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Research Article

Leveraging Blockchain and AI for Transparent and Equitable Protected Area and Recreation Co-Management

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ABSTRACT

Protected areas and recreation management face persistent challenges in ensuring transparency, fostering equitable participation, and building trust among diverse stakeholders. Traditional co-management models often struggle with opaque decision-making processes, unequal power dynamics, and inefficient data management. This paper explores the transformative potential of integrating blockchain and artificial intelligence (AI) technologies to address these shortcomings. Blockchain, with its inherent characteristics of immutability, transparency, and distributed ledger technology, can provide a secure and verifiable platform for recording decisions, transactions, and resource allocation, thereby enhancing accountability and trust. AI, conversely, can analyze complex datasets, identify patterns, optimize resource distribution, support equitable decision-making processes by incorporating diverse perspectives, and personalize recreation experiences while minimizing ecological impact. By synergistically combining these technologies, a new paradigm for co-management emerges, one characterized by enhanced transparency, improved equity, data-driven insights, and increased stakeholder engagement. We discuss specific applications, potential benefits, and significant challenges related to implementing blockchain and AI in protected area and recreation co-management, offering a vision for a more just, effective, and sustainable future for conservation and outdoor recreation.

Keywords: Protected areas; recreation management; co-management; blockchain; artificial intelligence; transparency; equity

1. Introduction

Protected areas, encompassing national parks, nature reserves, and other conservation designations, are vital for safeguarding biodiversity, maintaining ecological processes, and providing essential ecosystem services. Alongside their conservation mandate, many protected areas also serve as crucial hubs for outdoor recreation, offering significant social, health, and economic benefits. The effective management of these complex systems requires navigating the often-competing interests of various stakeholders, including government agencies, local communities, Indigenous peoples, conservation organizations, tourism operators,

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and recreationists. Co-management, a collaborative approach where responsibility and authority are shared between government agencies and other stakeholders, has emerged as a preferred model for protected area and recreation governance [1]. Co-management aims to improve decision-making quality, enhance compliance with regulations, foster local support, and promote social equity and environmental sustainability [2].

However, the implementation of co-management is fraught with challenges. Issues of power imbalances, lack of trust among stakeholders, insufficient transparency in decision-making and resource allocation, and difficulties in managing and sharing diverse forms of data often hinder the effectiveness and legitimacy of co-management initiatives [3]. The digital revolution offers potential solutions to some of these long-standing problems. Technologies such as blockchain and artificial intelligence (AI), which are rapidly transforming various sectors, hold significant promise for enhancing transparency, equity, and efficiency in protected area and recreation co-management. While blockchain is often associated with cryptocurrencies, its underlying technology a distributed, immutable ledger has broader applications in creating transparent and tamper-proof records of transactions and interactions [4]. AI, with its capacity for advanced data analysis, pattern recognition, and predictive modeling, can provide valuable insights to support complex decision-making and optimize management strategies [5]. The potential for "smart park technologies" to aid in climate change mitigation and environmental resilience further highlights the relevance of advanced technological solutions [6]

Leveraging these technologies in a co-management context could fundamentally alter how stakeholders interact, how decisions are made, and how resources are managed. A blockchain-based system could record every decision made by a co-management body, every financial transaction related to the protected area, and every allocated permit or access right, creating a permanent and publicly verifiable audit trail (with appropriate privacy considerations) [7, 8]. This inherent transparency could significantly reduce opportunities for corruption and build trust among stakeholders. Concurrently, AI could analyze this wealth of data, along with ecological and social data, to identify equitable resource distribution models, predict the potential impacts of different management decisions on various stakeholder groups, and even personalize recreation experiences to manage visitor flows and minimize environmental impact [9].

This paper argues that the strategic integration of blockchain and AI technologies offers a novel and powerful approach to overcoming key challenges in protected area and recreation co-management. By enhancing transparency and accountability through blockchain's immutable ledger and improving the fairness and effectiveness of decisions through AI's analytical capabilities, co-management can become more robust, equitable, and sustainable. The following sections will delve deeper into the specific applications of each technology, explore their synergistic potential when combined, discuss the significant challenges that must be addressed for successful implementation, and outline future directions for research and practice in this promising interdisciplinary field. Ultimately, this paper envisions a future where technology serves as a catalyst for stronger, more trusting, and more equitable partnerships in the stewardship of our vital natural heritage and the provision of enriching recreation opportunities.

2. Understanding protected area and recreation Co-Management

Protected area co-management is a governance paradigm that recognizes the limitations of purely state-centric or purely community-based management approaches. It involves power-sharing and joint responsibility between government authorities and other relevant stakeholders, typically local communities, Indigenous peoples, and sometimes non-governmental organizations or the private sector [1]. The specific forms of co-management vary widely depending on the legal and socio-cultural context, ranging from advisory committees with limited power to formal legal partnerships with shared decision-making authority and resource control [2]. The theoretical underpinnings of co-management emphasize principles of participation, devolution of power, recognition of local knowledge, and the pursuit of both conservation and livelihood objectives [10].

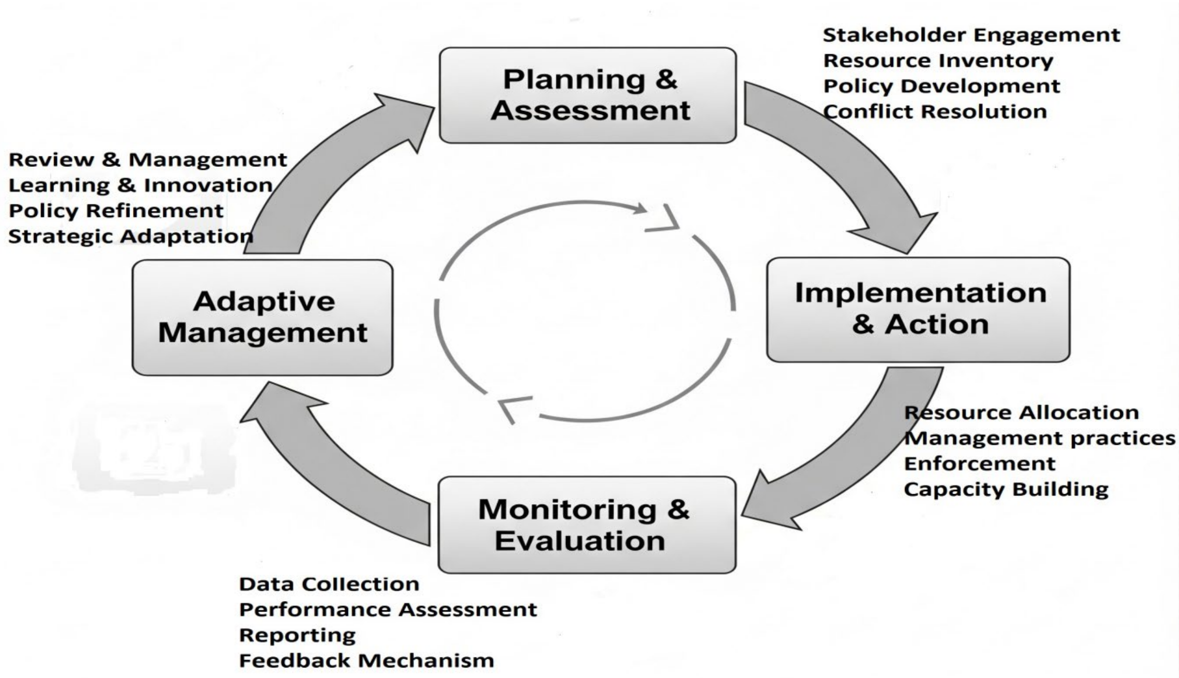

Figure 1. Framework for protected area and recreation comanagement

The benefits of successful co-management can be substantial. Increased local involvement often leads to greater compliance with regulations, as communities feel a sense of ownership and responsibility [3]. The integration of traditional ecological knowledge can enhance conservation effectiveness, particularly in complex ecosystems [11]. Co-management can also contribute to local economic development through benefit-sharing mechanisms and sustainable resource use [12]. For recreation management within protected areas, co-management can help balance visitor needs with conservation imperatives, ensuring that recreation activities are managed sustainably and that local communities benefit from tourism [13]. Research on the role of park interpretation in enhancing visitor experiences and conservation awareness in Nigerian National Parks further supports the importance of effective recreation management [14].

Despite its promise, co-management faces significant hurdles in practice. A primary challenge is the inherent power imbalance that often exists between government agencies and other stakeholders. Government bodies typically retain ultimate legal authority and control over significant resources, which can undermine genuine power-sharing and lead to tokenistic forms of participation [3]. Building and maintaining trust among diverse stakeholders with potentially conflicting interests is also a continuous challenge. Historical grievances, lack of transparency in past interactions, and differing worldviews can create an environment of suspicion and hinder effective collaboration [15]. Transparency in decision-making is another critical issue. When the processes by which decisions are made are unclear or inaccessible to some stakeholders, it erodes trust and can lead to perceptions of unfairness or bias [16]. This is particularly true for decisions regarding resource allocation, such as the distribution of tourism revenues, permits for resource use, or funding for conservation projects. Without a clear and verifiable record of how these decisions are made and implemented, accountability is difficult to establish.

Ensuring equity in co-management is multifaceted. It involves not only equitable representation in decision-making bodies but also the equitable distribution of benefits and burdens arising from protected area and recreation management [17]. Studies examining income inequality and the impact of National Parks on the livelihood of surrounding households highlight the importance of addressing these socio-economic disparities within co-management frameworks [18, 19, 20]. Research also explores the determinants of income diversification among support zone communities, emphasizing the need for equitable benefit sharing (Jacob et al., 2020a). Achieving equity requires mechanisms to ensure that the voices of marginalized groups, including Indigenous peoples and poor communities, are heard and given genuine consideration [21]. The socio-cultural importance of sacred forests conservation also underscores the need for culturally sensitive and equitable approaches [22, 23].

Furthermore, effective co-management relies on access to and management of diverse data. Ecological data, socio-economic data, visitor data, and financial data all inform management decisions. However, this data is often fragmented, held by different stakeholders, and difficult to share securely and efficiently [24]. Lack of standardized data collection methods, issues of data ownership and privacy, and the absence of integrated data platforms hinder evidence-based decision-making and monitoring of co-management effectiveness [25, 26]. The challenges of data management directly impact transparency and equity, as unequal access to information can exacerbate existing power imbalances [27]. Research on forest revenue generation and the application of time-series analysis in predictive modeling of forest revenue sources demonstrates the complexity of managing such data [19, 28].

3. Blockchain technology and potential relevance

Blockchain technology has gained prominence primarily through its association with cryptocurrencies like Bitcoin, but its underlying principles offer far-reaching applications beyond the financial sector (Table 1). At its core, a blockchain is a distributed, immutable ledger that records transactions or data across a network of computers [4]. Instead of a single, centralized database, the ledger is shared and synchronized among all participants in the network. Each new transaction is grouped into a block, which is then cryptographically linked to the previous block, forming a chain. Once a block is added to the chain and verified by the network participants, it is extremely difficult to alter or delete the data it contains, making the ledger effectively immutable [29].

Table 1. Blockchain technology and its relevance to Co-Management and protected area

Feature	Description	Relevance	Author
Decentralization	No single entity controls the ledger; authority is shared across participants.	Empowers multiple stakeholders equally, reducing central dominance.	[4]
Immutability	Data cannot be altered once verified and added to the chain.	Ensures permanent, verifiable records of decisions, permits, finances, etc.	[29]
Transparency	Transactions visible on the ledger (depending on blockchain type), though sensitive data may be encrypted.	Improves accountability and stakeholder trust through visible validation.	[30]
Security	Cryptographic hashing links blocks, preventing tampering and fraud.	Protects data integrity in co-management decisions and monitoring.	[31]
Smart Contracts	Self-executing coded agreements triggered by predefined conditions.	Automates tasks (e.g., fund distribution, permit issuance) reliably.	[32]
Applications	Used for carbon credits, sustainable supply chains, land	Extends to recreation and protected areas:	[33]

	ownership records.	transparency, trust, secure data.

Several key characteristics of blockchain technology make it relevant to addressing the challenges of co-management:

Decentralization: The ledger is not controlled by a single entity but is distributed across the network. This reduces reliance on a central authority and can increase resilience and resistance to censorship or single points of failure [4]. In a co-management context, a decentralized ledger could be managed by representatives of different stakeholder groups, reducing the power of any single agency.

Immutability: Once data is recorded on the blockchain, it is extremely difficult to change or delete. This creates a permanent and verifiable history of all transactions and activities [29]. For co-management, this means decisions, financial flows, permits issued, and monitoring data could be recorded in a way that builds trust through verifiable history.

Transparency: Depending on the type of blockchain (public or permissioned) and the design, the ledger can be publicly viewable, allowing participants to see the history of transactions. While sensitive information might be encrypted, the fact that a transaction occurred and was validated is transparent [30]. This inherent transparency can significantly improve accountability in co-management processes.

Security: Cryptographic principles are used to secure the data on the blockchain, making it highly resistant to tampering and fraud [31]. Each block contains a cryptographic hash of the previous block, so any attempt to alter a past block would break the chain and be immediately detectable.

Smart Contracts: These are self-executing contracts with the terms of the agreement directly written into lines of code. They run on the blockchain and automatically execute when predefined conditions are met, without the need for intermediaries [32]. Smart contracts could automate aspects of co-management agreements, such as the distribution of funds based on specific triggers or the automatic issuance of permits under certain conditions, ensuring that agreements are executed reliably and transparently.

The potential applications of blockchain in environmental governance and resource management are beginning to be explored. Examples include tracking carbon credits, managing supply chains for sustainable products, and recording land ownership in a secure and transparent manner [33]. In the context of protected area and recreation co-management, blockchain's capabilities offer direct solutions to the issues of transparency, trust, and secure data management. Previous research has explored the relevance and challenges of Geographic Information Systems (GIS) in protected forest management, which shares principles of data integrity and spatial transparency with blockchain applications [34]. Similarly, strategies for ICT application in sustainable forest management also lay groundwork for considering new digital ledger technologies [35].

Imagine a blockchain-based system where every decision made by a co-management committee, every financial contribution and expenditure related to the protected area, and every permit issued for recreation or resource use is recorded. This ledger would be accessible to all stakeholders on the network (according to predefined permissions), creating an unprecedented level of transparency [7, 8]. The immutability of the ledger would ensure that these records could not be altered retroactively, building trust and accountability. Smart contracts could automate the distribution of benefits from tourism or other activities based on pre-agreed rules, ensuring equity and reducing the potential for manual errors or manipulation. Furthermore, ecological monitoring data and visitor statistics could be securely recorded on the blockchain, providing a verifiable and tamper-proof source of information for decision-making [9, 36]. While the application of blockchain in this domain is still nascent, its fundamental features align well with the requirements for building more transparent, trustworthy, and accountable co-management systems.

4. Artificial intelligence and relevance

Artificial Intelligence (AI) refers to the development of computer systems capable of performing tasks that typically require human intelligence, such as learning, problem-solving, perception, and decision-making [37]. Modern AI encompasses a wide range of techniques and applications, with machine learning (ML) being a particularly relevant subfield. ML algorithms enable systems to learn from data without being explicitly programmed, identifying patterns, making predictions, and improving their performance over time [38]. AI's capabilities offer significant potential for enhancing the effectiveness and equity of protected area and recreation co-management by providing advanced tools for data analysis, decision support, optimization, and personalized interaction (Table 2). Key areas where AI can be applied include:

Data Analysis and Pattern Recognition: Protected areas and recreation sites generate vast amounts of data, from ecological surveys and camera trap images to visitor movement patterns and social media sentiment. AI, particularly ML algorithms, can process and analyze this data to identify trends, detect anomalies (e.g., illegal activities), and gain deeper insights into complex ecological and social systems [39]. Research on the temporal analysis of timber exploitation and the application of time-series analysis in predictive modeling of forest revenue sources in Nigeria demonstrates the utility of such analytical approaches [40, 20]. The use of bioacoustic surveillance also highlights the potential for AI in unveiling wildlife insights in protected ecosystems [41].

Predictive Modeling: AI models can be trained on historical data to predict future trends, such as visitor numbers, potential environmental impacts of recreation, or the spread of invasive species [42]. Predictive capabilities allow co-management bodies to proactively address potential issues and allocate resources more effectively.

Decision Support Systems: AI can power decision support systems that help co-management committees evaluate the potential consequences of different management options. By analyzing complex interactions between ecological, social, and economic factors, AI can provide insights into how various decisions might impact different stakeholders and conservation outcomes [43]. This can facilitate more informed and potentially more equitable decision-making. Studies evaluating the efficiency of protected areas, such as Old Oyo National Park, using approaches like Data Envelopment Analysis (DEA), provide a foundation for AI-driven optimization in park management [44].

Optimization of Resource Allocation: AI algorithms can optimize the allocation of limited resources, such as patrol efforts, maintenance budgets, or staff time, based on real-time data and predictive insights. This can lead to more efficient and effective management operations [45]. For recreation management, AI can optimize trail maintenance schedules or the placement of interpretive signage based on usage patterns.

Personalized Recreation Management: AI can be used to personalize visitor experiences while simultaneously managing visitor flows to minimize environmental impact. By analyzing visitor preferences and real-time park conditions, AI-powered applications could recommend less crowded trails, suggest alternative activities during peak times, or provide tailored information about responsible recreation practices [46]. Research on visitors' perceptions of service delivery and satisfaction in Nigerian National Parks provides valuable data for developing such personalized approaches [47,48].

Stakeholder Input Analysis: Co-management involves incorporating input from diverse stakeholders, often through public consultations, meetings, and submissions. AI, particularly natural language processing (NLP), can analyze large volumes of textual and even audio input to identify key themes, sentiments, and concerns across different stakeholder groups [49]. This can help ensure that a wider range of voices are considered in the decision-making process, contributing to equity. Studies on community participation in protected area management highlight the importance of effective stakeholder engagement [50,51].

Monitoring and Enforcement: AI can enhance monitoring efforts through automated analysis of sensor data, satellite imagery, or aerial drone footage to detect illegal logging, poaching, or unauthorized construction [52]. Research on anti-poaching effectiveness and wildlife poaching in Nigerian National Parks underscores the challenges in this area, where AI could provide significant support (53,54]. The use of bioindicator species, including mammals and reptiles, also offers avenues for AI-driven environmental health assessment [55,56].

In the context of equitable co-management, AI can play a crucial role in identifying and (mitigating biases in data and decision-making processes. By analyzing the impacts of past decisions on different stakeholder groups, AI can help identify patterns of inequity and suggest alternative approaches that promote fairer outcomes [57]. For instance, AI could analyze how resource allocation decisions have historically affected marginalized communities and propose adjustments to ensure a more equitable distribution of benefits in the future, drawing insights from studies on income inequality around National Parks [58,59).

Table 2. Relevance of Artificial Intelligence (AI) in Protected Area and Recreation Co-Management

AI Application	Description	Relevance	Author
Data Analysis & Pattern Recognition	AI (esp. ML) processes ecological surveys, camera traps, visitor patterns, social media sentiment.	Detects anomalies (e.g., illegal activities), reveals trends in ecosystems and visitor behaviour. Nigeria: timber exploitation forecasting and bioacoustic surveillance.	[39 - 41]
Predictive Modeling	AI predicts visitor numbers, environmental impacts, invasive species spread.	Enables proactive management by forecasting ecological and social risks.	[42]
Decision Support Systems	AI integrates ecological, social, and economic data to simulate management outcomes.	Supports equitable and informed decision-making; DEA studies in Old Oyo National Park show optimization potential.	[43, 44]
Resource Allocation Optimization	AI optimizes deployment of limited resources (patrols, budgets, staff time).	Improves efficiency in monitoring, trail maintenance, signage placement, and park operations.	[45]
Personalized Recreation Management	AI personalizes visitor experiences and manages flows via preference and real-time data.	Recommends less crowded trails, alternative activities, or tailored visitor information; Nigerian parks' visitor studies provide data foundations.	[18,46, 48]
Stakeholder Input Analysis	NLP analyzes consultation data (text/audio) to identify themes, sentiments, concerns.	Ensures broad representation in co-management decisions and enhances inclusivity in governance.	[49, 50]
Monitoring & Enforcement	AI automates analysis of drones, sensors, or satellite data for detecting illegal activities.	Enhances anti-poaching, logging detection, and bioindicator monitoring in Nigerian parks and beyond.	[52-54]

Table 2. (*Continued*)

5. Application of blockchain to co-management

The application of blockchain technology in protected area and recreation co-management directly addresses the critical need for enhanced transparency, accountability, and trust among diverse stakeholders. By providing a secure, immutable, and potentially distributed ledger, blockchain can fundamentally change how information is recorded, shared, and verified within co-management frameworks. One of the most direct applications of blockchain is in creating a transparent and immutable record of decisions. Every significant decision made by a co-management committee, from approving management plans to setting recreation fees or allocating resources, could be recorded on a blockchain. Each entry would include details such as the date, the decision made, the rationale (potentially linked to supporting documents stored off-chain but referenced on-chain), and the stakeholders involved in the decision-making process. This creates a permanent audit trail that is accessible to all authorized participants on the network. Unlike traditional paper-based records or centralized digital databases that can be subject to alteration or loss, the blockchain record would be highly resistant to tampering, ensuring that the history of decisions is accurate and verifiable [30]. This level of transparency builds trust by allowing stakeholders to see exactly when and how decisions were made, reducing suspicion and fostering accountability.

Financial transparency is another area where blockchain offers significant advantages. Co-management often involves the management of financial resources, whether from government budgets, donor funds, tourism revenues, or conservation payments. A blockchain-based financial system could track every incoming and outgoing fund related to the protected area and its recreation activities. Each transaction would be recorded on the immutable ledger, providing a clear and verifiable history of how money is being spent [33]. Research on forest revenue generation and the assessment of international partnership funding among National Parks in Nigeria highlights the need for robust financial tracking mechanisms that blockchain could provide [28,60]. Smart contracts could automate the distribution of tourism revenues to local communities based on pre-agreed formulas, ensuring that benefit-sharing mechanisms are implemented reliably and transparently. This level of financial accountability is crucial for building trust, particularly in contexts where historical mismanagement or corruption has been an issue. Stakeholders could independently verify how funds are being utilized, increasing confidence in the co-management process.

Secure and transparent management of permits and access rights is also a promising application. Permits for activities such as guided tours, resource harvesting (where permitted), or specific recreation access could be issued and managed as digital assets on a blockchain. Each permit would have a unique digital identity recorded on the ledger. The blockchain would track the issuance, transfer (if applicable), and usage of these permits, creating a transparent and verifiable record [4]. This could help prevent the illegal issuance of permits, ensure fair allocation based on established criteria, and provide real-time data on resource use or visitor numbers. For recreation management, this could mean tracking the number of hikers on a specific trail or the number of boats on a lake in a transparent and verifiable manner, aiding in managing capacity and minimizing environmental impact. Studies on correlates of revenue and tourist flow in National Parks provide a basis for understanding the data that could be managed via blockchain for recreation access [61].

Furthermore, blockchain can facilitate secure and transparent data sharing related to protected area management. While sensitive ecological or personal data would not typically be stored directly on a public blockchain, the blockchain can be used to record the *metadata* of data transactions or to manage access permissions to data stored off-chain [31]. For example, records of ecological monitoring data collection events, the source of the data, and who has accessed it could be immutably recorded on the blockchain. This provides a transparent audit trail for data provenance and usage, which is essential for building trust in the data used for decision-making. The significance of Satellite Remote Sensing and GIS Applications in environmental meteorology, and the relevance of GIS in protected forest management, underscore the importance of robust data infrastructure that blockchain could enhance [34,62]. Smart contracts could also be used to automate data sharing agreements between different stakeholders, ensuring that data is shared securely and according to agreed-upon terms.

The use of smart contracts to automate co-management agreements can enhance both transparency and equity. Rather than relying on manual processes or intermediaries, key aspects of co-management agreements can be encoded into smart contracts that automatically execute when specific conditions are met [32]. For instance, a smart contract could automatically trigger a payment to a local community conservation fund when a certain tourism revenue threshold is reached, or automatically grant access permissions to a research team upon verification of their credentials. This automation reduces the potential for delays, errors, or discretionary interference, ensuring that agreements are implemented reliably and transparently according to the predefined rules.

Table 3. Applications of blockchain technology in protected area and recreation Co-Management

Application Area	Description	Author
Decision Transparency	Immutable ledger records decisions, including date, rationale, and stakeholders involved.	[30]
Financial Accountability	Blockchain records all financial inflows and outflows; smart contracts automate distribution.	[28,33,60]
Permit & Access Rights	Permits issued as digital assets with unique blockchain identities, tracked through the ledger.	[4,62]
Data Sharing & Provenance	Blockchain records metadata of ecological and monitoring datasets, managing access rights securely.	[31,34,62]
Smart Contracts for Agreements	Encodes co-management rules into self-executing contracts triggered by conditions.	[32]

6. Application of artificial intelligence to co-management

Artificial intelligence offers a suite of powerful tools that can support more equitable and effective decision-making within protected area and recreation co-management frameworks. By analyzing complex data, identifying patterns, and providing predictive insights, AI can help co-management bodies navigate challenging trade-offs, optimize resource use, and ensure that the needs and perspectives of diverse stakeholders are considered (Table 4). One key application of AI is in analyzing diverse stakeholder input to inform decision-making. Co-management processes often involve collecting input from a wide range of stakeholders through various channels, including public meetings, written submissions, and surveys. Manually processing and synthesizing this information to understand the full spectrum of views and identify common ground or areas of conflict can be challenging and time-consuming. Natural Language Processing (NLP), a branch of AI, can automate the analysis of large volumes of textual data from stakeholder consultations, identifying key themes, sentiments, and concerns expressed by different groups [49]. This can provide co-management committees with a more comprehensive and objective understanding of stakeholder perspectives, helping to ensure that a wider range of voices are considered in the decision-making process, and potentially leading to more equitable outcomes. Studies on community participation in protected area management in Nigeria underscore the importance of such engagement [50,51,63]. AI can also be used to analyze demographic data and participation rates in consultations to identify potential biases or under-representation of certain groups, allowing managers to proactively reach out to marginalized stakeholders.

AI can also contribute to equitable resource allocation by analyzing data on historical distribution patterns, conservation needs, and the socio-economic conditions of local communities. Machine learning algorithms can identify potential inequities in how resources (e.g., conservation funds, tourism benefits, access permits) have been allocated in the past and propose alternative allocation models that promote fairness and address historical imbalances [57]. For instance, AI could analyze tourism revenue data alongside data on community poverty levels and conservation needs to suggest a benefit-sharing model that prioritizes investment in communities most impacted by conservation restrictions or those with the greatest need for support, drawing insights from research on income inequality and poverty incidence among rural households around National Parks [19,20,64].

In optimizing protected area and recreation management operations, AI can lead to more effective and potentially more equitable outcomes. By analyzing real-time data from sensors, monitoring equipment, and visitor tracking systems, AI can optimize patrol routes to deter illegal activities more effectively, predict areas at high risk of wildfire and allocate resources accordingly, or manage visitor flows to prevent overcrowding in sensitive ecological areas [46,52]. Research on anti-poaching effectiveness in Old Oyo National Park and the challenges of bushmeat trade in Nigeria provide practical contexts where AI could significantly enhance enforcement and management strategies [65,66]. While optimization might seem purely efficiency-focused, it has equity implications. For example, effectively managing visitor flows can prevent the degradation of natural resources that disproportionately impacts communities reliant on those resources, and equitable access to well-maintained recreation facilities is important for social well-being. AI can also optimize the scheduling of maintenance activities to minimize disruption to local communities or recreationists, considering the overview of recreational infrastructure and facilities in Nigerian cities [67].

AI-powered predictive modeling can support proactive and equitable management. By predicting the potential impacts of climate change on specific ecosystems or the future distribution of invasive species, AI can help co-management bodies plan adaptation and mitigation strategies that consider the differential vulnerability of various stakeholder groups [42]. The application of time-series analysis in predictive modeling of forest revenue sources and studies on land use/cover changes in forest areas demonstrate the utility of such predictive capabilities in environmental management [54,59]. For recreation management, predicting future visitor demand can help in planning infrastructure development or implementing reservation systems in a way that ensures fair access while preventing over-tourism in sensitive areas.

Furthermore, AI can assist in monitoring and evaluating the effectiveness of co-management interventions from both a conservation and a social perspective. By analyzing data on ecological indicators, socio-economic conditions, and stakeholder satisfaction, AI can help identify which management strategies are achieving their intended outcomes and which may need adjustment [39]. This continuous evaluation, supported by AI's analytical capabilities, allows co-management bodies to adapt their approaches over time, ensuring that management remains effective and responsive to the needs of both the environment and the people who depend on it. The use of bioacoustic surveillance to unveil wildlife insights in protected ecosystems and the application of bioindicators in recreational planning and development are examples of how AI can enhance monitoring and evaluation [60,68]. AI can also be used to monitor for unintended negative consequences of management actions on specific stakeholder groups, allowing for timely adjustments to promote equity. Finally, AI can facilitate personalized communication and engagement with stakeholders. By analyzing stakeholder preferences and communication styles, AI-powered systems could tailor information and outreach efforts to different groups, improving participation and understanding of co-management processes. For recreationists, AI could provide personalized recommendations for trails or activities based on their interests and physical abilities, while also subtly guiding them towards less crowded areas to distribute impact more evenly [46]. The role of park interpretation in enhancing visitor experiences and conservation awareness further supports this application [14].

Table 4. Applications of artificial intelligence in protected area and recreation co-management

Application Area	Description	Author
Stakeholder Input Analysis	NLP analyzes large volumes of consultation data (text/audio) to identify themes, sentiments, and underrepresented voices.	[49 - 51]
Equitable Resource Allocation	ML identifies inequities in past allocations and proposes fairer models based on socio-economic and conservation needs.	[19,20,57]
Operational Optimization	AI processes real-time data from sensors, visitor tracking, and monitoring systems.	[46,52,66]
Predictive Modeling	AI forecasts environmental and social changes using historical and time-series data.	[42,54,59]
Monitoring & Evaluation	AI analyzes ecological, socio-economic, and satisfaction data for adaptive management.	[39,60,68]
Personalized Engagement	AI tailors communication and recreation services based on stakeholder preferences and needs.	[14,46]

7. Integrating blockchain and AI for synergistic effects

The true transformative potential for transparent and equitable protected area and recreation co-management lies in the synergistic integration of blockchain and artificial intelligence technologies as indicated in Table 5. While each technology offers significant benefits on its own, their combination creates a powerful ecosystem where transparency, trust, data integrity, and intelligent analysis converge to support more effective and equitable governance.

At the core of this synergy is the ability of blockchain to provide a secure, immutable, and transparent foundation for the data that AI analyzes. AI algorithms are only as good as the data they are trained on and the data they process for decision support. If the underlying data is inaccurate, manipulated, or untrustworthy, the AI's outputs will be flawed and potentially lead to inequitable outcomes. By recording key data points and transactions on a blockchain, such as financial flows, permit issuances, management decisions, and even verified ecological observations, co-management bodies can ensure that the data fed into AI systems is reliable and tamper-proof [4,31]. The application of ICT in sustainable forest management and the significance of GIS and remote sensing in environmental management highlight the existing need for robust data infrastructure that blockchain can solidify [35,69). This verifiable data foundation significantly increases the trustworthiness of the vision generated by AI.

Conversely, AI can enhance the utility and interpretation of the data stored on the blockchain. While the blockchain provides a transparent record, the sheer volume of data on a mature blockchain could be overwhelming for humans to analyze effectively. AI can process this blockchain data to identify patterns, anomalies, and trends that might not be immediately apparent. For example, AI could analyze blockchain records of financial transactions to detect unusual spending patterns that might indicate inefficiency or potential corruption, drawing on studies of forest revenue generation [28,70]. It could analyze blockchain records of permit issuance and visitor movements (recorded with privacy considerations) to understand recreation pressure points and predict future usage patterns [46], informed by research on tourist flow and visitor perception [47,62]. This integration allows co-management bodies to move beyond simply having transparent data to actively gaining actionable insights from that data.

The combination of blockchain and AI can significantly strengthen accountability mechanisms. Blockchain provides the immutable record of who did what and when (related to recorded transactions and decisions), while AI can analyze this record to identify deviations from established procedures or agreements. Smart contracts on the blockchain can automatically trigger actions or notifications based on AI-driven analysis of on-chain data. For instance, if AI analysis of ecological monitoring data (referenced or summarized on-chain), perhaps from bioacoustic surveillance or bioindicator studies, indicates that resource use under a specific permit (recorded on-chain) is exceeding sustainable levels, a smart contract could automatically suspend the permit or trigger a review by the co-management committee, with the entire process recorded transparently on the blockchain [60, 71]. This also aligns with efforts to evaluate park efficiency [44].

Furthermore, the synergy can lead to more equitable outcomes in resource allocation and benefit sharing. Blockchain can ensure the transparent and automatic distribution of benefits (e.g., tourism revenues) according to rules encoded in smart contracts [32]. AI can inform the design of these smart contracts by analyzing data on community needs, historical inequities, and the impact of protected area management on different groups [57]. For example, AI could analyze socio-economic data and conservation costs incurred by different communities to propose a formula for revenue sharing that a smart contract then executes transparently on the blockchain, building on insights from studies on income inequality and livelihood impacts around National Parks [19,20]. This combination ensures that benefit-sharing is not only transparently executed but also based on a more informed and equitable framework.

In the realm of adaptive management, the integration of blockchain and AI is particularly powerful. As co-management strategies are implemented, data on their effectiveness (both ecological and social) can be recorded on the blockchain, providing a verifiable history of interventions and their outcomes. AI can then analyze this historical data to evaluate the success of different strategies and identify areas for improvement [39]. This continuous learning loop, powered by the integrity of blockchain data and the analytical capabilities of AI, allows co-management bodies to adapt their approaches over time, making management more effective and responsive to changing conditions and stakeholder needs.

Table 5. Synergistic integration of blockchain and AI in protected area and recreation co-management

Synergy Area	Role of Blockchain	Role of AI	Combined Benefit	Author
Data Integrity & Trust	Provides secure, immutable, tamper-proof foundation for financial, permit, and ecological data.	Relies on trustworthy data to generate accurate, equitable insights.	Ensures reliable datasets for AI analysis, eliminating manipulation risks and enhancing trust in outputs.	[4,31,69]
Data Analysis & Insight	Records massive volumes of transactions and decisions in transparent form.	Processes blockchain records to identify patterns, anomalies, and trends in finance, permits, or visitor flows.	Transforms raw transparency into actionable insights for proactive and equitable decision-making.	[28,47,62]
Accountability & Enforcement	Immutable logs of decisions, permits, and ecological monitoring data.	Detects deviations from agreed rules; triggers smart contract-based enforcement	Strengthens compliance by combining unalterable records with automated, intelligent	[44,60,71]

Synergy Area	Role of Blockchain	Role of AI	Combined Benefit	Author
		automatically.	monitoring.	
Equitable Resource Sharing	Smart contracts execute automatic distribution of revenues or benefits.	Analyzes socio-economic and conservation data to design fair allocation models.	Ensures transparent execution of revenue-sharing rules informed by AI-driven equity analysis.	[20,32,57]
Adaptive Management	Creates a verifiable history of interventions and outcomes.	Analyzes blockchain records to assess strategy effectiveness and suggest improvements.	Establishes a continuous learning loop for responsive, evidence-based co-management.	[39]

Table 5. (*Continued*)

8. Challenges and considerations for implementation

While the potential benefits of leveraging blockchain and AI for protected area and recreation co-management are significant, their successful implementation is contingent upon addressing a range of technical, ethical, governance, and social challenges as indicated in Table 6. Ignoring these considerations could lead to failed projects, exacerbate existing inequalities, or erode stakeholder trust. A primary challenge is technical feasibility and scalability. Blockchain technology, particularly public blockchains, can face scalability issues, with limitations on the number of transactions they can process per second [72]. For managing high volumes of data, such as real-time visitor tracking or extensive ecological monitoring, this could be a significant hurdle. Permissioned blockchains, which restrict participation to known entities, might offer better scalability and privacy controls but require a higher degree of coordination and trust among the participating organizations. The energy consumption of some blockchain consensus mechanisms (like Proof-of-Work) is also a concern from an environmental sustainability perspective, although more energy-efficient alternatives (like Proof-of-Stake) are becoming more prevalent [73]. The challenges and relevance of GIS in protected forest management and the strategies for ICT application in sustainable forest management provide a context for understanding technical integration in this domain [34; 35].

Data privacy and security are critical ethical considerations. While blockchain offers transparency, certain data related to protected area management and recreation activities can be highly sensitive. Information about the location of rare species, the timing of anti-poaching patrols, or the personal details of recreationists must be handled with extreme care [74]. While the blockchain can record that a transaction occurred, the sensitive details might need to be stored off-chain with access controlled via the blockchain and smart contracts. Ensuring robust data encryption, access controls, and compliance with data protection regulations (like GDPR) is essential. Similarly, AI systems rely on data, and the collection and use of this data must be ethical and transparent, with clear policies on data ownership and usage.

Algorithmic bias in AI is a significant concern for ensuring equity. AI algorithms are trained on data, and if this data reflects existing societal biases or historical inequities, the AI's outputs and recommendations can perpetuate or even amplify these biases [57]. For example, an AI model trained on historical resource allocation data might learn to favor certain communities over others if the historical data reflects biased decision-making. Ensuring that AI models are developed and evaluated for fairness and that mechanisms are in place to identify and mitigate bias is crucial for promoting equitable outcomes in co-management. This requires careful selection and preparation of training data, as well as ongoing monitoring of AI system performance. Insights from studies on income inequality and the impact of protected areas on community livelihoods are crucial for informing bias mitigation strategies [19,20,75].

Governance and regulatory frameworks need to adapt to accommodate blockchain and AI in co-management. Clear legal and institutional frameworks are required to define the roles and responsibilities of different stakeholders in managing these technologies, the legal status of blockchain records and smart contracts, and the rules governing the use of AI for decision support [73]. Establishing data governance policies that address data ownership, access, and usage rights is paramount. The decentralized nature of blockchain can also pose challenges for traditional governance structures, requiring new models of collaboration and decision-making within the co-management body. Research on resource governance structures in Nigerian National Parks provides a valuable context for developing such frameworks [76].

Digital literacy and capacity building among stakeholders are essential for the successful adoption of these technologies. Many stakeholders involved in co-management, particularly local communities and Indigenous peoples, may have limited access to technology or lack the technical skills to effectively participate in blockchain or AI-driven systems [77]. Providing adequate training, ensuring access to necessary infrastructure and devices, and designing user-friendly interfaces are critical for ensuring inclusive participation and preventing the technologies from becoming another source of inequity. Trust in the technologies themselves is also a factor; stakeholders need to understand how these systems work and feel confident that they are fair and secure. The potential of participatory GIS (PGIS) in natural resource management highlights the importance of involving communities in technological solutions [78].

Implementation costs can be substantial. Developing and deploying blockchain and AI solutions requires significant investment in infrastructure, software development, training, and ongoing maintenance. Securing funding for these initiatives, particularly in resource-constrained protected area management contexts, can be a major challenge [79]. Bridging the challenges faced by Micro, Small, and Medium Enterprises (MSMEs) in accessing resources for recreational development projects is an example of the financial hurdles that need to be addressed [80]. A careful cost-benefit analysis is needed to ensure that the potential benefits outweigh the implementation costs and that funding models are sustainable in the long term.

Finally, the complexity of co-management dynamics itself can be a barrier. Co-management involves navigating complex social relationships, power dynamics, and potentially conflicting objectives [3]. Simply introducing new technologies will not resolve these underlying issues. Successful implementation requires a participatory process that involves all stakeholders from the outset, building consensus on how the technologies will be used and ensuring that they serve to empower stakeholders and strengthen collaboration, rather than imposing top-down technical solutions. The design and implementation process must be culturally sensitive and respect local knowledge systems and governance structures, drawing on insights from studies on community participation and conflict resolution in protected areas [50,75].

Table 6. Challenges and strategies for implementing blockchain and AI in protected area and recreation co-management

Challenge	Key Issues	Strategies / Solutions	Expected Outcome	Author
Technical Feasibility	Limited transaction speed; high energy use of some blockchains.	Use permissioned chains; adopt energy-efficient consensus; integrate with GIS/ICT.	Scalable, efficient, and sustainable systems.	[72,73]
Data Privacy & Security	Risk of exposing sensitive ecological or personal data.	Store sensitive info off-chain; use encryption, access control, and	Protects privacy and builds stakeholder trust.	[74]

Challenge	Key Issues	Strategies / Solutions	Expected Outcome	Author
		smart contracts.		
AI Bias & Equity	Biased data can reinforce inequalities.	Fairness audits; diversify datasets; monitor AI outputs for equity.	Reduces bias and promotes fair outcomes.	[57,75]
Governance & Regulation	Lack of legal clarity on blockchain/AI use and accountability.	Create legal frameworks; define data ownership; adopt multi-stakeholder governance.	Clear accountability and legitimate use.	[73,76]
Digital Literacy	Limited access and technical skills among local/Indigenous groups.	Training programs; user-friendly tools; participatory GIS to support inclusion.	Broader participation and reduced exclusion.	[77,78]
Implementation Costs	High setup, training, and maintenance costs.	Cost–benefit analysis; phased adoption; public–private and donor funding.	Sustainable financing and long-term use.	[79,80]
Social Dynamics	Power imbalances and conflicting interests in co-management.	Bottom-up design; cultural sensitivity; conflict resolution; consensus building.	Stronger legitimacy and cooperation.	[3,75]

9. Future directions and research needs

The application of blockchain and AI in protected area and recreation co-management is still in its nascent stages, offering fertile ground for future research and development. Several key areas warrant further investigation to fully realize the potential of these technologies and address the challenges associated with their implementation. One crucial area for future research is developing and testing specific use cases for blockchain and AI in diverse co-management contexts [81]. Pilot projects are needed to explore the practical application of these technologies in different types of protected areas (e.g., marine protected areas, forest reserves, cultural landscapes) and for various recreation activities [82]. Research should focus on evaluating the effectiveness of these applications in enhancing transparency, improving equity, and achieving conservation and recreation goals. This includes developing metrics to measure the impact of these technologies on stakeholder trust, participation, and the equitable distribution of benefits and burdens [83]. The concept of Smart Park Technologies for climate change mitigation and environmental resilience offers a promising avenue for such exploration [6].

Further research is also needed on designing inclusive and accessible blockchain and AI systems for diverse stakeholders. This involves exploring user interface design that is intuitive for individuals with varying levels of digital literacy, investigating offline or low-connectivity solutions for remote communities, and developing culturally appropriate approaches to technology adoption [77]. Research should also examine how to effectively incorporate traditional ecological knowledge and local values into AI models and blockchain governance structures, drawing on studies of indigenous water management strategies and the socio-cultural importance of sacred forests [22,84,85]

The interoperability between different blockchain platforms and AI systems is a critical technical challenge that requires further research and development. As different protected areas or regions might adopt different technological solutions, ensuring seamless data exchange and collaboration between these systems is essential for scaling up successful initiatives and enabling broader data analysis for regional conservation planning [86]. Standards and protocols for data sharing and system integration need to be developed, building on existing research on ICT application in sustainable forest management and GIS applications [35].

Research on the long-term sustainability and governance models for blockchain and AI in co-management is also vital. This includes exploring different funding models for technology development and maintenance, investigating decentralized governance structures for managing the blockchain network, and developing clear protocols for updating or modifying smart contracts [73]. The legal and regulatory implications of using these technologies in environmental governance require continued examination and the development of appropriate legal frameworks, informed by studies on resource governance structures in National Parks [76]. Furthermore, research should focus on addressing the ethical implications of AI and blockchain in co-management in greater depth. This includes developing frameworks for identifying and mitigating algorithmic bias, establishing guidelines for the ethical collection and use of data, and exploring mechanisms for ensuring accountability when AI systems make decisions that have significant impacts on stakeholders or the environment [57,74]. The potential social impacts, such as changes in employment or power dynamics, also require careful study, drawing insights from research on income inequality and livelihood impacts [19, 20].

The potential of using tokenization (creating digital tokens on a blockchain) in co-management warrants further exploration. This could involve tokenizing access permits, conservation credits, or even ecological assets, creating new mechanisms for resource management and potentially generating revenue for conservation through innovative financing models [33,87]. Research is needed to explore the feasibility, benefits, and risks of tokenization in this context, including its potential impact on equity and access, informed by studies on revenue generation and tourist flow in protected areas [28,61].

Finally, interdisciplinary research that brings together experts in conservation biology, recreation management, social science, computer science, and law is crucial for advancing the understanding and application of these technologies in co-management. Collaborative projects that involve protected area managers, local communities, and technology developers are essential for ensuring that solutions are relevant, practical, and meet the needs of all stakeholders. Research on environmental stewardship, bioindicators in recreational planning, and bioacoustic surveillance exemplifies the interdisciplinary nature of this field [41,68,71].

Conclusion

The strategic integration of blockchain and artificial intelligence (AI) offers a compelling solution to the persistent challenges of transparency, equity, and sustainability in protected area and recreation co-management. While traditional models often struggle with power imbalances and opaque decision-making, blockchain's inherent decentralization, immutability, and transparency provide a robust foundation for verifiable records and enhanced accountability. Concurrently, AI's capacity for advanced data analysis, insight generation, and optimized resource allocation empowers more equitable and adaptive management. The synergy between these technologies, where blockchain secures data for AI-driven insights, promises a future of data-driven decision-making, automated benefit sharing, and strengthened stakeholder trust.

However, realizing this vision necessitates addressing significant hurdles. Technical challenges like scalability and energy consumption, critical ethical considerations around data privacy and algorithmic bias, the development of robust governance frameworks, and fostering digital literacy among all stakeholders are paramount. Furthermore, substantial implementation costs demand innovative and sustainable funding models. Despite these complexities, the potential for a more just and sustainable future for both people and nature, where decisions are transparently recorded and resources equitably distributed, is too significant to overlook. Therefore, we recommend a concerted effort involving interdisciplinary research, participatory design processes, and a commitment to leveraging these technologies as tools for empowerment and collaborative stewardship of our planet's invaluable natural treasures..

Conflict of interest

The authors declare no conflict of interest

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