology for conservation managers and policymakers, moving beyond aspirational digital trends toward a functional, transparent, and inclusive system for landscape governance. The result is a transformative approach that secures the long-term legitimacy of biodiversity financing through technological accountability and measurable stewardship.

Keywords: FinTech, protected areas, governance, smart contracts, institutional trust

1. Introduction

Protected recreation landscapes face a precarious crossroads where rising human demand strains delicate ecosystems. Pressures from visitation, climate change, and chronic underfunding are exacerbated by opaque governance, allowing conservation funds to be lost through systemic loopholes [1, 2]. This gap has fostered public skepticism; however, financial technology (FinTech) offers a remedy by embedding transparency and accountability directly into financial flows [3].

Many agencies are already implementing digital payments and blockchain-based funds to revolutionize conservation support [4]. For example, fee digitalization in Rwanda and Kenya has significantly reduced revenue leakage [5]. Through blockchain, donor contributions become traceable links connecting inputs to on-ground outcomes, increasing credibility for all stakeholders [6].

This shift addresses a broader societal demand for transparency, providing communities with tangible evidence that revenue-sharing agreements are honored. FinTech restores legitimacy by making stewardship visible, thereby strengthening stakeholder participation [7]. Despite challenges like low digital literacy or resistance to transparency, this article argues that by integrating financial honesty with human stewardship, FinTech acts as a catalyst for institutional change, ensuring financial integrity supports long-term ecological health [8, 9].

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1.1. Research aim and contribution

This paper proposes a governance system embedding transparency and fairness into protected area financing. It introduces the Trails-to-Tokens (T2T) model, a theory-building framework designed to transition from arbitrary, cash-based systems to digitally tracked, performance-based stewardship. The study addresses three core research questions (RQ):

1) *How can decentralized ledgers bridge the "trust gap" between institutions and local custodians?*
2) *What structural elements are essential for automating verifiable stewardship rewards via smart contracts?*
3) *To what extent can token-driven governance reduce documented revenue leakage compared to centralized manual systems?*

The T2T model is most effective in landscapes with emerging digital infrastructure and high tourism dependence. Conversely, it excludes areas lacking internet access or facing extreme political opposition to decentralization that prevents the use of transparent ledgers.

2. Conceptual Background

Protected recreation landscapes embody a deep emotional and ecological tension, often supported by fragile or opaque governance structures. To argue that FinTech can reshape stewardship, we interrogate four domains: the evolving character of these landscapes, defining governance dilemmas, financing limitations, and the transformational rationale for FinTech. These dynamic terrains are continuously shaped by institutional habits and ecological urgency.

2.1. Understanding protected recreation landscapes

Protected recreation landscapes are complex social-ecological systems where human desires intersect with biological cycles, serving as ecological refuges, economic engines, and cultural stabilizers [10]. Their value is inherently multilayered, encompassing ecological stability, spiritual grounding, and recreational joy. However, this multifaceted nature introduces significant management complexity, as administrators must navigate rising visitation, climate shocks, and community demands for equity, often operating under budgets that fail to reflect the magnitude of these responsibilities [11].

The integrity of these landscapes depends fundamentally on trust, which must be visible through governance practices reflecting fairness and accountability. Visitors seek assurance that their presence contributes positively, while local communities require proof that restricted resource access translates into tangible social benefits. Furthermore, donors demand transparent evidence that investments yield conservation outcomes rather than being lost to bureaucratic inefficiency or corruption. Unfortunately, many governance systems remain rooted in outdated administrative cultures relying on manual reconciliation and unverified agreements that were never designed for modern public scrutiny or digital expectations. This study begins by acknowledging that the current governance environment is not merely outdated; it is structurally misaligned with contemporary conservation realities, necessitating a shift toward more transparent, digitally enabled frameworks.

2.2. Governance and stewardship realities in protected areas

Stewardship represents the moral act of caring for protected landscapes, yet this commitment is frequently undermined by systemic institutional limitations. While organizations publicly pledge accountability, chronic underfunding often forces governance to prioritize short-term revenue over long-term ecological resilience [12, 13]. In the Global South, prevalent cash-based systems facilitate revenue leakage at every stage, leaving local communities with less than their agreed shares and fueling resentment toward opaque financial processes [14].

This collapse of stewardship stems directly from a lack of transparency, as visitors and donors lack the tools to verify if their contributions truly support rangers or habitat recovery [15]. Such skepticism creates deep social divisions, often leading to increased illegal hunting or corruption when the system is perceived as inherently unfair [1]. Ultimately, the primary challenge is a fundamental crisis of trust that necessitates FinTech as an essential mechanism for restructuring institutional integrity [4, 16].

2.3. Conventional financing models and their chronic weaknesses

Protected areas have long relied on four main financing streams: gate fees, concessions, government allocations, and donor funding. Although these mechanisms have kept parks functional for decades, they also produce structural vulnerabilities that undermine both governance and ecological strategies, as indicated in Table 1.

2.3.1. Gate and user fees

Gate fees, the public face of park financing, often struggle with fragile, outdated oversight. Cash-based collection creates significant revenue leakage through undocumented transactions and inconsistent enforcement, causing recorded income to rarely align with visitor traffic [1, 17]. Beyond financial loss, this system erodes institutional trust. When visitors and local communities observe arbitrary fees or informal payment negotiations, the legitimacy of the entire revenue model weakens. Such inconsistencies reduce the public's willingness to pay, even among conservation-minded individuals [17, 18]. Ultimately, weak financial governance transforms a potential source of stability into a source of doubt,

Table 1
Chronic weaknesses of conventional financing models in protected areas

Financing mechanism	Critical weaknesses	Broader consequences
Gate and user fees	Cash leakage, variable pricing, fraud	Low trust; distorted revenue data
Concessions	Opaque records, delayed remittances	Social conflict; inequitable distribution
Government allocations	Political volatility, austerity cuts	Planning paralysis; weak monitoring
Donor funds	Short project cycles, reporting gaps	Dependency; limited sustainability

undermining the social foundations necessary for effective conservation. To ensure sustainability, these systems must transition toward transparent, standardized digital processes that foster accountability and restore stakeholder confidence in how conservation resources are managed and distributed.

2.3.2. Concession and licensing

Concessions like eco-lodges are vital for connecting conservation with sustainable livelihoods [19]. However, these schemes are often weakened by secretive, discretionary decision-making and skewed bargaining power [20]. Contracts negotiated without documentation or community consultation allow elite actors to capture advantages, leaving local populations with minimal benefits.

Revenue sharing remains plagued by manual, inconsistent reporting and limited administrative capacity to monitor compliance. This enables under-reporting and contract avoidance, resulting in payment delays or unexplained deductions for communities. Such financial disappointment fuels deep frustration and conflict, often leading to protests or conservation disengagement. Without transparent digital auditing and rigorous enforcement, concessions risk exacerbating the very inequalities conservation aims to resolve. Unless integrated into a framework of local ownership and institutional strengthening, donor funds and concessions alike may inadvertently perpetuate dependency and systemic fragmentation.

2.3.3. Government allocations

Public investment signals national commitment, providing the stable baseline required for long-term conservation. However, allocations are vulnerable to political shifts and fiscal crises, where conservation is often deprioritized for infrastructure [21].

These fluctuations trigger staff reductions, salary delays, and the suspension of essential patrols. Crucial ecological monitoring may cease, leaving biodiversity loss undetected, while irregular wages erode morale and retention [17, 22]. Furthermore, chronic uncertainty discourages strategic innovation, fostering a reactive survival culture rather than visionary stewardship. This institutional fragility is particularly dangerous for areas battling climate change and poaching, as financial instability compromises overall outcomes [21]. To ensure resilience, public funding must be shielded from political volatility and integrated into a robust financial architecture that supports continuous, long-term ecological and institutional health.

2.3.4. Donor funds

Donor funding is essential for infrastructure and species recovery in protected areas. However, short project cycles (2–5 years) driven by external priorities often lead to temporal fragmentation, leaving interventions incomplete and staff unsupported [15, 23]. This instability hinders long-term ecological processes that require decades of continuity.

Parks also face intense pressure for traceability; many lose funding not due to misuse but because they lack the digital infrastructure and financial literacy to meet rigid administrative demands [4]. Furthermore, donor-driven agendas can distort local priorities, compelling managers to focus on specific trends rather than ecological realities [24]. This cycle fosters community fatigue and institutional dependency. While indispensable, donor aid must be integrated into long-term financial architectures grounded in local ownership and institutional strengthening to ensure sustainable conservation outcomes.

2.4. FinTech as an emerging finance pathway

FinTech is not a universal remedy but a set of digital instruments—including blockchain, smart contracts, and transparent ledgers that can address structural governance issues [3]. Its true value lies in transforming relationships between agencies, communities, and donors through ethical governance rather than simple modernization. By ensuring transparent financial flows, FinTech restores the moral contract between people and nature, fostering respect and trust. Ultimately, these innovations represent a vital socio-ecological necessity that facilitates four critical operational changes:

2.4.1. Traceability and immutable records

Blockchain's most significant contribution to conservation finance is the provision of traceable, immutable records through a cryptographic structure that prevents the alteration of logged data [4]. By establishing a permanent audit trail, blockchain ensures that stakeholders—from park managers to local communities—can verify both financial flows and ecological monitoring data [4, 25].

Theoretical and empirical evidence support this transformative potential. Decentralized monitoring systems enhance regulatory transparency, delivering both economic and environmental benefits [26]. Within this context, entrance fees and donor contributions are converted into a public chain of custody, where the origin, timestamp, and destination of every transaction remain verifiable. Furthermore, the CONSCIOUS framework demonstrates how blockchain facilitates collaboration by providing tamper-proof communication across Non-govermental Organizations (NGOs), government agencies, and community groups [27]. This shared log reduces suspicion and increases institutional legitimacy. Ultimately, by shifting from opaque operations to a visible ecosystem, blockchain reshapes financial architectures, ensuring resources are traceable from origin to final application.

2.4.2. Reduced leakages and administrative burdens

Blockchain payment architectures, utilizing QR codes and digital wallets, eliminate the need for manual accounting and physical cash handling. This transition accelerates transactions while removing opportunities for informal payments or unrecorded side deals [28]. By encrypting visitor payments and automating verification via protected area gates, the system ensures a permanent, fraud-resistant financial record.

Furthermore, blockchain integration with IoT sensors enables on-demand data logging, drastically reducing administrative workloads by removing the need for manual receipt recording. This creates a transparent, continuous audit trail accessible to both management and stakeholders. The resulting model inherently fosters accountability and minimizes cash leakage, allowing staff to redirect their capacity from administrative oversight to critical ecological stewardship and conservation efforts [4]. This technology-driven shift ensures that financial management remains legitimate and efficient, supporting the long-term sustainability of protected areas through institutional strengthening and increased operational transparency.

2.4.3. Automatic revenue sharing and community equity

Smart contracts revolutionize conservation by automating revenue sharing through self-executing, rule-based disbursements [29]. By programming a stewardship fund to receive a fixed percentage of park revenue instantly, the model eliminates the need for manual, opaque transfers and bypasses biased intermediaries.

Within the Regenerative Finance (ReFi) movement, these decentralized models address environmental justice by ensuring shared value for eco-stewards [30]. Smart contracts can further integrate with "oracles"—external data sources like satellite imagery or biodiversity sensors—to verify ecological outcomes. This allows payments to be linked directly to certified conservation actions rather than just financial thresholds. Consequently, local communities are automatically credited their fair share based on performance data rather than informal negotiations [25]. This outcome-based system enhances trust and transparency, providing reliable stewardship incentives that guarantee financial rewards for proven environmental success.

2.4.4. *New models of visitor engagement*

Blockchain and FinTech innovations are transforming visitors from fee-payers into active nature custodians through digital passes and Non-fungible Tokens (NFTs) linked to conservation milestones [31]. These verifiable Tokens serve as souvenirs and stakeholder assets, incentivizing repeat visits and generating new revenue streams [28]. Additionally, blockchain enables traceable micro-donations; visitors scan QR codes to provide small, frequent contributions, tracking their impact via a tamper-proof ledger [25].

Gamified conservation through smart contracts further engages visitors through eco-quests, such as citizen-science data uploads, rewarded with Tokens [32]. These Tokens can be redeemed for discounts or governance rights within community-led Decentralized Autonomous Organizations, aligning with ReFi principles, where visitors become co-investors. Most importantly, blockchain's inherent transparency will ensure that every donation and award is permanent and publicly verifiable [33]. This radical openness builds immense stakeholder trust, fostering a legitimate, collaborative financial architecture for the long-term protection and management of natural ecosystems (Figure 1).

FinTech sits at the center of four domains—revenue integrity, transparency, community equity, and visitor engagement—acting as a connective mechanism that reinforces trust across the socio-ecological system.

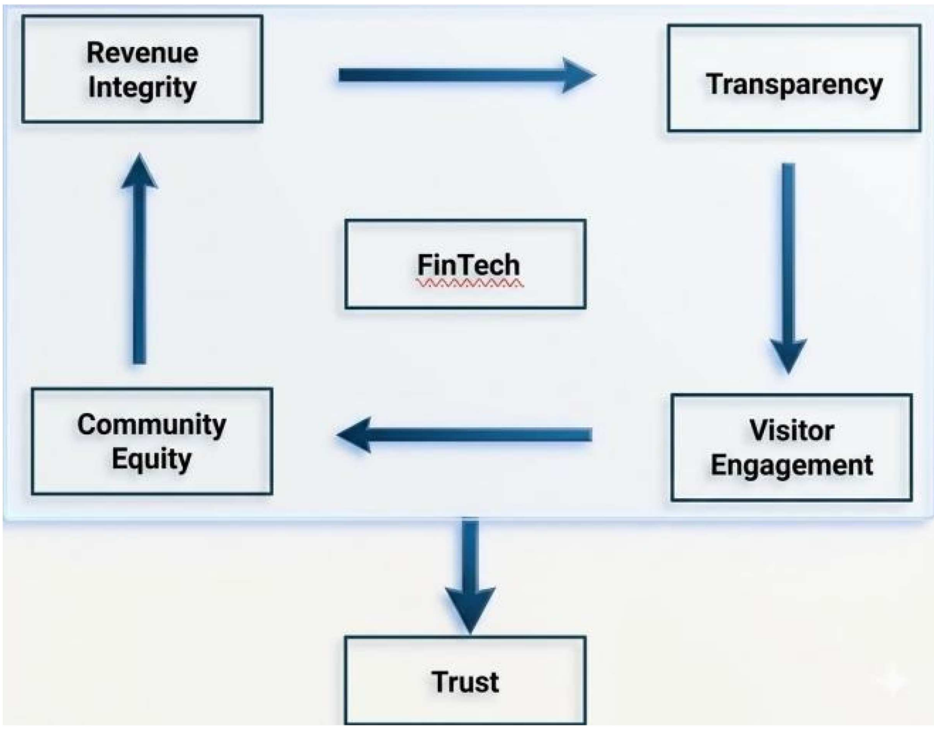
3. Theoretical Framework and Investigatory Logic

The comprehensive conceptual framework for blockchain-enabled conservation finance consists of four interrelated theories, namely, Socio-Ecological Systems (SES) theory, Commons Governance theory (CGT), Institutional Trust theory (ITT), and Innovation Diffusion theory (IDT). Combining these different viewpoints, the framework covers not only the ecological, social, and institutional but also technological dimensions of conservation finance and provides both explanatory and normative insights. These theories provide the analytical lens required to address the RQs (RQs 1–3) introduced in Section 1.1, shifting the model from a technical proposal to a theoretically grounded governance architecture.

3.1. Socio-Ecological Systems (SES) theory

According to the SES theory, social and ecological subsystems are interdependent, co-evolve, and interact dynamically [36]. In conservation finance, the SES theory supplies the means to identify the resource system (protected area ecosystems), resource units (e.g., tourism services and ecosystem functions), governance system (rules, institutions, and oversight), actors (communities, park authorities, donors, visitors), interactions (financial transactions, monitoring, and enforcement), and outcomes (ecological health, equitable benefits, and trust) [34]. A number of recent empirical studies demonstrate that resilient SESs are dependent on adaptive feedback mechanisms, institutional flexibility, and

Figure 1
Conceptual positioning of FinTech in protected area stewardship



multilevel governance structures. As an instance, long-term monitoring of socio-ecological coupling in Western China showed that while ecological subsystem resilience got better, social subsystem resilience still needs further investment to maintain overall system health [25]. Through the use of blockchain technology, conservation finance can become a vehicle that not only supports but also strengthens the dynamics of system adaptability and feedback responsiveness by offering features, such as indelible records, real-time monitoring, and transparent fund flows [25].

3.2. Common Governance theory (CGT)

CGT, rooted in Elinor Ostrom's pioneering research, examines the intricate ways local users self-organize to manage shared, common-pool resources in a sustainable manner [27, 35]. Protected areas serve as prime examples of these resources, as they are inherently subtractable and costly to exclude users from, which necessitates the use of locally adapted, polycentric governance to prevent ecological overuse [34, 36].

Blockchain technology significantly deepens these institutional principles by providing distributed ledgers and smart contracts that automate compliance and facilitate the continuous monitoring of resource consumption. This digital integration enforces institutional rules without the risk of manual intervention, thereby closing the gap for discretionary exploitation or corrupt practices [4]. For example, performance-based smart contracts can be meticulously designed to disburse conservation funds only upon the objective verification of specific ecological outcomes. Ultimately, this digital reinforcement complements traditional collective action, ensuring that community equity and resource sustainability flourish within more reliable and transparent management institutions [25, 29].

3.3. Institutional Trust theory (ITT)

ITT posits that governance reform is essential for efficiency and societal trust. In complex conservation settings, stakeholder trust depends on perceptions of institutional justice, openness, and consistency [33]. Conversely, opaque financial management and inconsistent rule enforcement erode trust, discouraging participation and escalating local conflicts (Folorunsho & Samuel, 2025).

FinTech solutions utilize immutable ledgers to establish this foundational trust. By automating fund distribution and enabling public verification, these tools minimize centralized human oversight and foster transparent institutional–stakeholder relationships. This technological transparency creates a dynamic shift: as institutions become increasingly accountable, stakeholder engagement and compliance strengthen. This establishes a positive feedback loop where enhanced transparency and active participation drive superior conservation outcomes [27, 33]. Ultimately, integrating these digital architectures ensures that financial governance supports the long-term social and ecological integrity of protected areas.

3.4. Innovative Diffusion theory (IDT)

Rogers' Diffusion Theory (2003) explains how new technologies are adopted within social systems based on five characteristics: relative advantage, compatibility, complexity, trialability, and observability [37]. In protected area stewardship, blockchain tools like automated smart contracts and digital payments represent significant innovations [25, 28]. Evidence suggests stakeholders adopt these instruments when ecological benefits are clear, systems align with existing workflows, and pilots demonstrate distinct advantages [38]. Successful scaling relies on diffusion channels, including influential NGOs and government agencies, which facilitate uptake. By identifying these factors, the theory helps implementers anticipate barriers such as digital literacy gaps or institutional resistance while providing strategic directions for scaling blockchain innovations across diverse governance levels.

3.5. Theory–technology integration logic

The T2T framework is not just a simple technology application in conservation. With it, conventional social theories are working very closely with the logic of cryptography. The result of this union is a digital structure that is in tune with the behavioral and structural intricacies of the protected landscapes. The following mapping shows how the theories provided the investigatory logic required to answer the study's RQs:

3.5.1. Question 1 (trust gap)—Institutional Trust theory → blockchain ledger

ITT posits that legitimacy depends on perceived competence and honesty. Trust deficits in protected landscapes often stem from unaudited financial records. The T2T model addresses this by shifting the burden of proof from error-prone officials to an Immutable Blockchain Ledger. As Vladucu et al. [39] note, blockchain serves as a "single source of truth." By recording visitor fees and donations on a public, unalterable ledger, the risk of fund diversion identified by Jacob et al. [1] as a primary biodiversity threat is structurally removed. The ledger provides transparency by design, bridging the trust gap by eliminating human discretion in record-keeping.

3.5.2. Question 2 (structural fairness)—Commons Governance theory → smart contract

Ostrom's principles emphasize clear resource-use rules and graduated sanctions [40]. In the T2T framework, smart contracts digitize these rules into self-executing code. By automating community-agreed bylaws, the system rewards custodians and excludes violators without human interference or friction. Success in community conservancies requires lowering transaction costs to benefit wildlife cohabitants [41]. Smart contracts limit these costs through decentralized "if-then" logic, guaranteeing payouts once verified stewardship conditions, such as anti-poaching patrols, are met. This ensures rewards are issued fairly based on objective data rather than subjective management decisions [42].

3.5.3. Question 3 (revenue leakage)—Socio-Ecological Systems (SES) theory → tokenized stewardship

SES theory suggests human and ecological systems are deeply intertwined, and T2T makes this coupling tangible through tokenized stewardship. By converting ecological work—like habitat restoration—into digital Tokens, the model ensures financial connectivity even when tourism is unstable. This builds essential resilience; Folgieri et al. [43] observed that tourism-dependent systems collapsed during the COVID-19 pandemic. Tokenization allows global conservation value to be allocated based on ecological performance rather than physical visitation. By tethering value to outcomes rather than entries, the model addresses the root causes of revenue leakage found in cash-based systems.

3.5.4. Logic for implementation (boundary conditions): Innovation Diffusion theory → T2T adoption

The application of IDT to T2T will provide metrics for evaluating adoption and institutional resistance. IDT posits that success hinges on technology aligning with community values and remaining user-friendly [44]. These boundary conditions are critical; for instance, the digital divide in remote areas can hinder decentralized ledger adoption [8]. Furthermore, tokenized governance must demonstrate a tangible advantage over manual methods to achieve critical mass. If cryptographic systems appear overly technical, they risk institutional rejection or elite capture [25]. By addressing constraints like low connectivity, T2T becomes a practical approach acknowledging the realities of digital decentralization [33].

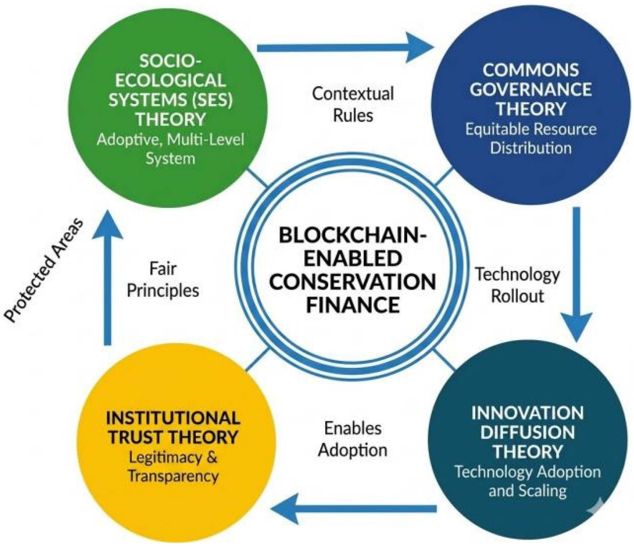
3.6. Integrative synthesis

By integrating SES, Commons Governance, Institutional Trust, and Innovation Diffusion theories, this framework provides a conceptual lens for analyzing blockchain-enabled conservation. SES theory situates protected areas within adaptive, multilevel systems, while Commons Governance offers principles for equitable resource management. ITT emphasizes that legitimacy stems from fairness and transparency, and IDT clarifies why certain technological interventions scale.

The integrated framework provides both explanatory and normative directions. Blockchain-powered revenue sharing and transparent ledgers act as trust enhancers and Commons Governance reinforcers, improving adaptive capacity within SESs (Figure 2). Diffusion-guided tools ensure that innovations are compatible and observable, enabling broad uptake. This integration creates a virtuous loop: transparent fund flows revitalize trust, which heightens stakeholder engagement, leading to better governance and system resilience [25, 33, 34]. Ultimately, the framework demonstrates that sustainable conservation finance depends on the convergence of ecological integrity, social legitimacy, and technological adoption.

This diagram illustrates the conceptual synthesis of SES, Commons Governance, Institutional Trust, and Innovation Diffusion theories. It represents the theoretical virtuous cycle where transparent fund flows and automated governance reinforce institutional legitimacy and landscape resilience.

Figure 2
Integrated theoretical framework for digital conservation governance



4. Conceptual Model Development

The creation of the T2T framework is a result of a conceptual research methodology consisting of four stages. The objective of this method is to guide the research sequentially from the empirical problem identification to a strong architectural synthesis, thus the final model can be theoretically appropriate and at the same time practically useful.

4.1. Phase 1: Problem identification and variable isolation

The first step of the project was a deep literature review of documented cases of governance failure in protected recreational areas, focusing on the context of developing countries. Through the collation of case studies from African parks in the West and East, namely, the Cross River National Park in Nigeria and conservancies in Northern Kenya, we have pinpointed two main independent variables that lead to the failure of the sustainable use of resources: financial opacity and trust deficits.

Financial opacity is basically a term to indicate revenue leakage, a gap between the amount of money made from tourism or donors and what is actually spent at the field level. Research has shown that traditional cash economies in such areas are drastically vulnerable to the kind of unrecorded sideline transactions and embezzlement of funds [1]. On the other hand, trust deficits are being regarded as the perceived financial insecurity of the local people. Wato et al. [45] emphasized that the local community's conviction toward conservation depends less on the amount of money given but on how governance fairness and predictability are perceived. This stage revealed that the main "investigatory problem" was not a shortage of funds but rather a breakdown in the institutional processes needed to transfer the funds in a transparent manner.

4.2. Phase 2: Theory–technology affordance mapping

The second phase was essentially a deductive mapping activity to match the recorded gaps in governance with the specific functional affordances of FinTech. Instead of seeing technology as a generic tool, we considered the features of FinTech as very specific interventions for the variables that were isolated in Phase 1. As an example, the financial opacity that was identified in the Nigerian parks was linked to the cryptographic immutability of blockchain, which, by its very structure, eliminates the possibility of fund diversion for personal use, as noted by Jacob et al. [1]. Along the same lines, trust deficits were matched to the self-executing feature of smart contracts. This reasoning makes the T2T framework a very precise and direct method of solving institutional bottlenecks as opposed to just a generic modernization proposal, thus rooting the structure in a problem-solution binary that lifts up its internal validity [39].

4.3. Phase 3: Architectural synthesis (the T2T model)

This step was about the actual formalization of the T2T system, outlining both the technical and figurative joining of stewardship inputs with digital outputs. We merged the SES theory and the Commons Governance principles to establish a performance-linked feedback loop. Essentially, this meant creating the mechanism where Trails (data-driven inputs such as geotagged patrols or e-permits) become the verification signal for Tokens (automated financial disbursements). By constructing this relationship, the paper shows how digital instruments can make the if-then logic of collective action operational; thus, human gatekeepers are replaced by transparent code. The merger that ensues develops a confirmable model that aims to keep the SES tightly coupled even in the face of a highly unstable governance environment [41].

4.4. Phase 4: T2T model validation via scenario analysis

Being a theoretical investigation, the last phase of the work opted for scenario analysis to test the theoretical strength of the model and to pinpoint its limit conditions. For the T2T framework, we used the COVID-19 tourism collapse as an empirical benchmark against which the concept was pitted. Spenceley and Meyer [42] argued that such an event led to management paralysis in conventional systems. Thus, while hypothesizing the features of a stewardship model that would be tokenized and funded by global biodiversity credits at large rather than by physical visitation fees alone, we showed how such a model would have kept the seasonal support staff salaries. Ultimately, this phase leaned on identifying the failure points, for example, the digital divide and institutional resistance, so the study is capable of recognizing the limits of digital decentralization that can be encountered in low connectivity areas [8].

5. FinTech Frontiers for Stewardship in Protected Landscapes

In recent years, FinTech has unlocked new pathways for generating funds, increasing transparency, and fostering stewardship in protected landscapes. Here, four interrelated frontiers comprising Digital Payment Ecosystems, Digital Revenue Transparency, Blockchain and Traceable Conservation Funding, and Visitor Stewardship Apps are used to highlight the real-world examples including Rwanda's cashless permits, Kenya Wildlife Service (KWS) reforms, blockchain wildlife credits, and US donation platforms. Table 2 highlights these benefits of the four FinTech frontiers in protected landscape stewardship.

5.1. Digital payment ecosystems

Digital payments for conservation fees and permits enhance financial governance by eliminating cash, providing tourist convenience, and ensuring traceability [25, 27]. Rwanda's cashless permit system exemplifies this, requiring all transactions through an online portal to minimize mismanagement [46]. This digital ecosystem allows authorities to forecast visitation, optimize staffing, and analyze seasonal trends to inform adaptive management strategies [33].

Furthermore, removing physical cash reduces corruption risks, thereby bolstering institutional credibility in regions with low governance trust [29]. These systems also promote inclusivity; integrating mobile money platforms democratizes access for local tourists who may lack credit cards while maintaining strict financial transparency. Ultimately, digital payments serve as a cornerstone of modern, accountable conservation finance, transforming raw transaction data into a strategic asset for both operational efficiency and ecological stewardship [25].

5.2. Digital revenue transparency

Digital payments are the foundation upon which the budget is built, but transparency is what makes the budget auditable and accessible to all stakeholders [29]. Digital financial platforms are

Table 2
FinTech frontiers and benefits in protected landscape management

FinTech frontier	Mechanism/technology	Example	Key benefits for stewardship
Digital Payment Ecosystems	Online permits, mobile money, tap-and-go, QR codes	Rwanda cashless permits	- Reduces cash leakage and corruption - Improves revenue predictability - Enhances visitor convenience and accessibility - Provides data for planning and resource allocation - Strengthens institutional credibility
Digital Revenue Transparency	Audit dashboards, real-time reporting, encrypted transactions	Kenya Wildlife Service eCitizen and KWSPay	- Increases transparency and accountability - Enables stakeholder monitoring and trust-building -Supports evidence-based governance -Reduces disputes over revenue allocation - Attracts donor confidence and long-term support
Blockchain and Traceable Conservation Funding	Smart contracts, tokenized biodiversity /wildlife credits, NFT-based ecosystem assets	Maasai Mara Wildlife Credits, ValueNature, BlueSwallow	- Ensures immutable, auditable transaction records - Links payments directly to ecological outcomes - Automates revenue sharing with local communities - Encourages community participation and stewardship - Reduces financial disputes and leakage

(*Continued*)

Table 2
(*Continued*)

FinTech frontier	Mechanism/technology	Example	Key benefits for stewardship
Visitor Stewardship Apps	Mobile apps, gamified engagement, micro-donations, AI-linked rewards	US donation platforms, AI-driven wildlife monitoring	- Transforms visitors into active contributors - Enhances engagement through gamification and tracking - Provides feedback and impact reporting - Generates recurring funding streams - Builds long-term community-donor relationships

essential in offering the communities and governments access to the most important dashboards and audit logs. The KWS is a good example of such a transition from cash to the eCitizen digital platform for park fees, which has greatly enhanced traceability [47]. The system they have, KWSPay, secures the transactions and also explicitly allocates a very small (5%) gateway fee for system maintenance, thus ensuring sustainability and accountability [48]. Apart from being easily traceable, these digital platforms are instrumental in evidence-based governance. Managers are able to monitor the sources of revenue and to match the financial inflows with the ecological priorities; for example, the analysis of Maasai Mara fees can be used to justify the deployment of rangers [49]. Moreover, if these platforms are merged with stakeholder portals, the communities will receive regular updates about the collection and distribution of the revenues. This uninterrupted visibility not only boosts trust but also removes feelings of corruption and builds social legitimacy, which is very important for conservation outcomes to last [27].

5.3. Blockchain and traceable conservation funding

In addition to digital payments, blockchain enables permanent, traceable conservation funding directly tied to ecological outcomes [4]. Through tokenization and smart contracts, performance-based mechanisms—such as biodiversity or wildlife credits—execute automatically once verified. A prime example is Kenya's Wildlife Credits program, where payments are triggered by measurable results, such as reduced poaching or habitat maintenance [45]. Blockchain provides donors with "digital receipts," ensuring their funds achieve specific ecological impacts.

This technology supports the international biodiversity credit market, utilizing satellite and community data to verify results before smart contracts automate distributions to local custodians [50]. Some initiatives even issue NFT-based credits for monitored land, offering investors real-time transparency [51]. By maintaining ecological accountability, these instruments attract new investment and provide communities with reliable financial flows. Ultimately, this shifts local stewardship toward a more secure, verifiable, and fair financial architecture, effectively reducing conflicts over revenue sharing [33].

5.4. Visitor stewardship apps

FinTech transforms visitors from passive fee-payers into active contributors by integrating engagement apps with transparent accountability systems. In the United States, donation platforms already allow tourists to provide micro-contributions to specific causes—such as ranger programs or species protection—providing visible feedback that deepens emotional investment in conservation outcomes [52]. Furthermore, emerging AI-driven systems can reward local custodians with digital payments for verified wildlife sightings, creating a direct link between monitoring and monetary incentives.

By gamifying stewardship, these platforms encourage tourists and citizen scientists to collect valuable ecological data in exchange for digital badges or Tokens. Such mechanisms maintain visitor interest long after their trip concludes, fostering a lasting sense of ownership and broadening funding sources beyond traditional gate fees [33]. Ultimately, these participatory ecosystems synchronize the incentives of tourists, communities, and institutions, turning every interaction into a verifiable contribution toward the long-term success of the protected area [4, 28].

6. Transparent Governance Transformed by FinTech

FinTech in protected areas triggers a systemic shift from reactive, nontransparent cash systems to proactive, digitally intelligent governance. This transformation relies on two core pillars: digital intelligence for adaptive decision-making and decentralized technologies to enforce transparent, performance-based social contracts that build institutional legitimacy.

6.1. Adaptive and predictive management

FinTech shifts conservation governance toward adaptive, predictive management by leveraging the wealth of data generated through automated payment systems. Digital interventions in regions like Rwanda and Kenya do more than handle transactions; they generate real-time datasets on visitor movements and revenue peaks [33]. When this financial intelligence is integrated with operational and ecological data such as anti-poaching logs or sensor feeds, it enables advanced predictive analytics.

Machine learning models can then identify environmental and operational risks, allowing managers to anticipate threats before they manifest [53]. For instance, correlating visitation peaks with wildlife migration routes can predict potential human–wildlife conflicts, enabling the proactive deployment of rangers to maximize ecological returns. This data-centered methodology fosters organizational agility, allowing managers to swiftly measure and adjust the effects of price changes or conservation projects in a continuous feedback loop [54]. Ultimately, this evidence-based approach replaces slow, retrospective cash-based cycles, significantly enhancing both management efficiency and institutional credibility.

6.2. Performance-based accountability and the institutional social contract

FinTech catalyzes a shift toward verifiable fairness through the automated enforcement of the institutional social contract. By encoding revenue-sharing terms into the blockchain architecture, disbursements execute automatically upon the fulfillment of predefined ecological benchmarks, replacing discretionary assurances with immutable, outcome-linked transfers [27]. The Maasai Mara Wildlife Credits pilot exemplifies this, where payments are contingent on measurable anti-poaching success, replacing informal assurances with immutable, verifiable, outcome-linked transfers [55]. The core innovation is the shift to two-way accountability. Because the ledger of transactions and performance metrics is shared and cryptographically secured, communities are empowered to actively monitor and verify institutional compliance [29]. This collective oversight, facilitated by the shared ledger, strengthens the institutional social contract by building trust through enforced transparency. By visibly and systematically protecting the interests of local custodians and donors, this FinTech architecture directly attacks the root causes of corruption and leakage [28]. This predictable, rule-based system enhances organizational institutional legitimacy, encouraging greater buy-in from all stakeholders (tourists and donors), who are more willing to invest when they perceive their contributions are managed with verifiable fairness, creating a resilient foundation for conservation finance.

7. Risks, Limitations, and Ethical Concerns

Although FinTech has the power to radically change the situation of protected areas, it cannot be considered a panacea. The implementation of the technology is accompanied by technical vulnerabilities, social inequities, and ethical dilemmas, all of which call for critical evaluation and careful planning. The failure to deal with these problems runs the risk of turning the well-intentioned digital interventions into new sources of inequity and mistrust. The major issues revolve around areas such as access and inclusion, technological resilience, and the morally right handling of power relations.

7.1. Digital divide and social exclusion

The biggest problem right now is the issue of the digital divide and access. One of the main uses of FinTech is based on the wrong idea that all stakeholders (e.g., visitors, staff, and less advantaged local communities) have equal access to a stable internet connection, necessary equipment (e.g., smartphones), and the required level of digital literacy [25]. In the case of a purely digital system in a remote area or developing region (e.g., cashless permits or blockchain credits), the urbanized or rich tourists may be in a better position to benefit from it; thus, local or rural visitors and community members who are still in cash-based transactions or do not have the technical means may be left out. As pointed out by Bengil [27], this digital exclusion becomes one of the ways that actively deepens the past inequities and creates a perception of unfairness that lowers social legitimacy [28]. When communities are deprived of digital oversight or revenue streams, doubt can substitute for transparency. It requires creating such hybrid systems that would mix the digital efficiency with manual, accessible alternatives and extensive community capacity-building programs.

7.2. Technological vulnerability and rigidity

Overdependence on digital structure brings substantial technological vulnerabilities and risks to the organization's activities. In a way that smart contracts improve the transparency, they also put a heavy load on complex infrastructure, which should always be available [56]. Threats to cybersecurity (e.g., ransomware attacks on financial data or unauthorized access that leads to the release of wildlife geolocation data) can be considered a risk to the entire conservation area and a loss of trust in the institutions. Moreover, the operational inflexibility of automated machines conflicts with the natural complexity of ecosystems. For example, a fixed, rules-based smart contract may not consider contexts such as a sudden natural disaster, disease outbreak, or fast ecological changes [29]. Suppose an algorithmic trigger does not consider a force majeure event; then the dependability and correctness of the system are compromised at once. Hence, it emphasizes the presence of backup systems and a human adaptive oversight layer; technology should support rather than replace the judgment of experienced managers on-site.

7.3. Ethical governance and power dynamics

The adoption of FinTech must confront deep-seated questions of ethics and power, particularly regarding data privacy and resource control, as indicated in Table 3. These systems generate vast amounts of personal, financial, and environmental

Table 3
Risks, limitations, and ethical concerns in FinTech application

Risk	Description	Implications	Mitigation strategies
Digital divide and accessibility	Lack of smartphones, internet, or digital literacy in rural or marginalized communities	Exclusion from revenue sharing, oversight, and stewardship; reduced trust and social legitimacy	Hybrid systems combining digital/manual reporting; Community training and shared access points; Local facilitation to ensure inclusivity
Technological vulnerabilities	System failures, cyberattacks, software bugs, power outages	Interrupted revenue flows, failed smart contracts, stakeholder frustration; reduced trust in technology	Redundant systems, cybersecurity measures, offline backup protocols, and human oversight for contingency decision-making
Operational limitations of automation	Smart contracts and automated reporting cannot account for ecological contingencies	Payments may be withheld erroneously; ecological or social contexts overlooked; reduced adaptive capacity	Incorporate human review for context-sensitive decisions; Flexible contract design with override mechanisms; Scenario planning

(*Continued*)

Table 3
(*Continued*)

Risk	Description	Implications	Mitigation strategies
Data privacy and ethical concerns	Collection of sensitive visitor, community, and ecological data	Risk of poaching, stigmatization, misuse; potential coercion or lack of informed consent	Privacy-preserving technologies, secure data storage, participatory consent protocols, transparent data-use agreements
Equity and power dynamics	Unequal access to technology and historical social hierarchies	Elite capture of benefits; intra-community tension; potential marginalization of vulnerable groups	Participatory governance, equitable benefit-sharing mechanisms, grievance redress procedures, capacity-building for marginalized stakeholders
Dependence on external funding and tech support	Reliance on donors or private tech providers	Sustainability risk if funding/support is withdrawn; loss of operational continuity	Develop local capacity for system management; Diversify funding sources; Gradual transition to community-owned infrastructure

data that, if improperly secured, could be exploited by poachers to target vulnerable habitats. Beyond security risks, the radical transparency of income and financial decision-making can inadvertently shift community dynamics, potentially entrenching existing power hierarchies where those with historical institutional ties gain disproportionately [57].

Ethical FinTech implementation depends on responsible data management and the co-design of platforms that utilize privacy-respecting protocols. Managers bear the responsibility of ensuring that the pursuit of efficiency does not undermine the fundamental principles of data protection or equitable rights [28]. Ultimately, deploying these technologies involves a complex institutional negotiation, requiring a delicate balance between the benefits of automation and the vital necessity of inclusion, resilience, and ethical human judgment.

8. The Trails-to-Tokens Model

The T2T paradigm (Figure 3) plays the role of the needed conceptual integration that merges FinTech's (Section 4) technological adjacent, fronts, the resulting governance (Section 5) shifts, and the critical implementation (Section 6) challenges into one coherent, practical model. T2T is not simply about using various digital tools; rather, it establishes a systemic feedback loop, understanding the protected area as an SES where human impact (Trails) is not only digitized but also encoded into financially and environmentally verifiable instruments (Tokens). The T2T framework is a three-component governance architecture that aims at establishing performance-linked stewardship in protected recreation areas. It connects the natural world of the ecological interaction with an open, digital layer of accountability. Figure 3 illustrates the architectural flow, mapping how physical stewardship acts (Trails) are translated into digital entries (Tokens).

1) **The Trails (input and value generation)**

This refers to the physical and social spheres. Its role is the conversion of human activities into real-time, verifiable, and direct input data. The data include financial input (digital payments for visitor permits, directly countering financial opacity) and stewardship input (recorded, geotagged data from local custodians on patrol hours, monitoring, and ecological maintenance). The verifiable data is the trigger for the next stage.

A framework representation of the proposed model, mapping the flow of physical stewardship data (Trails) to digital financial instruments (Tokens). The diagram highlights the structural interaction between data oracles, smart contracts, and community digital wallets as a theoretical response to RQs 1 and 2.

2) **The Tokens (digital architecture and performance linkage)**

This represents the central digital layer. The Tokens are not intended as speculative assets or general-purpose cryptocurrencies; rather, they are instruments that can be verified for the ecological and financial accountability of the system. The system operates on two main mechanisms: (1) blockchain ledger, which ensures the transparency of all the transactions and data inputs by providing a permanent record, and (2) smart contract. This automated, self-executing contract is the enforcement mechanism. It has been programmed to release the automated payouts (revenue shares) only when the verifiable stewardship input (e.g., habitat integrity confirmed, litter removal verified) corresponds to the pre-agreed ecological or social performance standards. By doing so, this mechanization is the very action that makes the direct, automatic connection between conservation work and financial incentive (accountability) realized.

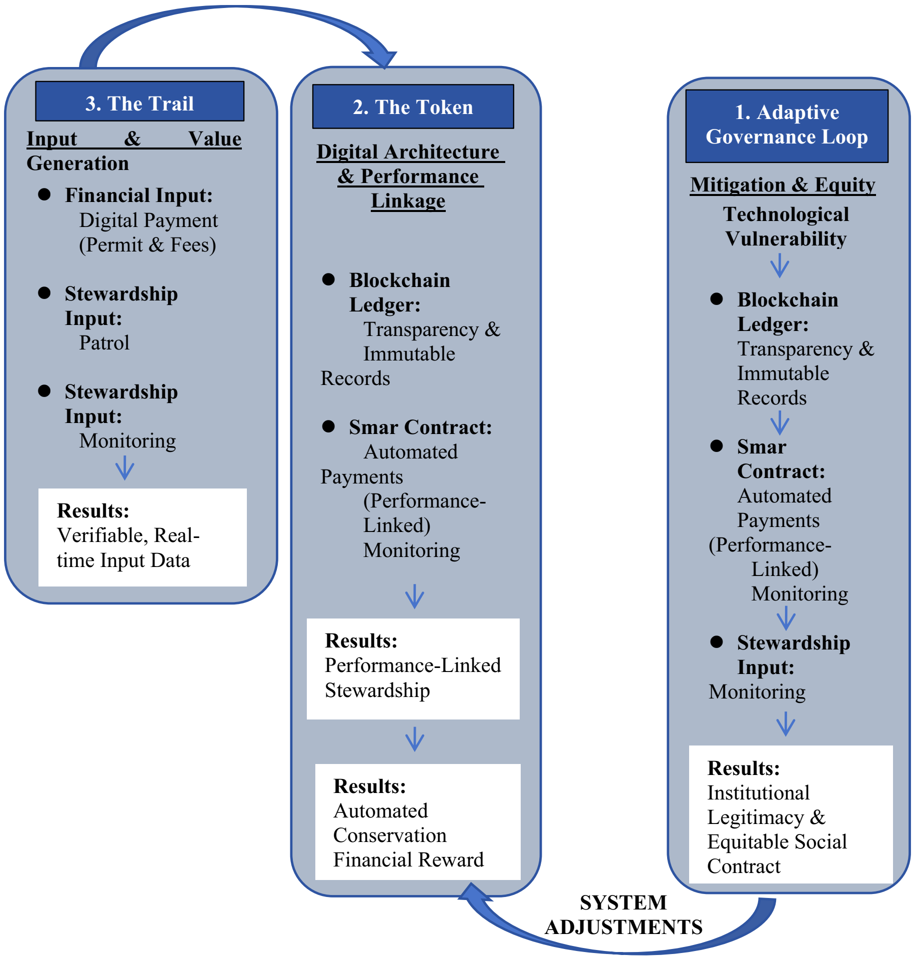
3) **Adaptive governance loop (mitigation and equity)**

The institutional level here is designed to handle systemic risks brought about by the tech adoption, mainly the issues of digital divide and technological vulnerability. It keeps the system alive through regular checks and openness to change. Its main tools are described in detail in the next section on hybrid models.

8.1. Theoretical foundation

The T2T model is explicitly based on the Commons Governance principles [35] and ITT. The component “Trails” deals with the essential requirements for natural resources management as a common-pool resource: it employs digital permits to specify and supervise the rules of exclusion and access for resource users (visitors). Next, the “Tokens” framework addresses the main issue of institutional trust. Usually, conservation management depends on the conduct of officials in charging and revenue sharing, which leads to distrust of communities and donors. By smart contracts directly encoding the rules of revenue distribution into immutable ones, T2T changes this discretionary trust

Figure 3
The Trails-to-Tokens (T2T) functional architecture



into automated, decentralized accountability [29], thus enabling institutional performance to be not only promised but also verifiable. The system, therefore, reinforces the social contract by offering a technological base for rule enforcement and predictable benefit-sharing [33, 58], which are the core elements of Commons Governance that is resilient.

8.2. Building the performance-linked social contract

The T2T architecture establishes an outcome-driven social contract linking authorities, visitors, and communities. By utilizing smart contracts, the model automates performance-linked stewardship, ensuring predictable and transparent financial flows. Unlike traditional models where revenue is obscured in general funds, T2T triggers immediate token distribution tied to specific ecological metrics [29]. Table 4's operationalization matrix details the performance indicators required for these disbursements.

Funding is released only upon digital verification of targets, such as anti-poaching patrols [55]. This replaces erratic cycles with a fixed, executable system, enhancing institutional legitimacy through auditable fairness. By mitigating corruption and revenue leakage, T2T transforms residents from passive recipients into empowered co-stewards. This structural provision for fairness ensures predictable financial returns, securing the long-term collaboration and compliance essential for sustained conservation effectiveness [4, 33].

The interactions described in this framework represent a synthetic result mapping. This section utilizes synthetic result mapping. It is explicitly stated that this is a simulation of data flow and not empirical field testing. By simulating the flow of data from physical "Trails" to digital "Tokens," this analysis validates the internal logic of the T2T architecture. It is important to note that these results do not constitute empirical field testing; rather, they serve as a conceptual blueprint. This approach demonstrates the internal logic of the architecture while acknowledging it cannot prove real-world outcomes without further pilot trials. This approach demonstrates how the model should function under optimal conditions, providing a foundation for future empirical researchers to test against real-world socio-political and technical constraints.

8.3. The reflexive governance loop

The T2T framework conceptualizes a reflexive governance loop to manage digital divides and ethical risks. To mitigate exclusion, a Hybrid Governance Model avoids total automation by merging digital ledger transparency with community-based methods [28]. Local coordinators act as intermediaries, manually entering stewardship data for low-connectivity users to ensure universal access to token payouts. The system integrates robust data privacy and flexible parameters to remain resilient against shocks. To avoid ecological reductionism, it harmonizes

Table 4
Operationalization matrix for the T2T model

Component	Variable	Measurement indicator	Verification source	Target metric
Trail (input)	Financial integrity	Variance between e-permits issued and blockchain ledger receipts	Public blockchain ledger	<1% Variance
Trail (input)	Stewardship effort	Number of verified patrol hours and geotagged incident reports	Mobile app GPS/time-stamped data	>90% Coverage
Token (output)	Ecological threshold	% Change in habitat health or species encounter rates	Satellite oracles/AI image analysis	>30% Improvement
Token (output)	Equity payout	Automated disbursement of X% funds to community e-wallets	Smart contract execution	<24 h

quantitative metrics with qualitative human judgment and traditional knowledge. Ultimately, T2T balances transparency with privacy and efficiency with inclusion. By embedding ethical adaptation into its architecture, the framework ensures technology supports equitable, long-term conservation goals.

9. Framework Validation Through Synthetic Result Mapping

Although the T2T model is a theoretical synthesis and a conceptual idea, its architectural components are basically conceptual ideas but are based on actual documented empirical failures of conventional protected area management. To actually implement the concept rather than just discuss it, this segment makes use of synthetic results, a method of showing the functional necessity and potential impact of the T2T model by mapping existing data from diverse studies onto the T2T model.

9.1. Proposition 1: Addressing revenue leakage and financial opacity

The T2T model's emphasis on blockchain-verified Trails addresses the documented decline in fiscal transparency within West African protected areas. Research in Nigeria's Cross River and Gashaka Gumti National Parks revealed that over 36% of staff attribute biodiversity loss to budget leakages and funding shortages [1]. Traditional cash-based or centralized systems often suffer from a gap between permit issuance and the revenue actually reaching the site. By utilizing the T2T method, every admission ticket becomes a unique digital token on a public ledger, creating a "single source of truth" for green initiatives [39]. This architecture ensures that funds are tracked flawlessly from the "Trail" (visitor entry) to the "Token" (ranger payment). By removing the discretionary power to divert funds, T2T directly solves the transparency issues identified in Nigerian case studies, guaranteeing that revenue supports its intended ecological purpose [1].

9.2. Proposition 2: Enhancing social equity and institutional trust

The T2T model utilizes smart contracts to automate community payments, directly addressing the trust deficit documented in East African conservancies. Evidence from Northern Kenya reveals that only a third of residents in high-wildlife areas feel financially secure under current systems, largely because support for conservation vanishes when revenue sharing feels arbitrary or delayed [45].

By replacing human intermediaries with automated code, T2T serves as a practical application of ITT. In this system, logging a community-led Trail such as a verified anti-poaching patrol triggers an immediate token payment. This evolution builds upon the Wildlife Credits concept by adding a robust FinTech layer that ensures absolute transparency [41]. Automating these interactions closes the equity payout gap, transforming a historically unreliable process into a high-trust system. Community members are thus guaranteed fair compensation for measurable stewardship, fostering the long-term institutional legitimacy necessary for effective conservation.

9.3. Proposition 3: Resilience against macro-economic shocks

The COVID-19 pandemic served as a resilience stress test for conservation models. Folgieri et al. [43] noted that the 2020–2021 decline in African protected area visitation led to management paralysis and increased poaching due to lost tourism revenue (Table 5). This reality highlights the risk of relying

Table 5
Conceptual mapping of empirical failures to T2T model solutions

Empirical baseline (problem)	Documented data point	T2T result (proposed solution)	Source
Financial opacity	R2 = 0.3122 downward trend in funding/accountability	Immutable Ledgers: Zero-variance between permits and revenue	Jacob et al. [1]
Trust deficit	Only 36.9% of the community feels financially secure	Automated Equity: Smart contracts trigger immediate, fair payouts	Wato et al. [45]

(*Continued*)

Table 5
(*Continued*)

Empirical baseline (problem)	Documented data point	T2T result (proposed solution)	Source
Revenue fragility	Management paralysis during 0% visitation (COVID-19)	Tokenized Stewardship: Diversified revenue via biodiversity credits	Folgieri et al. [43]
Operational gaps	Lack of real-time monitoring of stewardship effort	Verified Input: AI and IoT Trails confirm work before Token release	Yadav et al. [25]

solely on physical "Trails" for income. To address this, the T2T model introduces a tokenized fund reserve, allowing international donors to pre-finance smart contracts. In crises, the focus shifts from visitor-generated revenue to stewardship-produced value. For example, park ranger patrols verified via GPS-linked AI, as suggested by Yadav et al. [25], can automatically trigger token payouts. Consequently, ecological protection is decoupled from tourism fluctuations. By rewarding stewardship outcomes rather than mere attendance, T2T provides the financial stability that was critically absent during global shocks, ensuring long-term conservation resilience.

10. Policy and Management Implications

One of the groundbreaking suggestions of financing technology for the protection of nature is the opportunity for profoundly altering the governance system in a way that moves the system beyond the traditional, closed, and separate approach to creating interdependent models that are transparent, fair, and responsive. The policy and management changes resulting from the capabilities (Section 4), the systemic transformation (Section 5), and the critical risks (Section 6) of FinTech are not simple technical fixes; they call for a complete institutional and regulatory overhaul. Below, we look at two essential policy design pillars necessary for translating the T2T framework (Section 7) into sustainable practice that ensures that digital tools are used to amplify ethical and ecological goals rather than undermine them.

10.1. Strategic policy architecture

Policymakers must integrate digital systems directly into national and local governance frameworks rather than treating them as technological add-ons [29]. Strategic policies should mandate immutable ledgers and real-time tracking to eliminate the discretionary behaviors and leakages inherent in cash-based systems [27]. True accountability requires that digital dashboards be accessible and understandable, empowering local communities to conduct participatory auditing and decentralized oversight [28].

Legislators must also establish robust ethical and regulatory controls to address data privacy and cybersecurity risks [27]. This ethical foundation is a prerequisite; policy must ensure that efficiency does not compromise stakeholder autonomy or safety. By formalizing digital integrity, management secures a rules-based system that fosters institutional professionalism. Ultimately, this transparency increases visitor willingness to pay and bolsters donor confidence, creating a stable environment for long-term conservation finance.

10.2. Adaptive management and the co-creation of digital equity

The second group of management implications focuses on creating adaptive governance structures sensitive to socio-ecological shifts and digital equity. As protected areas face climate pressures, policies should institutionalize flexible smart contract parameters and iterative reviews that merge real-time FinTech data with community feedback [29, 33]. To bridge the digital divide, regulations must mandate hybrid models balancing automation with human verification [25]. For example, local intermediaries can validate work from stewards with low digital literacy before blockchain inscription.

As explored in Section 7, this transition shifts corruption risks from financial leakage to data integrity, necessitating ethical training and independent auditing to prevent elite capture. Furthermore, co-design and participatory monitoring ensure that tokenized rules rectify, rather than deepen, existing power imbalances [27]. By embedding these fairness mechanisms, managers can translate technological potential into durable, ethical stewardship. Ultimately, fostering inclusive digital literacy remains the cornerstone for preventing technological exclusion in decentralized conservation.

11. Analytical Synthesis and Critical Perspectives

The T2T model signals a departure from the tried and tested human-centered methods of bureaucratic supervision toward an algorithmic transparency-based system. It achieves this by redistributing the point of truth from a central office to a distributed ledger, thus removing the discretionary power that often leads to revenue leakage. However, this change is far more than just a technical upgrade; it redefines the relationship between conservation authorities, local communities, and international stakeholders. For academic integrity purposes, the implementation needs to be interpreted through three separate lenses: conceptual contributions, normative claims, and practical assumptions of feasibility.

11.1. Conceptual, normative, and practical distinctions

This paper conceptually extends the T2T logic by bridging physical stewardship with digital value through a granular mapping of conservation labor. Unlike traditional financing, which relies on aggregate reports susceptible to manipulation, T2T tokenizes individual acts of stewardship to ensure a more accurate representation of local efforts. This normative framework aligns with Ostrom's commons principles by decentralizing conservation to local agents, thereby mitigating elite capture through mechanical enforcement that bypasses traditional power dynamics.

However, moving from theory to practice necessitates addressing critical hurdles, such as the lack of reliable internet and digital devices in remote regions. The success of T2T hinges on organizational readiness and overcoming technophobia rooted in low digital literacy [8]. Furthermore, a persistent usage divide often prevents communities from converting digital assets into real socioeconomic benefits [35, 59]. Without significant workforce upskilling and regulatory support for digital assets [39], T2T risks remaining an inaccessible high-tech model for many Global South environments. The specific environmental and institutional requirements for successful deployment are synthesized in Box 1.

Box 1
Boundary conditions for T2T implementation

- *High Feasibility: Regions with established mobile money infrastructure, high visitor volume, and existing community-led conservancy frameworks.*
- *High Risk/Failure Points: Landscapes with total internet "black holes," legal restrictions on digital assets, or extreme political centralization that resists financial transparency.*
- *The "Usage Divide": Implementation will likely fail if there is no secondary market or regulatory support to convert digital Tokens into local socioeconomic benefits.*

11.2. Different views and governance risks

While the T2T framework leverages tokenization for transparency, it must be rigorously assessed against the risks of techno-solutionism. Critics warn that without a foundation in ecological economics, such models risk becoming extractive logics that reduce spiritual or cultural values to market metrics [60]. Furthermore, integrating IoT and blockchain presents ethical concerns regarding privacy. Tying financial payouts to tracked movement may inadvertently create a "panopticon," where real-time monitoring outpaces legal protections for data ownership and risks biometric policing [61]. If payments depend strictly on GPS locations, the system could be exploited for control rather than conservation.

Additionally, transitioning to blockchain can foster platform dependence, where decentralization becomes a facade controlled by external entities. This further marginalizes the digitally illiterate and risks reproducing existing power imbalances [52, 62]. Ultimately, T2T is not a standalone remedy; it requires a sociotechnical balance between digital code and community dialogue to ensure it does not merely automate inequality.

12. Future Research Directions

The T2T model represents a transformative shift in conservation governance, yet its scalability and ethical deployment require empirical validation. Future research must bridge the gap between technical promise and long-term outcomes through a structured four-phase pilot protocol:

Phase 1: Baseline Assessment: Quantify cash leakages and evaluate trust using ITT scales.

Phase 2: Technical Sandbox: Implement a closed-loop digital wallet for trial logging without financial risk.

Phase 3: Smart Contract Trial: Execute payouts for simple, photo-verified stewardship tasks.

Phase 4: Impact Analysis: Correlate automated payouts with ecological resilience over a 24-month cycle.

Research must prioritize the empirical verification of biodiversity outcomes, such as species recovery, to avoid a "performance illusion" of mere financial efficiency [28, 33]. Furthermore, participatory action research is essential to prevent digital marginalization in areas with low connectivity [27]. Studies should explore hybrid governance algorithms that balance automated monitoring with human oversight to ensure ethical and technical resilience [29]. Beyond technical hurdles, research must address "techno-solutionism"—the risk that tokenization commodifies nature or shifts motivations from intrinsic to extrinsic rewards. Managing the "surveillance paradox" through community-governed privacy protocols is vital for long-term social justice and ecological stability.

13. Conclusion and Recommendations

The T2T model evolves conservation from bureaucratic oversight to algorithmic transparency by linking stewardship to digital finance. To move beyond speculation, authorities must pilot blockchain-enabled smart contracts integrated with IoT monitoring. While addressing fiscal leakage, success hinges on bridging the digital divide through literacy and legal frameworks recognizing digital assets. Critics warn against techno-solutionism and nature's commodification; thus, prioritizing community-owned protocols is vital to prevent elite capture. Ultimately, this study provides a scalable roadmap through an operationalization matrix and pilot protocol to hard-code institutional trust and ensure technology serves as a resilient, ethically defensible tool for inclusive governance. Consequently, it is recommended that managers prioritize local digital literacy and hybrid governance to ensure blockchain implementation empowers stewards rather than enabling digital exclusion.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Daniel Jacob: Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Imaobong Jacob:** Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Kingsley Udofa:** Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Koko Daniel:** Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Simon Idoko Okweche:** Validation, Investigation, Resources, Data curation, Writing – review & editing. **Emmanuel Dan:** Investigation, Resources, Data curation, Writing – review &

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