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Blockchain and regenerative finance: charting a path toward regeneration

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The Regenerative Finance (ReFi) movement aims to fundamentally transform the governance of global common pool resources (CPRs), such as the atmosphere, which are being degraded despite international efforts. The ReFi movement seeks to achieve this by utilizing digital monitoring, reporting, and verification (D-MRV); tokenization of assets; and decentralized governance approaches. However, there is currently a lack of a clear path forward to create and implement models that actually drive the "Re-" in ReFi beyond perpetuating the existing extractive economics and toward actual regeneration. In addition, ReFi suffers from growing pains, lacking a common interoperability framework and definition for determining what a ReFi project is and how the individual components align toward the grand ambition. This paper provides a definition of the ReFi stack of interconnected components and examines how it can address limitations in climate change accounting, finance and markets, and governance. The authors also examine the theory of regenerative economics and CPRs to encourage further discussions and advancements in the ReFi space. The crucial question remains if and how ReFi can drive a change in paradigm toward the effective regeneration of global CPRs.

KEYWORDS

blockchain technology, climate change, decentralized governance, distributed ledger technology, common pool resources, polycentricity, climate accounting

1 Introduction

1.1 Global common pool resources governance

Polycentric governance is often considered a solution to the exploitation of the "commons problems," meaning that non-excludable, open-access, and unregulated common pool resources (CPRs) are often overexploited (Ostrom, 1999). Polycentricity describes a scenario in which multiple elements mutually adjust and establish relationships with each other without the presence of a central authority (Kim, 2020). Although polycentricity and other works on global commons governance have defined the challenges and proposed related design principles in response (Dietz et al., 2003; Ostrom, 2010; Stern, 2011), this work falls short of counteracting the increasing degradation of CPRs. According to Pahl-Wostl and Knieper (2014), "[p]olycentric governance systems must fulfill at least two criteria to function as systems: i) presence of multiple centers of decision-making and coordination by ii) an overarching system of rules." In this context, "coordination" can refer to anything from informal information sharing and learning to more formal coordination that may include monitoring systems or conflict resolution (Galaz et al., 2012; Dorsch and Flachsland, 2017).

However, despite the attempt of the Paris Agreement to use polycentric governance at a global scale to coordinate climate action through both international, national, and sub-national decision-making, as well as developing an overarching system of rules, there is a risk and concern regarding increasing fragmentation (Schröder, 2018). Scholarly literature notes such increasing fragmentation and complexities in global environmental governance (Elsässer et al., 2022), particularly among the Paris Agreement actors (Biermann et al., 2009; Pattberg and Widerberg, 2016; Atkinson et al., 2017). For example, all national parties to the Paris Agreement are required to submit biennial transparency reports under the new enhanced transparency framework, with a global assessment process (the "Global Stocktake") every 5 years to understand global progress. Despite the widely acknowledged importance of monitoring and evaluation, many developing countries continue to lack the necessary institutional capacity (Aldy, 2018). Similarly, in the context of locally generated forms of self-organization, Atkinson et al. (2017) observed that the "vast majority of locally based self-organized climate change groups" are "fragmented and embryonic" and "lack the capacities/resources to engage" with larger networks, preventing "mutual learning," and "concerted action."

The fragmentation of global carbon pricing systems can be interpreted as a market failure because it leads to a socially suboptimal distribution of goods and services. In essence, market failure happens due to information asymmetry and the inability to properly price the social cost of carbon in a free market. Article 6 of the Paris Agreement recognizes the importance of carbon markets. However, in the light of climate change and the ongoing biodiversity collapse, markets seem to fail to deal with problems, which is why there is a need for polycentric governance solutions at a global scale. The current lack of an overarching set of rules at the non-jurisdictional level and the lack of efficacy of international accords (e.g., of the Paris Agreement and other international treaties) exacerbates the fragmentation of global carbon pricing schemes, which are often stated to be a critical climate policy tool (van den Bergh et al., 2020; Baranzini et al., 2017). Currently, 68 different carbon pricing schemes exist globally, with prices ranging from less than $1 to more than $130 for a metric ton of CO_2 equivalent (tCO_2e) (World Bank, 2022), emphasizing the difficulty in developing aligned incentives for global coordination as outlined in Article 6 of the Paris Agreement (UNFCCC, 2015; Franke et al., 2020).

Similarly, the British newspaper "The Guardian[1]" and the German publication "Die Zeit[2]" published articles stating that "90% of rainforest offsets certified by the biggest carbon standard—Verra—are worthless" due to incorrect methodologies applied by Verra to measure avoided deforestation. Although the aforementioned articles are controversial, the recognition that incumbent certification methodologies like the ones used by Verra are not keeping pace with the pace of technological change is critical, especially because the analog approaches raise serious questions about the accuracy of carbon avoidance and removal claims.

1.2 Regenerative finance

In this section, we provide an overview of how the Regenerative Finance (ReFi) movement defines itself and provide an overview of historic and recent projects and developments. In Section 2, we clarify the value proposition of ReFi for the climate change area and define the critical components and overall structure to contrast what is needed with the sometimes lofty ambitions or even hype in the space. For this assessment, we primarily focus on ReFi as it evolves in the climate change area to reduce the level of abstraction, as the vast majority of applications focus on this area. Following this definition, we outline a ReFi-technology stack of components in the next section and discuss how these components provide value by addressing present climate change challenges and limitations. In Sections 3, 4, 5, we highlight current issues and challenges and then discuss if and how ReFi delivers on its goals.

ReFi is an emerging movement that uses digital technologies, such as Internet of Things (IoT) sensors, machine learning (ML), and blockchain, to improve information sharing and implement an overarching system of rules. It seeks to leverage such technologies to develop the financial means to implement economic concepts such as those of "economies of permanence" and "regenerative economy" for the governance of global CPRs. The concept of economy of permanence refers to the maintenance of "*reliable inputs and healthy outputs by not exhausting critical inputs or harming other parts of the broader societal and environmental systems upon which it depends*." It was first articulated in 1945 to promote and sustain human prosperity and well-being (Kumarappa, 1945). The ReFi movement then specifically focuses on the concept of a regenerative economy, as defined by Fullerton (2015), which "maintains reliable inputs and healthy outputs by not exhausting critical inputs or harming other parts of the broader societal and environmental systems upon which it depends" (p. 22).

Currently, there is no widely accepted or formal definition of ReFi. However, most experts agree that ReFi includes a collection of applications that enable digital monitoring, reporting, and verification (D-MRV) of a CPR[3]. The resulting D-MRV data allow for the tokenization of the CPR as a real-world asset to attribute value to the underlying material reality of the resource in the form of community currencies or ground regenerative NFT collections, social tokens, and other innovative financial and market applications

1 Available at: https://www.theguardian.com/environment/2023/jan/18/revealed-forest-carbon-offsets-biggest-provider-worthless-verra-aoe (accessed 1/21/2023).

2 Available at: https://www.zeit.de/wirtschaft/2023-01/co2-certificates-fraud-emissions-trading-climate-protection-english (accessed 1/21/2023).

3 Cite the joint publication by Kolektivo Network and Curve Labs that is currently under review but will be published before we finalize this paper (link to current review version: https://docs.google.com/document/d/1gTVzuIWSKFtPCxgNGDyqMkDkXMmk_PpA50NvcQlR4SI/edit?pli=1#heading=h.r7rwmv37462). Other examples: https://blog.refidao.com/refi-roundup-52/; https://blog.toucan.earth/decarbonized-27-tokenization-consultation-opens-refi-for-regenerative-carbon-markets-future-of-digital-mrv/; Even from Gold Standard: https://www.goldstandard.org/our-story/digitising-mrv.

(e.g., Curve Labs[4]; Climate Collective[5]). Here, tokenization underpins a valuable claim to a positive impact created on a commons, thereby enabling businesses to capture a quantifiable value from the creation of public goods (George, Merrill, and Schillebeeckx, 2021). In addition, other ReFi definitions state the ambition of implementing regenerative economics at a global scale to create more equitable and sustainable financial, social, and environmental systems for human well-being; for instance, by addressing issues of sustainability such as climate change, biodiversity loss, and resource scarcity, as well as the underlying socioeconomic and institutional structures that exacerbate these crises (e.g., Regen Living[6]). Other definitions of ReFi center around the role of ReFi in market-based conservation and other types of ecosystem preservation financing[7]. In general, ReFi aims to create economic systems that enable harmonious interactions between humans and natural ecosystems.

Early ReFi applications started evolving at the beginning of 2017 (ReFi DAO, 2023), with applications and efforts including Giveth,[8] Commons Stack,[9] Open Forest Protocol,[10] and Regen Network.[11] More recently, ReFi projects started attracting significant attention from investors and users. For example, the project Flowcarbon, a climate technology company focused on building market infrastructure for the voluntary carbon market space, recently raised $70M in venture capital funding led by a16z crypto[12]. Similarly, Celo raised $20M in October 2021 to become "the home" of ReFi[13]. The KlimaDAO bootstrapped a community of over 37,000 members[14] with its $KLIMA token peaking at a price of 3,777$ in October 2021 and with a current price of around 1.5$ at the beginning of 2023[15]. At the same time, incumbents are currently conducting assessments of the ReFi space with the expectation that new policies resulted early 2023 to clarify the extent to which incumbent registries will support tokenization [e.g., the announcements by the American Carbon Registry (ACR)[16], the Gold Standard proposal to allow the creation of digital tokens for carbon credits[17], and Verra's public consultation on "Third-Party Crypto Instruments and Tokens"[18]].

In this research, we define ReFi as a *decentralized movement leveraging blockchain technology and web3 applications for the coordinated financing, governance, and regeneration of CPRs.* This definition describes the tools employed by ReFi (e.g., digital and web3 approaches), as well as what ought to be the main motivation for ReFi (i.e., the regeneration of CPRs), and the purpose of ReFi, which is to finance and improve the governance of CPRs.

2 The ReFi stack and its value proposition

A ReFi ecosystem consists of a combination of technological and traditional processes that interact and shape each other. We summarized these processes into an overview of a "ReFi Stack" (Figure 1), which includes systems of i) accounting using D-MRV approaches, ii) finance and market creation through tokenization and the pooling of assets, and iii) decentralized governance approaches for coordination and incentive design. Decentralized governance serves as the overarching system that intersects both information transparency and accountability. The academic literature underscores the crucial role of information transparency in enabling effective governance by granting stakeholders access to accurate and timely information, thus facilitating informed decision-making and reducing information asymmetry. Moreover, transparent information serves as the foundation for holding individuals and organizations accountable for their actions and outcomes, thereby cultivating trust and legitimacy within governance processes. Conversely, financial mechanisms play a pivotal role in shaping governance incentives through concepts such as incentive structures, risk management, and performance-based compensation. These mechanisms incentivize individuals and organizations to make responsible decisions and pursue long-term value creation.

The ReFi stack further encompasses both primarily digital and analog processes across the three systems of accounting, markets, finance, and governance. In addition, the ReFi stack will include digital processes that take place "on-chain" (i.e., on a blockchain protocol) or "off-chain" (i.e., in a regular data management system). The integration of on- and off-chain processes can often be automated through "application logic contracts," more popularly referred to as "smart contracts," which are usually deployed to ensure interoperability among computer networks running on diverse platforms. These contracts can trigger the automatic execution of transactions triggered when the obligations of the parties involved in the contract are met according to predefined governance rules and verification guidelines (Franke et al., 2020). Smart contracts can be classified into three distinct types based on their functions: financial or transactional contracts primarily serve

4 Available at: https://blog.curvelabs.eu/the-promises-and-pitfalls-of-regenerative-finance-4910f0f6f690 (accessed 12/21/2022).

5 Available at: https://kumu.io/climate-collective/web3-climate-map (accessed 1/21/2023).

6 Available at: https://medium.com/regenliving/what-is-regenerative-financing-refi-8bebaf2e0a4d (accessed 12/21/2022).

7 Available at: https://blog.curvelabs.eu/the-promises-and-pitfalls-of-regenerative-finance-4910f0f6f690 (accessed 3/22/2023).

8 Available at: https://giveth.io/ (accessed 2/11/2023).

9 Available at: https://commonsstack.org/ (accessed 12/21/2022).

10 Available at: https://www.openforestprotocol.org/ (accessed 2/11/2023).

11 Available at: https://www.regen.network/ (accessed 12/21/2022).

12 Available at: https://www.flowcarbon.com/knowcarbon/flowcarbon-raises-70m-to-tokenize-carbon-credits-and-build-an-on-chain-market (accessed 12/21/2022).

13 Available at: https://blog.celo.org/the-celo-foundation-climate-collective-and-toucan-collaboration-deepens-to-bring-refi-to-the-e714700b96d0 (accessed 12/21/2022).

14 Available at: https://www.klimadao.finance/community (accessed 12/21/2022).

15 Available at: https://www.coingecko.com/en/coins/klima-dao (accessed 12/21/2022).

16 Available at: https://americancarbonregistry.org/news-events/program-announcements/acr-updates-program-rules-for-tokenization-of-carbon-credits (accessed 12/21/2022).

17 Available at: https://www.goldstandard.org/blog-item/gold-standard-announces-proposals-allow-creation-digital-tokens-carbon-credits (accessed 12/21/2022).

18 Available at: https://verra.org/public-consultation-verras-approach-to-third-party-crypto-instruments-and-tokens/ (accessed 12/21/2022).

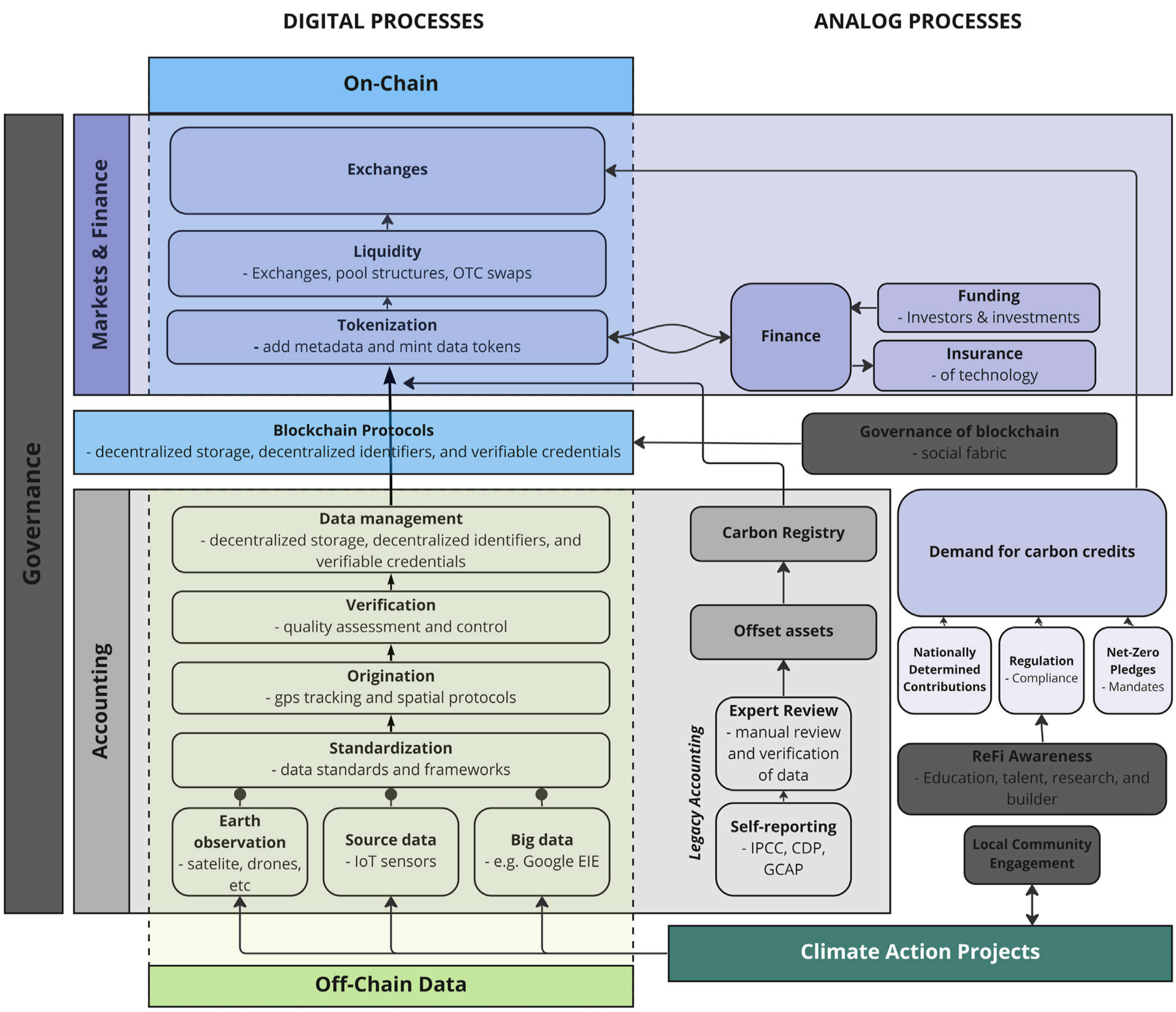

FIGURE 1
Components of the ReFi stack.

as digital agreements that execute financial transactions based on predefined conditions, as most prominently applied in Decentralized Finance (DeFi). Governance contracts codify rules of organization and decentralized decision-making processes, such as voting and consensus mechanisms. Lastly, application logic contracts refer to smart contracts that contain the essential business rules and logic that govern the behavior and operations of decentralized applications (dApps). These contracts automate various processes within the dApp ecosystem, ensuring the trustless execution of transactions and interactions. They often leverage external data and information resources called Oracles, which act as intermediaries between smart contracts and the external world. In the case of ReFi, these oracles may include earth observation data, source data, and big data sources, enabling the integration of real-world information into the dApp ecosystem. Oracles are software, hardware, or human sources and processes that access, validate, and transmit data on-chain to make the data available for blockchain-based applications (Al-Breiki et al., 2020; Mammadzada et al., 2020).

In this section, we explore the three most integrative levels of the ReFi stack (Figure 1, far left): i) the accounting process using D-MRV (Section 2.1), ii) the creation of a financial market through tokenization (Section 2.2), and iii) the decentralization of governance (Section 2.3).

2.1 Accounting using D-MRV

The first key component of ReFi is accounting using D-MRV approaches, comprising data collection, aggregation, and analysis. Such D-MRV approaches use digitally native data collection approaches like earth observation, source data like local sensors, and big data approaches and can increase information availability and interoperability while improving quality and transparency (CLI, 2019; Belenky et al., 2022; SAF and UNEP, 2022). Currently, however, most climate data are still collected through analog and manual processes such as sampling or self-reporting. Such legacy

MRV costs are frequently prohibitively high, particularly in larger or geographically dispersed systems, posing a significant barrier to more effective coordination (Huitema et al., 2009; Wyborn, 2015). Using digital technologies to improve MRV and thus coordination allows different institutions and actors to adopt mutually beneficial standards, lowering transaction costs, gaps, and overlaps and improving alignment (Abbott, 2014).

As a result of these different data collection approaches and general differences in the way data formats are developed and selected by the different actors leading to very heterogeneous data formats, standardization is critical to making different data sets comparable so that they can be aggregated. Collecting spatial data to track the origination of emissions or mitigation projects by using GPS tracking devices and spatial protocols is important to assign them to a jurisdiction to accurately account for emissions and emission reductions by an entity and reduce the risk of double-counting (Fritz et al., 2019; Rolnick et al., 2019; Schletz et al., 2022a).

Verification is the process of checking and testing the accuracy, consistency, and completeness of data to ensure accuracy and reliability. Most current verification is carried out manually as an expert review process, but ML presents a promising area for the automation and scaling of these processes. ML can be used to automate the verification of collected data (Rolnick et al., 2022) by triangulating between large data sets from different sources as a reference for consistency checks and tamper-attempt indication (Marjani et al., 2017; Howson et al., 2019). Furthermore, ML can model complex, non-linear, and non-parametric data relationships to produce potentially more complete and new greenhouse gas (GHG) emission data (NASEM, 2022). These ML algorithms and models can use a series of data inputs to train a model to uncover statistical patterns, making predictions on new, "unseen" data (Huntingford et al., 2019; Milojevic-Dupont and Creutzig, 2021). In the legacy context, most data verification is carried out in a manual expert review process. For example, in the forest biomass context, forest carbon stock inventory methods measure single trees by hand, being time-, labor-, and cost-intensive. Moreover, these manual measurements are often used as the basis for a linear extrapolation of carbon stock under the assumption that the rest of the forest will be similar to the measured area. This approach is scientifically questionable and leads to distrust in forest financing (Reiersen et al., 2022). Here, a combination of deep learning and remote sensing can greatly increase scalability and accuracy (Ganz et al., 2019; Schiefer et al., 2020; Weinstein et al., 2021; Reiersen et al., 2022). One example of such an approach is the new KacSat methodology, approved by OxCarbon, in which ground-truthing is based on a randomized but stratified sample of the entire forest area based on high-resolution satellite image recognition. The number of measurements taken per stratum is correlated to the prevalence of each stratum in the entire project area. A total of 49 ML models are then used to continuously improve the estimation until the margin of error of forecast in the test data is below 5% (Merrill et al., 2022). Trust in the methodology is built by making data openly accessible and conducting a scientific peer review process before applying the methodology.

Climate data management is the collection, storage, organization, and use of climate-related data. It is critical because it facilitates a wide range of activities related to understanding and responding to climate change, including research, market pricing, policy development, and decision-making. Decentralized storage refers to the use of blockchains to store data in a decentralized manner rather than relying on a single centralized entity or consortium. Decentralized storage, decentralized identifiers (DIDs), and verifiable credentials are needed due to the increasing volume, complexity, and sensitivity of climate data and the need to ensure that these data are managed in a secure, transparent, and trustworthy manner. DIDs are unique, persistent, and verifiable identifiers that can be used to identify and authenticate individuals, organizations, or other entities (Davie et al., 2019; Li et al., 2019; Sporny et al., 2021). Verifiable credentials are digital documents that contain information about an individual or entity and that are cryptographically signed by a trusted issuer to ensure their authenticity (Sporny et al., 2019; Wang et al., 2019; Lux et al., 2020). Verifiable credentials can be used to provide proof of identity, qualifications, or other attributes and can be stored and shared in a secure and verifiable manner using DIDs and decentralized storage. Accounting applications constitute a core component of the ReFi value proposition, and as outlined in this section, several promising digital processes have the potential to improve data availability and reliability. Such improved accounting applications can then provide a foundation for improved trust and, in this way, contribute to the other core ReFi components, namely, finance and market creation and decentralized governance.

2.2 Finance and market creation through tokenization

In the finance area, tokenization has the potential to increase pricing transparency in the carbon offset market by creating a digital representation of carbon credits, which can be recorded and traded on a secure, decentralized blockchain ledger. Tokenization refers to the process of converting a real-world asset into a digital token that contains all relevant information as meta-data such as the metric, issuing country, project name, and year generated (i.e., vintage) (García-Barriocanal et al., 2017; Franke et al., 2020). Tokenization allows for digitally based ownership representations and provides a way for carbon offset projects to be financed and for the ownership of carbon credits to be transferred in a transparent and verifiable way. The minted tokens are either "fungible tokens" or "non-fungible tokens (NFTs)." Fungible tokens are divisible and interchangeable, whereas NFTs are a unique digital representation of a physical or digital item (Idelberger and Mezei, 2022). By tokenizing D-MRV or legacy registry information, the tokens can be tracked and traded in a transparent and verifiable manner, helping to ensure the integrity and reliability of the carbon offset market. By creating more data transparency and providing more trust in the carbon market space, it becomes harder for actors to engage in opportunistic behavior (e.g., by marking up the price of a carbon credit manyfold based on the higher bidder). The Climate Warehouse[19] is a more centralized approach to improve transparency using tokenization and D-MRV with the explicit goal of reducing the risk of double selling and double claiming and improving common resource management among countries, thus leading to better governance.

19 Available at: https://www.theclimatewarehouse.org/ (accessed 03/21/2023).

Currently, marketplaces for voluntary carbon offset markets are still in their infancy, with most transactions still taking place over the counter (OTC) (Nowak, 2022). OTC carbon markets refer to the trading of carbon credits outside of a regulated exchange but have been criticized frequently due to lack of pricing transparency, as the prices of carbon credits are often not publicly disclosed and can vary significantly depending on the buyer and seller (Betz et al., 2022; Hodgson, 2022). Another factor contributing to the lack of pricing transparency in OTC carbon markets is the lack of consistent reporting and verification standards. The variety of standards, as well as the information asymmetry that permeates the market, leads to uncertainty and potentially inflated prices. As a result, these OTC markets suffer from a lack of scale (Chen et al., 2021) due to a lack of price visibility and discovery that compromise carbon offset quality (Betz et al., 2022; Nowak, 2022). This makes it challenging for end users to determine whether they are paying a reasonable price and what portion of the money goes to the original project developer.

ReFi can improve market liquidity and the availability of assets in several ways, including the use of exchanges, pool structures, and OTC swaps. It can support the development of exchanges that facilitate the trading of carbon offsets and other financial instruments. These exchanges can be centralized (CEX) or decentralized (DEX), depending on the specific design and operating model. By providing a platform for the trade of carbon offsets and other financial instruments, exchanges can help increase market liquidity, making it easier for buyers and sellers to find counterparties and trade these instruments. Pool structures in the carbon offset market involve aggregating carbon offsets into thematic indexes, which are collections of carbon offset projects that share certain characteristics or themes. This process provides a highly scalable and transparent pathway for creating "tokenized carbon pools," which are collections of multiple project-specific tokenized carbon tonnes bundled into carbon index tokens. These index tokens can be traded and sold as differentiated products based on the unique characteristics of the carbon offset projects included in the respective index. These carbon pools can, similar to mutual funds or exchange-traded funds (ETFs), offer investors a way to invest more broadly under a specific theme, such as energy or forest tokens. This is particularly beneficial for investors who may have a limited capacity to conduct specific token selection. At the same time, indexes may introduce additional layers of complexity in determining the individual token composition. OTC swaps are private, bilateral agreements between two parties to exchange financial instruments, such as carbon offsets, at a later date. ReFi initiatives support OTCs for carbon offsets by providing a platform for matching buyers and sellers, providing transparent information on the assets, and settling to trade in a flexible and customized manner.

KlimaDAO, for example, tokenizes "real-world carbon assets" to create a transparent and efficient blockchain-based market exchange. Tokenization provides a "highly scalable and transparent pathway" to create "tokenized carbon pools," which bundle multiple project-specific tokenized carbon tonnes (TCO_2 tokens) into carbon index tokens.[20] This allows for greater liquidity and transparency in the carbon offset market, as the tokenized credits can be easily bought and sold with a clear record of ownership and transaction history on the blockchain. These index tokens enable price discovery for various classes of carbon assets because they are traded and sold as differentiated products (e.g., wine) based on the unique characteristics of each carbon project token included in the respective index.[21] Such index tokens are available for trading as green NFTs on decentralized exchanges and as carbon-backed currencies [22].

The demand side is determined by the ambition of climate goals of non-state, subnational, and national actors and the resulting need to offset climate emissions. Nationally determined contributions (NDCs) are submitted by parties under the Paris Agreement to outline national climate goals. The parties can purchase mitigation outcomes from other countries under Article 6 to offset their emissions to achieve the NDC goals. Regulation plays a crucial role in driving demand through the compliance carbon offset market. In the compliance market, organizations purchase carbon offsets to comply with regulatory requirements. The most prominent example of a compliance market would be the EU Emissions Trading System (EU ETS).[23] The EU ETS is an interesting application for the transparent sharing of information and credibility of the market. The immutable nature and publicly visible record of blockchains enable robust accounting practices that avoid ambiguity over ownership and double counting of emissions reductions, which is a central issue of the Article 6 mechanisms under the Paris Agreement (Schletz et al., 2020). Certificate traceability and transparent data exchange could create resilient proofs of authenticity, protecting against transnational sales and frauds. Net-zero pledges are made by many organizations and governments, committing to reduce their GHG emissions to zero or to offset any remaining emissions through the purchase of carbon offsets. In order to achieve pledges not subject to regulatory requirements, organizations or individuals can use the voluntary carbon offset markets to purchase offsets.

2.3 Decentralized governance approaches

CPRs, as defined by Ostrom (2015), are often associated with local systems, such as inshore fisheries, small grazing areas, groundwater basins, irrigation systems, and communal forests, which can be governed at the community level. However, ReFi aims to tackle larger-scale problems, such as the global atmosphere, that require coordinated actions from the local to the global level. In this context, Stern (2011) focused on rival and global commons that are bounded only at the global scale and do not all share similar cultural and institutional contexts and where millions or billions of actors are involved and affected (Rozas et al., 2021). Accordingly, involving such large numbers of actors requires expanding the

20 Available at: https://forum.klimadao.finance/d/117-rfc-carbon-project-development-initiative (accessed 12/21/2022).

21 Available at: https://forum.klimadao.finance/d/117-rfc-carbon-project-development-initiative https://docs.toucan.earth/toucan/pool/pools (accessed 12/21/2022).

22 Available at: https://earthstate.ixo.world/klima-dao/ (accessed 12/21/2022).

23 Available at: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en#:~:text=The%20EU%20ETS%20is%20a,and%20remains%20the%20biggest%20one (accessed 12/21/2022).

complexity of "broader social contexts" within which people make decisions and share power (Dietz et al., 2003). Furthermore, Dietz et al. (2003) identified five "adaptive governance requirements for complex systems" that are specific to global commons. These governance requirements outline ReFi's need to facilitate the interactions of users and information flows, dealing with conflicts that arise among actors with different interests, inducing compliance with rules through appropriate combinations of formal and informal mechanisms, providing physical and technological, as well as institutional infrastructure, and designing institutions that allow for adaptation.

ReFi aspires to tackle such issues and support polycentric governance solutions that function on a supra-national level and facilitate global coordination by unifying local communities and the global community in their efforts. In this context, Mindel et al. (2018) explored the concept of polycentric governance and its application to digital data as an information commons. An information common is defined as a "highly accessible, self-rising information system in which stakeholders share an overarching goal" (Mindel et al., 2018, p. 609). Such a commons needs to focus on the needs of data originators and ensure that users and funders contribute properly (de Lima et al., 2022), using a fair valuation for the data provided (Jia et al., 2019). Information commons are implemented through decentralized systems such as decentralized autonomous organizations (DAO)s to provide high-quality data available to all actors. DAO principles and rules are initially established and implemented by the community and subsequently encoded in smart contracts, enabling automatic enforcement and on-chain governance of these processes. The governance procedures are typically documented in a white paper and evolve through iterative feedback from the community, highlighting the intricate interplay between off-chain and on-chain governance mechanisms. As the community strives for increasing decentralization, exemplified by platforms such as Ethereum, DAOs offer valuable insights into decision-making and coordination structures within technology-enabled, decentralized, and polycentric governance models. Furthermore, it is important to note that even after the initial codification of governance principles on the blockchain, significant off-chain governance is still required. Many blockchain organizations face challenges in clearly defining rules for continuous adjudication and conflict resolution. Poor management of these aspects may result in forking, a specific governance mechanism in which a community splits into different groups with diverging principles.

Schlager and Ostrom (1992) argued that efficient resource use is dependent on institutional settings, ranging from hierarchical to decentralized organizations, and is moderated by the respective environment. Governance systems in the form of information commons are built upon freedom of access and, thus, are nonexclusive in nature. However, this also makes such systems susceptible to existential threats as users are free to leave the system at any point in time (Mindel et al., 2018). Thus, governance solutions between sovereign states to enforce ReFi solutions must consider and accommodate on-chain mechanisms to support mutual adjustments among the involved autonomous actors while continuing to enforce the set common goal (Mindel et al., 2018, p. 609).

Blockchains enable new decentralized ownership and governance approaches, and thus the creation of an information commons, by distributing data ownership over a network of nodes that each hold a copy of the whole data ledger (Franke et al., 2020). Additionally, privacy-preserving methods of data governance are made possible by decentralized storage systems and techniques such as verified credentials, DIDs, and zero-knowledge proofs (ZKPs) (Ben-Sasson et al., 2015; Sporny et al., 2019; Hyperledger, 2021; Schletz et al., 2022b). Blockchain uses cryptography and time-stamping to store the data, making the history immutable and the system data resistant to tampering (Kewell et al., 2017; Franke et al., 2020). The tracking and aggregation of data on climate emissions can also be facilitated by integrating blockchain with smart contracts and oracles (Schletz et al., 2022b; NASEM, 2022). As a result, blockchain technology can enable individual actors to contribute and agree on climate data in a way that is private and transparent, as well as trusted.

At the same time, the intersection of on- and off-chain activities poses the most complex interoperability and governance challenges due to the diverse range of stakeholders, including governments, businesses, investors, local communities, and consumers, as well as the web3 and technology developers. Centralized and manual legacy registries are currently the primary source of all ReFi assets, challenging the decentralized ReFi ethos. Similarly, blockchain technology is frequently hailed as a tool to automate governance while neglecting that the "governance of blockchain" (Ølnes et al., 2017) also raises a number of new governance challenges.

Scholars have warned that polycentric governance systems with "cross-scale linkages" or interactions between actors at different levels of political or social organization (Heikkila et al., 2011) are vulnerable to dominance or capture by powerful interests (Adger et al., 2005; Bixler et al., 2016). These cross-scale linkages are often characterized by power asymmetries, with more powerful actors dominating the linkages and further skewing knowledge and information in their favor (Adger et al., 2005). In the case of climate data, the risk of corporate-owned platforms creating a data monopoly for big tech has been noted by Schletz et al. (2022). Instead, climate data should be treated as a "digital data commons" with the potential to make high-quality data available to all actors, particularly those in the Global South, while safeguarding data outside corporate control (Schletz et al., 2022a). Blockchain technology has the potential to address these existing power imbalances and establish the necessary decentralized digital infrastructure to create a digital data commons. However, technology can simultaneously entrench or even aggravate the *status quo* of centralized control and extractive economics. Accordingly, the co-creation of such a technology system with local communities, policymakers, and lawmakers is essential to ensure that the system is designed to provide real incentives to drive positive impacts for most of humanity rather than the centralized tech elite.

3 The lack of "Re" in ReFi

3.1 Extractive and regenerative theory of economic relations

At its core, the ReFi movement aspires to initiate a paradigm shift away from present extractive economics and toward regenerative economics. Assets in an extractive economy derive their value from being exchanged because they can be displaced at the right time, either physically (e.g., extracting coal when the demand is high) or legally (e.g., acquisition of a property right when supply is high). Such displacements yield arbitrage opportunities for natural resources and human labor whose exploitation for maximum short-term profit is the core principle of value creation of extractive economies, with a disregard for the negative externalities and social costs associated. Extractive economics are often contrasted with regenerative economics, which seeks to create a more sustainable and equitable economy by prioritizing the regeneration of natural resources, community well-being, and long-term value creation. Although extractive economics is based on the assumption of unlimited growth, ecological and regenerative economics recognize that economic growth is constrained to the ecological limits of the planet and is balanced by the regeneration of natural capital (Daly, 2014). The resulting difference between the extractive and regenerative models is that they are grounded in vitality, viability, and evolutionary capacity (Benne and Mang, 2015; Mang and Reed, 2012; du Plessis, 2012). Vitality refers to the ability of a system to create and maintain abundance, diversity, and health. Viability refers to the ability of a system to survive and adapt to changing conditions while maintaining its fundamental purpose and values. Evolutionary capacity refers to the ability of a system to learn, innovate, and evolve to continuously improve its performance and adapt to changing circumstances. Together, these principles create positive feedback loops, resilience, flexibility, and a continuous cycle of improvement in service to life.

The present ReFi literature does not engage with these regenerative principles and models, so it remains uncertain and undefined how ReFi can support such a paradigm shift toward a regenerative global model. Currently, ReFi is mostly limited to tokenizing carbon credits and increasingly other forms of nature credits to create a form of commodity money or asset, which can be traded on markets to incentivize companies and individuals to reduce their carbon footprint. The promise of tokenization is that it can enable companies to capture private value from the support of public goods without expropriating or displacing the co-benefits created through this approach. If such tokens would manage to avoid the negative aspects of speculation and, for instance, be automatically retired upon purchase, companies could increase their support for nature and reap benefits of increased reputation, loyalty, and customer acquisition, for instance, by embedding such tokens in their interactions with their key stakeholders, thereby altering the very nature of those interactions (e.g., Schillebeeckx and Merrill, 2022).

However, the counterargument is that ReFi only perpetuates the current extractive logic and does not result in a true regeneration of the atmosphere by driving the increasing commodification of nature. This commodification of carbon assets primarily leads to short-term thinking, with a focus on buying and selling carbon credits rather than making long-term investments in sustainable practices and infrastructure. Accordingly, this approach merely maintains the *status quo* of speculation, perpetuates the current extractive logic, and does not result in a true regeneration of the atmosphere.

More research and engagement with the ecological and regenerative economics theory are needed to define how ReFi can create a more sustainable and equitable economy by prioritizing the regeneration of natural resources, community well-being, and long-term value creation.

3.2 Regeneration of common pool resources

CPRs are resources shared by individuals or groups of appropriators; the appropriators are the persons that will subtract units of the resources or benefit from the yield of the resources. The concept of CPR is designed to highlight a specific scarcity situation in which appropriators must find strategies to maintain or regenerate the resources that they benefit from, despite the "dilemma" they find themselves in—aka the commons' dilemma. For CPR and its associated dilemma to apply, specific conditions must be met. These conditions have to do with the nature of the resources of the CPRs and with the situation in which the appropriators find themselves (Gardner et al., 1990).

The first condition is "*Resource Unit Subtractability.*" A resource is subtractable if harvesting by one appropriator of a unit of the resource makes a unit of that resource unavailable to another appropriator (e.g., subtracting a ton of fish from a fishing ground). This further assumes that multiple appropriators must exist (aka. the "*multiple appropriators*" condition). A CPR will include resources whose appropriation will be carried out by changing the "flow" of the resource (e.g., fishing more at one spot) or changing the stock extraction (e.g., killing fishing spots). Accordingly, one challenge of the common dilemma is to manage flow and stock to allow the regeneration of the CPR. Regeneration is achieved by ensuring the natural replacement rate is consistently higher than the withdrawal rate. This is possible to achieve within human life when considering local commons but much harder to achieve when considering global commons, which are likely to require multiple generations of continuous efforts before true regeneration and revitalization (e.g., a reduction of carbon in the atmosphere) can happen. A third condition is the "*suboptimal outcomes*" condition. This condition is at the core of the dilemma characteristic of CPRs. Suboptimal outcomes ensue in CPRs because the economically rational strategies of *individual* appropriators lead to suboptimal outcomes from the point of view of the group of appropriators. Beneficiaries of CPR tend to maximize their individual benefit to the detriment of the ability of the CPR to regenerate (Clark, 1974; Dasgupta and Heal, 1979; Clark, 1980). At a global CPR scale, arriving at a common understanding becomes even more challenging due to diverging collective interests as appropriators come from all cultures, all countries, all political-economic systems, and all political ideologies (Stern, 2011).

Although many externalities of appropriation are borne mainly outside the community of major users, often by people on other continents or in future generations, major appropriators, such as global corporations, can often avoid many of the costs of resource degradation to them by moving to other jurisdictions, different resource bases, or different lines of business (Stern, 2011).

To avoid outpacing the natural replacement rate and leading to suboptimal outcomes, appropriators must adopt a coordinated strategy that determines the "rules of the game," as it were, in the exploitation of the common pool resource (Gardner et al., 1990). There are three dominant views on how regeneration can be achieved: i) top-down centralization, ii) privatization, and iii) bottom-up institutions. The CPR dilemma created a mismatch between the scale of individual appropriators' interests and the scale of the CPR's interest. Each governance strategy is about correcting the mismatch by acting on the appropriators of the CPR's scale. The privatization strategy is about reducing the scale of the CPR to make its replacement rate visible to the appropriator (i.e., the appropriator can see its impact on the smaller lots to which the appropriator has proprietary access). This indeed brings the scale of the CPR back to that of the appropriator and solves the dilemma. This strategy, of course, is difficult to apply to commons to which physical boundaries do not apply (e.g., climate and oceans). Local and regional carbon pricing schemes are the first attempt at such privatization but have only shown limited success so far due to the high heterogeneity of methodologies and ambition levels. More recently, carbon border taxes, or more formally carbon adjustment mechanisms (CBAMs), were proposed by the European Union as a tool to unify the cost of GHG emissions[24]. In its current form, the European CBAM applies to European companies that import emission-intensive products to add the same carbon price as a domestically produced item to level the playing field.

In turn, the centralization strategy scales up the appropriators by forcing them to act in harmony to avoid the outpacing of the natural replacement rate by the withdrawal rate. In this case, general and impersonal rules, which can enforce actions aligned with the CPR dynamics, are followed by the appropriators without them having to know what the rules really seek to achieve. The centralized governance strategy solves this dilemma by scaling up the actions of the appropriators to match the scale of the CPR dynamics. An earlier application of this centralized approach in the climate space was the clean development mechanism (CDM) under the Kyoto Protocol. The problem with centralization at the global level is that it runs against national sovereignty, thereby making this option impossible for the governance of global commons. This is a common thread in challenges of, for instance, maritime, economic, and public international law where nations conform to international agreements on the protection of natural resources and of other common goods, such as human rights and international trade, only insofar as these agreements benefit internal markets and geopolitical agendas. For instance, the protection of common goods such as fish stocks in the high sea is difficult to achieve despite the existence of international regulation applying to many jurisdictions (e.g., Sections 86 and 87 of the United Nations Convention on the Law of the Sea, 1982). However, the effective governance of such common resources is left to a few powerful nations that have little incentive to collaborate other than for strategic or extractive economic purposes. Instead, local initiatives that acknowledge this dilemma and work to ensure they do not overexploit a resource without replenishing it in an accordant ratio could provide inspiration. For example, the Indiana University Bloomington Campus Tree Care Plan[25] provides a simple but efficient rule that if one tree gets cut down for development purposes, they must plant three trees.

In terms of bottom-up institutions, the Paris Agreement represents a significant shift in contrast to the centralized governance of the Kyoto Protocol. The Agreement combines bottom-up and decentralized governance mechanisms to achieve collective action by all national parties. At the same time, the Agreement seeks to allow Parties greater flexibility and ownership in the development and implementation of climate policies to address their unique circumstances and challenges. Although this approach has led to an unprecedented number of parties committing, the approach faces challenges and limitations, including the need for improved coordination and financing mechanisms and the potential for power imbalances, especially in regard to marginalized communities.

Traditional alternatives for improving coordination in response to such global governance challenges exist, but they do not have the binding force of agreements that operate at the scale of sovereign states such as international treaties [e.g., alternatives, such as memorandums of understanding that can operate between ministries of different countries and or various organizations in a less legally binding and more flexible way than treaties (McNeill, 1994)]. Thus, the problem is not that the infrastructure for large-scale global coordination on the protection of commons is impossible or does not exist [e.g., the laws of commons or the set of international treaties that directly or indirectly protect global commons such as the Convention of the Law of Sea 1982 (Garcia, 2021)]. Simply, global actors are compelled to act in a way that serves their own national interest to the detriment of the protected commons, or these global actors will act at smaller scales without being able to benefit from the full strength of legal instruments such as treaties.

4 ReFi's growing pains

Most importantly, ReFi needs to define a clear path forward of how it distinguishes itself from the *status quo* of extractive economics and create and implement models that actually drive the "Re-" in ReFi. Disrupting the extractive dynamics is far more complex than "just" improving information flows and coordination but requires breaking the foundational logic and approach of the system. ReFi cannot accomplish this paradigm change and create actual value by only commoditizing carbon offsets into a form of money or assets. For this paradigm change, ReFi needs to focus on the creation of information commons that leverages the potential of D-MRV approaches, resulting in open, decentralized, and transparent data where data originators, users, and funders are all aligned (de Lima et al., 2022). One of the author's experiences in co-developing reforestation projects and setting up a new carbon crediting agency that relies on D-MRV and improved sampling of ground-truth data is a testament to the problems of analog methodologies. In interviews conducted with a reforestation organization in Indonesia that worked with Livelihoods Fund and Verra in the past, it became, for instance, clear that the ground-truthing approach proposed by OxCarbon, which uses high-resolution satellite data to classify the focal forest area according to different densities and then requires the collection of tree data for each sample based on randomized stratified sampling, was never used by this organization in the past. The only samples they had ever taken were convenience samples in easy-

24 Available at: https://www.europarl.europa.eu/news/en/press-room/20221212IPR64509/deal-reached-on-new-carbon-leakage-instrument-to-raise-global-climate-ambition (accessed 04/20/2023).

25 Available at: https://www.arborday.org/programs/treecampusUSA/applications/file-open.cfm?fileName=uploads/Tree%20Care%20Plan%202016_final.pdf (accessed 6/1/2023).

to-access locations, after which those measurements were simply extrapolated to the entire area for the issuance of carbon credits. Better data can then be used to develop novel and alternative financing models that are not solely dependent on donations and carbon credits for driving nature conservation and regeneration.

In this paper, we define the structure of the ReFi stack and explain how different approaches can address present limitations in climate change accounting, markets, and governance. Here, the present regenerative economics theory can inspire ReFi developments. Fullerton's (2015) eight principles for regenerative economics emphasized the importance of balancing the human economy with the natural world and prioritizing the creation of long-term value for people and the planet. They also emphasized the importance of being in the right relationship; viewing wealth holistically; being innovative, adaptive, and responsive; empowering participation; honoring community and place; creating edge effect abundance; enabling robust circulatory flow; and seeking balance. This approach prioritizes the integration of social and environmental aspects into economic decision-making processes. The principles emphasize the need for democratic decision-making processes, community-based solutions, diversity, interconnectivity, and a balance between short- and long-term goals.

However, how these principles can be applied and inform the developments in the ReFi space requires investigation and discussion across different communities, such as academia and decentralized science (DeSci), climate change experts, and web3 developers. Much research and work are needed to guide the ReFi community path toward its ambitions, with a focus on engaging and educating policymakers and other decision-makers to drive systemic change. Communities such as the Climate Collective[26], the Blockchain Infrastructure Carbon Offset Working Group (BICOWG)[27], and the Sustainable Blockchain Summits[28] are already playing a crucial role in this area of coordination and advancing awareness inside and around ReFi.

In addition to this fundamental question, there exist several growing pains associated with blockchain and related web3 tools, as well as challenges related to coordination and governance of on- and off-chain activities. We defined ReFi as a *decentralized movement leveraging blockchain technology and web3 applications for the coordinated financing, governance, and regeneration of common pool resources.* This definition highlights the key objectives for ReFi movements, which include using web3 applications as a means to achieve coordination among parties involved in the regenerative economy. The ultimate aim is to finance the regeneration of CPRs in a way that aligns with the basic principles of polycentric governance. This involves ensuring that ReFi actions are aligned with relevant principles (Fullerton, 2015) and driving the fundamental change toward the scales required for changing global systems.

The ReFi ecosystem comprises complex on- and off-chain activities, and the achievement of on-chain interoperability that reflects the governance and rule-setting among the off-chain communities presents several challenges (Schletz, 2022). On-chain interoperability requires addressing the standardization and technological interoperability issues, such as creating carbon standards, token standards, and web3-native decentralized storage solutions, as well as developing new governance mechanisms such as DAO infrastructure. Standardization of carbon assets and tokens, as well as decentralized storage solutions, is also essential to enable and maximize synergies across components of the ReFi stack. Conversely, off-chain community governance and rule-setting depend on community engagement, education, and project development. This requires establishing a shared narrative and best practices, as well as engaging local communities in the development of mitigation projects. ReFi aspires to become a voice heard at the national and international levels of climate policy. Integration with academic research and the climate community can aid in closing knowledge gaps in the ReFi and web3 spaces. Similarly, outward awareness is essential for developing the digital literacy and capacity needed to collaborate with climate decision-makers and policymakers. This will aid in the adoption of a common language with legacy climate actors. Accordingly, ReFi needs to overcome its own interoperability limitations before delivering on the promise of improving interoperability in the larger climate ecosystem.

The complexities of connecting on- and off-chain community activities within a project and then across interconnected projects are the source of such limitations (Beck and Jain, 2023). Although blockchain is frequently portrayed as a governance mechanism, its use raises new governance complexities that have yet to be addressed. For example, De Filippi and Loveluck (2016) stated that an "excessive reliance on technological tools to solve issues of social coordination and economic exchange" (p.2) is inherently limited. Technology alone cannot govern socio-technological systems (De Filippi and Loveluck, 2016). How do these technological constraints play out in the ReFi space? Complex power dynamics exist beneath the technological infrastructure and risk accentuating historical power dynamics in which global interests take precedence over local priorities. The absence of a formal framework for the governance of now digitized global commons in the ReFi space ensures that, as of this moment, there is no clarity as to whether ReFi communities will govern the commons more successfully than countries or incumbent transnational governance processes. In global systems, such as the ones governing CPRs, power tends to aggregate centrally, often just within a small group of actors (i.e., countries and corporations).

5 Conclusion

In this paper, we conducted a critical assessment of the current state of ReFi and raised critical questions and central points of critique that, in our opinion, will determine the impact of the ReFi movement going forward. These questions and critiques include the challenges associated with blockchain and related web3 tools and challenges related to the coordination and governance of on- and off-chain activities. Interoperability and community governance and rule-setting implementation are critical challenges for ReFi evolution, and the absence of a formal framework for the governance of now

26 Available at: https://climatecollective.org/ (accessed 1/19/2023).

27 Available at: https://bicowg.org/ (accessed 1/19/2023).

28 Available at: https://sbs.tech/ (accessed 1/19/2023).

digitized global commons in the ReFi space raises questions about whether ReFi communities will govern the commons more successfully than countries or incumbent transnational governance processes. The governance and rule-setting of the off-chain community through the design of community rules for technology evolution, adjudication, and conflict resolution is a colossal governance challenge such as the UNFCCC Conferences of Parties processes (e.g., the Kyoto Protocol and the Paris Agreement). This raises doubts about the effectiveness of ReFi in fully embracing Fullerton's (2015) eight principles or Ostrom's design principles for common-pool resource (CPR) management. Therefore, it is worth exploring alternative blockchain deployments that can contribute to CPR governance and regeneration without relying on private for-profit financial instruments for managing public goods. Such research avenues could shed light on innovative approaches to address the governance complexities associated with CPRs and foster the regeneration of natural resources and community well-being.

We applied this critical approach not to call everything into question or even state that ReFi does not have meaning but rather to issue a wake-up call and ask the fundamental question to inspire discussion and future developments. We think that ReFi has potential to drive large-scale change, which is currently not sufficiently developed:

1. D-MRV and the creation of an information commons that leverages the potential of decentralized and transparent data can increase trust and transparency and support the development of novel and alternative financing and governance models.
2. Tokenization and the pooling of index tokens can democratize financing by making it accessible to a wider range of buyers and investors. It can also improve liquidity and reduce barriers to exit for investors by enabling fractional ownership and transferability of assets. In addition, it is necessary to focus on providing economic incentives for the long-term development of projects and ecosystems rather than focusing on and driving the commodification of single carbon and environmental assets.
3. ReFi can enable decentralized decision-making processes and more transparent and auditable governance structures through the information commons to improve climate action coordination. ReFi can also enable more inclusive and participatory governance, allowing stakeholders such as farmers, landowners, and local communities to have a greater say in decision-making processes.

Accordingly, Stern (2011) provided a set of seven design principles for evolving the governance of global commons, which can serve as a guiding framework for the ReFi ecosystem. First, investing in scientific research is essential to comprehend the resources and their interactions with users and stakeholders. Second, establishing independent monitoring of the resource and its use is crucial to ensure accountability to a range of interested and affected parties. The information commons proposed in this study provide such a function. Third, the meaningful participation of participants in framing questions, defining the scientific results, and developing rules is necessary. Fourth, integrating scientific analysis with broader deliberation is crucial. Fifth, higher-level actors should facilitate the participation of lower-level actors. Sixth, it is important to engage and connect a variety of institutional forms, from local to global, in developing rules, monitoring, and sanctioning. Lastly, planning for institutional adaptation and change is crucial to ensure the regeneration of global commons.

In expanding the ReFi community's current naive self-perception, it is essential to integrate scientific analysis with broader deliberation, thereby driving systemic change. The question of how we use digital technologies to drive regeneration needs further exploration and discussion across different communities. This requires engaging and educating academia, as well as policymakers and other decision-makers. By implementing the outlined design principles, the ReFi community can plan for institutional adaptation and change to drive regenerative practices of global commons in the long term.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

MS: research design, conceptual framework, research on ReFi, and writing. AC: research design, conceptual framework, and writing. AH: conceptual framework, writing, and review. SS: conceptual framework, writing, and review. RB: conceptual framework, writing, and review. MW: conceptual framework, writing, review, and figure design. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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