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REVIEW ARTICLE

Tokenized Carbon Credits

Derek Sorensen[*] [†]

Abstract. Blockchains are well-suited for tokenizing, trading, and retiring voluntary carbon credits. However, tokenized carbon credits are a heterogeneous body of tokens on the blockchain, which hampers some key goals of the industry. We give a detailed exposition of the current state of tokenized carbon credits and the surrounding blockchain-based ecosystem, with the goal of clarifying current impediments to token interoperability and trading with high liquidity.

1. Introduction

Blockchains are well-suited for tokenizing, trading, and retiring voluntary carbon credits, as recognized by the UN,[1] the World Bank,[2] the World Economic Forum,[3] and others.[4–9] They offer several advantages to legacy systems, including transparency and censorship resistance, which lend themselves to robust accounting practices and which can help prevent double counting carbon credits.[2,5] However, tokenized carbon credits are defined by a varied set of standards, both of token contracts as well as the kind of carbon credits that are acceptable.[10] This hampers interoperability and trading with high liquidity,[5,10,11] which can lead to fragmented, inefficient, and volatile markets.[2,10,11]

To promote interoperability between tokenized carbon credits, and to support current efforts in creating a unified token standard,[12,13] we survey the current state of tokenized carbon credits. Our goal is to clarify the technical hurdles to interoperability, so we evaluate tokenized carbon credits from a technical, rather than economic or climate, perspective. We do not make value judgments on the various methodologies which quantify carbon capture, and which back tokenized carbon credits, nor on the reputation or reliability of any particular producer of tokenized carbon credits.

We note that central to the climate debate as it relates to blockchains is the energy expenditure of large proof-of-work chains such as Bitcoin.[14,15] This included Ethereum up until the so-called *Merge* in September 2022.[16] Since the Merge, all the projects discussed here operate on proof-of-stake chains, which consume negligible amounts of electricity to secure the blockchain.[17] Thus here we will not treat the energy expenditure of blockchains.

1.1. Outline—We proceed as follows. In Section 2 we survey related work. In Section 3, we survey tokenized carbon credits and consider how they are tokenized, what substantiates their value, and their individual tokenomics. In Section 4, we discuss how tokenized carbon credits are most frequently traded on blockchains. In Section 5, we consider various on-chain applications built on tokenized carbon credits. In Section 6, we discuss how climate data is made available

[*] Derek Sorensen (ds885@cam.ac.uk) is a PhD candidate at the University of Cambridge and a member of the Cambridge Centre for Carbon Credits (4C).
[†] bc1qjajqs8zntgn5fy38wap8untf8dtz0z8cv8v6pj

on-chain, both for tokenization as well as related applications. In Section 7, we mention related organizations and collectives which aim to promote the usage of blockchains for carbon trading, some of whom are attempting to make standards for tokenized carbon credits. In Section 8 we conclude.

2. Related Work

Tokenized carbon credits are central to *Regenerative Finance* (ReFi), a subset of Decentralized Finance (DeFi), named after a broader movement in regenerative capitalism,[18,19] which is primarily concerned with climate change mitigation through digital assets of various kinds.[11,20] ReFi consists of a wide range of applications that can be studied from many disciplines, including business,[21] law,[8,11] economics,[22,23] and computer science. Tokenized carbon credits have been studied in relation to the energy industry,[24] the transition into sustainable energy,[22] and how to maximize the efficiency of current grids by allowing for peer-to-peer energy trading.[25] There is also research regarding solutions for measurement, reporting, and verification (MRV),[26] and sustainable supply chains.[27,28]

Further work on tokenized carbon credits includes climate market design,[2,4,29] surveys of ReFi applications and of related organizations and initiatives,[5,21] studies of the impact and efficacy of blockchain technology in sustainability efforts,[6,30,31] possible blockchain-based green fintech applications,[7] and studies from the perspective of legacy voluntary carbon markets.[10] There has also been work in the grey literature on bridging voluntary carbon markets onto blockchains,[32] but this approaches the issue from a less technical and more market-driven approach than what we give here.

A salient theme from previous work is that governments, agencies, and researchers share an explicit goal of interoperable tokenized carbon credits that can be traded with high liquidity. This is also an explicit, central goal for producers of tokenized carbon credits. Part of the issue is that tokenized carbon credits are expected to behave like commodities,[2,4] and therefore be fully fungible on-chain as an asset class. However, a cursory examination of the industry reveals a heterogeneity which makes it difficult to do so in practice; we will see this in detail in Section 3.

Our contribution is an exposition of the technical details of tokenized carbon credits with the aim of supporting interoperability, mutual fungibility, and unified token standards. This work could be useful in unifying a fractured marketplace and achieving the goals of the industry. More broadly, our goal is to support efforts to build open, decentralized, and composable financial infrastructure for tokenized carbon credits which leverages advantages of decentralized finance (DeFi).[33,34]

3. Tokenized Carbon Credits

Tokenized carbon credits vary in at least two ways: in what justifies their value and in the implementation details of the token contract. The first relates to interoperability from a qualitative perspective. Tokens that represent equivalent or comparable things are easier to interoperate than tokens which represent distinct or incomparable things. The second relates to interoperability from a more technical and engineering perspective. The fungibility status, metadata, entrypoints, and level of adherence to established standards of various token contracts may impact the ease or difficulty of developing applications that build on and facilitate interoperability among

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multiple tokenized carbon credits. Because we study tokenized carbon credits through the lens of interoperability, we examine tokenized carbon credits within these broad categories: first, in what justifies their value as a legitimate carbon credit, and second, in the implementation details of their token contracts. We elaborate on each of these categories.

First, tokenized carbon credits must be substantiated in some way as atmospheric carbon dioxide rigorously captured and stored, or something similar to it (*e.g.* avoided emissions). This requires a methodology for data collection and processing that accurately quantifies the amount of carbon stored. As with any discipline, such methodologies can vary in nature, rigor, and reliability. Some tokenized carbon credits draw on established methodologies such as those of Verra or Gold Standard,[10] as they are backed by carbon credits on legacy ledgers. Others are minted natively on a blockchain using new methodologies, based on machine learning and satellite data. In either case we encounter the problem of tokenization, which is how one accurately represents some off-chain asset or data on a blockchain in such a way that transactions on the blockchain correctly govern any corresponding real-world asset or event.

More subtly, every entity that tokenizes carbon credits makes a choice on criteria for acceptable carbon credits. For those tokenized from a legacy ledger, the tokenizing party must set criteria for which carbon credits from the legacy ledger are allowed to be tokenized. The most common guards relate to vintage (*e.g.* that credits must be less than ten years old), or restrict to a certain class of carbon credit (*e.g.* restricting to nature-based credits or requiring that credits be from carbon sequestration rather than prevented deforestation). The reason for these choices can vary greatly, from a value judgment on the quality of some credits, to the specific ethos and goals of a particular team. For tokenized carbon credits which employ their own methodology to verify captured carbon and mint credits, the methodology itself makes a judgment on what constitutes rigorous carbon capture, and thus a carbon credit, and what does not. We will look at these details as they relate to what substantiates a tokenized carbon credit, though we reiterate that we are not in a position to make value judgments on one methodology over another.

Secondly, tokenized carbon credits differ in their implementation details, in particular in their token contracts and their characteristics. To our knowledge, tokenized carbon credits all conform to token standards typical for the blockchain on which they are deployed. For Ethereum, these are the ERC20 and ERC721 standards, and for Binance, these are the BEP20 and BEP721 standards for, respectively, fungible and non-fungible tokens. Standards for fungible and non-fungible tokens tend to be highly compatible, though not exactly the same. For example, tokens on separate blockchains will require bridging, and are secured by distinct consensus algorithms.[35] Even so, these technical differences are not insurmountable.

Tokenized carbon credits differ technically in other ways, including the degree to which they are fungible. Some are natively fungible, while others are tokenized as NFTs, containing granular data on the carbon credit or carbon project backing it in their metadata, which can then be fractionalized or traded for a fungible token. Tokens can also differ in how much carbon one token represents (*e.g.* 1 tonne per token) or whether they represent captured carbon or avoided emissions. Most importantly, tokens differ in the tokenomics, or in the various incentive mechanisms that underpin the token, its trade, and distribution.

With this broad framework in mind, we consider several tokenized carbon credits which are hosted by various blockchains, highlighting their features as it relates to these two categories of variability. For each of these tokens, we follow their technical structure starting with the ledger

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Table 1. Tokenized carbon credits vary in fungibility status, methodology, associated fungibility layers and utility tokens, and the hosting blockchain.

Company	Token	Fungible	Methodology	Fungibility Layer	Chain(s)
Toucan	TCO2	N	Verra	Base Carbon Tonne (BCT) Nature Carbon Tonne (NCT)	Polygon/Celo
Flowcarbon	GCO2	N	Gold Standard	Goddess Nature Token (GNT)	Celo
MOSS	MCO2	Y	REDD+	—	Ethereum
Carbovalent	SCT	N	Verra/Gold Standard	Blue Carbon Credit (BCC) Forest Carbon Credit (FCC)	Solana
Nori	NRT	N	US Croplands (Custom)	NORI (Utility Token)	Ethereum
Likvidi	LCO2	Y	REDD+	LIKK (Utility Token)	Ethereum

or methodologies that back the tokens, how they are bridged or minted onto the blockchain, and then moving to the token type and how they address issues of fungibility and liquidity. We note that these projects are at varied technological readiness levels (TRL).[6] Of the carbon credits we survey, at the time of writing Toucan is fully competitive, Nori is in deployment, and some aspects of Flowcarbon are still at the proof of concept stage. Because our goal is to understand differences in design and implementation, the details of these projects are relevant to our discussion irrespective of their TRL.

3.1. Toucan—Toucan tokenizes Verra credits onto Polygon via their *Carbon Bridge*.[36] Anyone who owns a Verra credit can use the Carbon Bridge, subject to two criteria: the backing methodology of the Verra credit must not be on their blocklist, and the credit's *vintage* (the difference between the date of verification and the date of issuance) must not exceed ten years. At the time of writing, the blocklist only has one methodology, AM0001, which relates to refrigerant manufacturing, and which Verra stopped producing in 2014.[37] The bridging process is elaborate, one-way, and non-custodial. To bridge, users create a BatchNFT token contract into which the credits can be bridged. They then retire the credits on Verra with specific information about their NFT contract, and then update their contract with the Verra serial number. Users then await approval from Toucan, where Toucan checks that the token contract and retirement on Verra align. If approved, Toucan mints the carbon credits into the NFT contract.

Once bridged, the NFT can be fractionalized using a token contract from Toucan's TCO2 class of ERC20 (fungible) token contracts. Each TCO2 token contract faithfully preserves the metadata of the NFT it fractionalizes, so distinct TCO2 contracts are not mutually fungible. However, the Toucan team has the explicit goal of enabling on-chain trading with high liquidity (as we have mentioned), so they have a pooling mechanism which acts as a fungibility layer on top of the TCO2 contracts. Each pool allows users to deposit TCO2 tokens in exchange for a fungible pool token which is backed by other TCO2 tokens that meet the pool's acceptance criteria. At the time of writing there are two pools, BCT (Base Carbon Tonne) and NCT (Nature Carbon Tonne), each of which has a list of approved methodologies of Verra credits which are allowed in the pool. BCT and NCT tokens can also be bridged from Polygon onto Celo.

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3.2. Flowcarbon—Flowcarbon tokenizes carbon credits from recognized, non-profit registries onto Celo.[38] They handle the entire tokenization process themselves instead of a public portal or API. Someone wishing to tokenize a carbon credit submits a request, after which the credits are transferred to and held custodially with a bankruptcy remote special purpose vehicle (SPV). Flowcarbon then mints a token for the user. The credits remain on the registry *unretired*, which means that, in contrast to Toucan, tokenization is a two-way bridge: tokenized credits can be redeemed for their underlying credits.

Tokens are minted using Flowcarbon's GCO2 class of ERC20 tokens, including in the metadata the relevant details to the underlying credits that were tokenized. These are similar to Toucan's TCO2 family of tokens, except that GCO2 tokens do not fractionalize an NFT. Flowcarbon has a fungibility layer similar to Toucan's, where their pooling token is a *bundle token*, each bundle has its own acceptance criteria, and bundle tokens are backed one-for-one by GCO2 tokens. At the time of writing, there are no active bundles. The Goddess Nature Token (GNT) is planned to be the first, whose acceptance criteria are that a carbon credit have a nature-based methodology and a five-year vintage period.

3.3. MOSS—MOSS tokenizes legacy-ledger carbon credits into its fungible MCO2 token on Ethereum.[39] The MCO2 token is backed one-for-one by carbon credits which are chosen at the discretion of the MOSS team from globally recognized registries. The tokenization process, then, is very simple and done by the MOSS team, where they issue tokens for credits that they have in custody. As the user does not participate in the tokenization process, any criteria or guards on which credits are acceptable for MCO2 are made and enforced by the MOSS team. MCO2 tokens represent ownership of an unretired carbon credit, held custodially by MOSS. The MCO2 token is also a fungible ERC20 token, where one MCO2 token represents a carbon credit for one tonne of prevented CO2 emissions. Since it is backed by a variety of credits, the MCO2 token is more similar to Toucan's BCT and NCT tokens (resp. Flowcarbon's GNT token), which are backed by a pool of tokens, than to the more granular TCO2 tokens (resp. the GCO2 tokens) which represent a specific tokenized carbon credit.

3.4. Carbovalent—Carbovalent, built on Solana, uses the *Morpheus Carbon Bridge*, a public bridge with a similar tokenization process to Toucan's, to allow users to tokenize legacy-ledger credits from Verra and Gold Standard.[40] The only guard is that all bridged carbon credits must have been issued within ten years of their claimed vintage end date. One creates an empty NFT contract on Solana, retires their credits on Verra or Gold Standard, and then updates their NFT with the serial number generated by the offset. Carbovalent then verifies and approves the bridging, activating the NFT.

Once bridged, NFTs can be fractionalized into Solana Carbon Tonne (SCT) tokens, where one SCT token corresponds to one tonne of sequestered or prevented emissions. SCT tokens can either be retired to offset emissions or deposited into the *Carbon Vault* in return for so-called *index tokens* Blue Carbon Credit (BCC) or Forest Carbon Credit (FCC). These index tokens function much like aforementioned pool tokens, except BCC targets coastal wetlands and FCC targets forests. One can then trade BCC and FCC on Carbovalent DEX, a decentralized exchange for carbon credits, or trade carbon credits on an orderbook DEX.

3.5. Nori—Nori substantiates their own carbon credits, issuing carbon credits to projects which can prove that they have captured carbon and have agreed contractually to store it for at least ten years.[41] An independent third party verifies the project, and the credits issued by

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Nori are called Nori Carbon Regenerative Tonnes (NRTs). At the time of writing, the only methodology successfully used to substantiate carbon credits has been a version of a custom methodology called *US Croplands*.[42]

Each NRT represents a verified claim that one tonne of carbon dioxide has been removed from the atmosphere, along with a contractual commitment that the removed carbon be sequestered for at least ten years. NRTs are retired immediately on the point of sale, so they cannot be traded on a secondary market. Even so, Nori has a fungible token, the NORI token, which acts as a fungibility layer over the NRTs. Each NORI token is redeemable one-for-one for an NRT, where the act of redemption retires the credit immediatly. In contrast to the NRTs, the NORI token can be traded on a secondary market.

The NORI token differs from previously mentioned fungibiliy-layer tokens. It is not backed by pooled credits, as NORI tokens are not minted in exchange for pooled NRTs. Instead, the NORI token is an independent cryptocurrency with complex tokenomics, including a token launch and distribution, a treasury, a supply cap, and an insurance mechanism. Nori holds unretired NRTs, and the tokenomics of the NORI token guarantee it to be redeemable one-for-one to retire carbon credits. The NORI token is a cryptocurrency, partially deriving its value from the value of NRT tokens, as well as a utility token, as it can be used to retire carbon credits. In the event of a breach of contract, where sequestered carbon backing an NRT is released before ten years, NORI tokens are automatically taken from the insurance pool to purchase and retire new credits.

3.6. Likvidi—Likvidi tokenizes carbon credits onto Ethereum, using its fungible LCO2 token.[43] Each LCO2 token represents one tonne of carbon dioxide sequestered from the atmosphere, but the token itself is backed by a portfolio of twenty different carbon projects in order to diversify risk associated with any particular project. Credits are currently tokenized from legacy ledgers, including Verra.

Likvidi also has a utility token, LIKK, which can be staked in return for rewards in the form of LCO2 tokens and *escrowed LIKK*, or esLIKK. LIKK and esLIKK are governed by their tokenomics, including a vesting schedule for stakers, a distribution rate, rewards for liquidity provision, a release schedule, and a supply cap at 1 billion tokens. Users can offset their own emissions with their staking rewards, and similar to the NORI token, LIKK is a cryptocurrency, meant to be used as a medium of exchange.

3.7. Others—There are many others not covered here, but we finish by mentioning a few that deal with carbon capture in some adjacent ways to the above. Regen Network is a custom blockchain made to host climate data and carbon credits.[44] It was built with the Cosmos SDK, whose native token is the REGEN token. They mint NCT tokens (of the same standard as the Toucan NCT tokens) as fungible tokens, and have partnered with Toucan to bridge between the Regen Network and Polygon.[45]

Other groups use NFTs to tokenize, conserve, and reforest land. Cascadia Carbon allows users to tokenize trees into a so-called *NFTree*, and gives rewards in their native token, CODEX, which is meant to be a carbon-backed stablecoin.[46] Other groups have the concept of an NFTree, including NFTreeHaus,[47] and some groups simply called NFTrees.[48,49] Further groups, like Rewilder, raise money with NFTs to purchase and conserve land, effectively tokenizing the land similar to the concept of an NFTree.[50] Finally, Save Planet Earth has various projects combatting climate change, which are facilitated by their cryptocurrency SPE, which is traded on BNB.[51]

ISSN 2379-5980 (online)
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As they grow, they will sell carbon offsets which can be bought with SPE, advocating their cryptocurrency as a medium of exchange more broadly.

3.8. Summary—While there is some reasonable amount of similarity between tokenized carbon credits—most tokens represent one tonne of captured carbon, captured by a reputable source—tokenized carbon credits vary in fungibility status, methodology, associated fungibility layers and utility tokens, and the hosting blockchain. Some represent retired tokens, some unretired; some allow for secondary market trading, while others do not; for some the bridge is two-way, while for others tokenized carbon credits cannot be redeemed for underlying carbon credits on a legacy ledger; and some are explicitly concerned with the permanence of carbon storage, implementing insurance protocols or diversifying risk, while others do not explicitly take permanence into account.

However, it is in the fungibility layer that we get particular disunion. Of the examples we gave, Nori and Likvidi achieve fungibility through a utility token (NORI and LIKK, respectively), each of which is governed by a custom tokenomic structure. Toucan's Nature Carbon Tonne (NCT) token and Flowcarbon's planned Goddess Nature Token (GNT) both target nature-based solutions, but are backed by distinct methodologies. Carbovalent's Blue Carbon Credit (BCC), which targets carbon sequestration in coastal wetlands, and Forest Carbon Credit (FCC), which targets carbon sequestration in forests, both target nature-based solutions, but at a more granular level. Toucan's Base Carbon Tonne (BCT), MOSS's MCO2 token, and Likvidi's LCO2 token represent generic carbon credits, though MCO2 credits are chosen and tokenized at the discretion of MOSS, BCT are Verra credits, and LCO2 tokens represent part of a diversified portfolio of credits. Each of these fungibility layers is an attempt to make carbon credits tradeable with high liquidity, but we can see that in practice these trading pools do not intersect.

4. Trading Carbon Credits

Fungibility layer tokens tend to be traded on automated market makers (AMMs) rather than orderbook-style exchanges. At the time of writing, Toucan's BCT can be traded on QuickSwap and SushiSwap (Polygon), and NCT can be traded on Osmosis via the Regen Network. Flowcarbon's GNT can be traded on SushiSwap as well. MCO2 can be traded on Uniswap and QuickSwap. The only exception is Carbovalent, which has an orderbook-style decentralized exchange, called Carbon DEX, which is a central limit order book (CLOB), though there is nothing technical preventing trading on an AMM. While some of these carbon credits trade on the same AMMs, to our knowledge there are no trading pools directly between tokenized carbon credits from distinct projects. There are definitely no trading pools that combine carbon credits from various projects for higher liquidity.

Carbon credits are also hosted on a variety of distinct chains. Of the tokenized carbon credits we surveyed, these include Solana, Ethereum, Polygon, Celo, and the Regen Network. Toucan is by far the most prolific of these, as their tokens are hosted on Polygon, Celo,[52] and Regen Network.[45] Much work has gone into blockchain interoperability,[35] including to develop cross-chain swaps and cross-chain smart contracts,[53,54] which may play a role in facilitating cross-chain carbon markets.

Despite fungibility layers, pooling mechanisms, and any cross-chain bridging, the market liquidity is fractured. Even so, each of the aforementioned projects hopes to trade on-chain with

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high liquidity. Toucan argues that pooling allows "for some level of commoditization by pooling similar carbon tokens," and claims that "this is necessary to produce a transparent price signal to the market for different categories of carbon credits."[36] Flowcarbon argues that "liquidity is at the heart of any efficient market," and that it "reduces market volatility and overall risk for the market participants."[38] Finally, Open Forest Protocol (OFP), whom we will see in Section 6, argues that carbon markets as-is are "fragmented, illiquid, and prone to problems of ... price volatility."[55] The simple advantage of the pool token as a solution for market liquidity is that it is fungible and higher in total quantity than its individual constituents.

The solution to this fractured market may include more complex and diverse pools. However, we note a tension between pooling for high liquidity and preserving the key characteristics of each carbon credit. Because existing token pools value all the constituent tokens equally, any time tokenized carbon credits are pooled together, their individual differences beyond the pool's acceptance criteria are discarded for the sake of fungibility. Any such pools will likely have to be able to value constituent tokens relative to each other, not just at a rate of one-for-one.

5. Programmable Carbon

In addition to trading, we consider interoperability in terms of the applications that are built on carbon credits. Because interoperability manifests itself in part in how easy or difficult it is to build applications on top of these credits, the kinds of applications which build on tokenized carbon credits are a key component that could inform token interoperability standards. There are already a variety of applications that build directly on tokenized carbon credits or the data which backs credits. Let us review a number of them, and then discuss some key takeaways.

5.1. Offsetting Services—A primary purpose of tokenized carbon credits is that they can be retired to offset emissions. Aside from the retirement functionality that all tokenized carbon credits given here offer, there are already some services built around offsetting emissions. For example, from the projects we have seen, Flowcarbon also offers automated offsetting for Web3 users and Nori offers automated offsetting for businesses.[56]

5.2. Carbon-Backed Digital Assets—There is an emerging landscape of tokenized digital assets which are backed by carbon credits or related climate data. KlimaDAO, who works with Toucan, issues a carbon-backed currency called KLIMA.[57] KLIMA tokens are backed by at least one retired carbon credit from various sources, including BCT and MCO2 tokens. KLIMA can also be minted by the rules governing the treasury, which themselves are governed by the DAO. The goal of this project is to drive up demand for carbon credits, creating what they call a *carbon economy* in which the currency is carbon-backed, and the true cost of carbon is internalized into every transaction.

There are various other projects with similar goals to KlimaDAO. Climatecoin has a coin, ClimateCoin, backed by carbon credits, a governance token, CLIMAT, and a DAO ecosystem that attempts to facilitate and fund sustainable development and make a transparent marketplace.[58] (Note that Climatecoin has a low TRL.[6]) KumoDAO is a small project which attempts to back a stablecoin with carbon offsets.[59] And, as previously mentioned, other examples include CODEX and the NORI token. Finally, Arbol sells agriculture and energy derivatives based on climate data collected and monetized on dClimate.[60]

ISSN 2379-5980 (online)
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5.3. Climate Insurance—Arbol also offers parametric insurance to guard against issues related to climate, *e.g.* unexpected weather. The payout is based on a predetermined trigger event, governed by a smart contract, which can be verified using data on dClimate (see Section 6).

5.4. Art and Gaming—Finally, there is a thriving art and gaming ecosystem built around tokenized carbon credits, ranging from NFTs to metaverse projects. Celostrials is an algorithmically-generated collection of NFTs on the Celo blockchain which have partnered with Toucan, and will allow holders of Celostrials to "carbonize" their NFT with NCT tokens.[61] Celostrials holders will also be able to earn so-called climate activity rewards. Flowcarbon is also launching a collection of NFTs, named Flow3rs, which were auctioned off to support various climate-positive projects, including projects which tropical forest conservation, biodiversity, and carbon sequestration.[62] Flowcarbon also calculates and offsets on-chain emissions of NFT projects. Moving on, Likvidi has the Origins Collection, which is a collection of one thousand twenty carbon-backed NFTs.[63,64] Holders of Origins NFTs can stake their NFTs and earn carbon credits, and have other benefits as part of the originators club. And finally, Ecosapiens is an NFT project where minted NFTs are backed by fifteen tonnes of captured carbon, and which are meant to be used as profile pictures (PFPs).[65]

Taking a slightly different direction, Nori has an API that allows any artist who mints NFTs to offset their minting, and then choose a percentage of their sales that are automatically diverted to purchase and retire carbon offsets. KlimaDAO also interacts with the offsetting process with an initiative called "love letters," where someone retiring carbon can include a message, or a "love letter to the planet," which accompanies the act of retirement. These love letters are encoded on the blockchain, and KlimaDAO has a dashboard where they can be seen.

Finally, in the metaverse space, Metamazonia is building a 3D, photorealistic metaverse to make a digital twin of certain parts of the Amazon rainforest.[66] The metaverse can be explored with an avatar. They use NFTs as a funding mechanism to prevent deforestation, promote R&D in the Amazon, and to fund other projects. NFTs correspond to pieces of land in the metaverse, which themselves correspond to coordinates in the physical reserve in the Amazon rainforest.

5.5. Relating to DeFi—Some of the aforementioned efforts relate to trends in decentralized finance (DeFi). In particular, these are carbon-backed digital assets like KLIMA and Climatecoin that attempt to back a more typical digital asset, such as a stablecoin, with carbon credits. Others include derivatives, both on climate data (*e.g.* Arbol)[60] and on carbon credits themselves (*e.g.* Carbovalent's index tokens).[40] While still in early stages, as tokenized carbon credits mature as a digital asset class, we may see more in the way of derivatives, yield farming, synthetics, and other DeFi-related applications.[33,34]

5.6. Key Takeaways—There is already a vibrant ecosystem of applications that build on tokenized carbon credits which align with the general goals of climate action, from art and NFTs to services and derivatives. As carbon credits grow in prominence on blockchains, this is likely to continue developing. From the lens of token interoperability, note that there is little to no technical hurdle to interoperation between various carbon credits, so long as they are on the same blockchain. Because these tokens conform to established token standards, swapping out *e.g.* which carbon credits are retired, or which carbon credits back an NFT of some kind (for two examples), would likely be little more than changing a contract address or a line of code.

The real hurdle, however, to interoperation between tokenized carbon credits in the above examples comes in the semantic meaning of each of the applications: retiring one carbon credit

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instead of another is not necessarily the same thing semantically, even though technically it is likely a nearly identical process; likewise, the carbon credits that back a particular NFT have to match the ethos and goals of the NFT project itself, so it is unclear *a priori* if one carbon credit can be substituted for another in these instances.

6. Climate Data Availability

Readily available climate data is essential for the process of verifying and tokenizing carbon credits which are substantiated by novel methodologies, and for building applications built on carbon credits which rely on up-to-date climate data. Despite the fact that at the time of writing most carbon credits are tokenized from legacy ledgers, for which data is collected and analyzed off-chain, there are good reasons for the data to be publicly stored, and for the methodology to be transparently applied to the data. These include verifiability, reproducibility, and reducing the need to trust intermediaries, and are generally in line with the advantages blockchains offer to voluntary carbon markets. Furthermore, if the process can be largely automated, and climate data can be collected and made available *en masse*, then the process of verification may become more scalable. Finally, if blockchain-based carbon credit projects rely only on legacy ledgers, then the project may be dependent on decisions made by verification agencies out of their control (see Verra's recent statement on tokenized carbon credits and Toucan's response).[67,68] We will take a brief look into three organizations which are looking to collect and store climate data in a decentralized fashion.

6.1. Filecoin Green—Filecoin is a decentralized ledger for storing data using the IPFS protocol. With Filecoin, a user can pay for storage to be hosted on the Filecoin network over a specified period of time. Filecoin Green is an initiative on Filecoin to store climate data and make it broadly available.[69] Their stated goal is to build infrastructure so that anyone can make transparent and substantive environmental claims. Their first initiative on climate data is to measuring the electricity consumption of their validators to be transparent about the emissions of the blockchain itself. Their goals are to host more extensive climate data and make it available to various applications, which could include tokenized carbon credits.

6.2. dClimate—dClimate is a decentralized network for climate data, consisting of four layers: the governance layer, through which dClimate operates like a DAO via its native WTHR token; the oracle layer, which makes climate data available to applications, operating like Chainlink; the blockchain and data storage layer, where data is stored via IPFS; and the marketplace layer, where users can access (and pay for) data.[70] Climate data is published confidentially until accessed and paid for by a user, though contributors can choose to make their data free. As we mentioned previously, Arbol offers parametric insurance against climate-related events, using dClimate as its data source. More broadly, dClimate is attempting to lower the barrier to entry for climate data capture and monetization, and could host data which is relevant to carbon credits and the corresponding ecosystem of applications.

6.3. OFP—The Open Forest Protocol (OFP)is a protocol built to manage forest data, with the goal of improving forests.[55] While the protocol hopes to eventually mint carbon credits backed by data managed by the protocol, it is also meant to be a more general forest data management tool. The protocol itself has a native token, the OPN token, which grants access to the OFP, allows a holder to verify or challenge the accuracy of a specific MRV data upload,

ISSN 2379-5980 (online)
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and governs the protocol's parameters as a DAO. When the time comes, the process of creating carbon credits with OFP is meant to be open and transparent. Users will be able to create a new project and upload data, which will generate an NFT contract for them. To mint tokens, on-the-ground forest data must be collected by the OFP field mobile app, after which validators check the legitimacy of the ground data. Acceptable methodologies to mint carbon credits, as well as any guards on what types of credits or methodologies are acceptable, will be governed by the DAO.

6.4. Key Takeaways—Making climate data readily available to blockchain-based applications, and incentivizing people and entities to collect and publish that data, will no doubt play an important role in how tokenized carbon credits are minted and in other financial derivatives built on-chain using the data. If the data is high quality, this could support a wide range of methodologies which compute over the data to substantiate tokenized carbon credits on the blockchain. If done in a transparent and verifiable way, this could be a highly effective marketplace of ideas that works to mitigate climate change and monetize carbon capture from the atmosphere, among other things.

7. Related Organizations

Finally, we mention a few groups that are interested in decarbonizing blockchains, in using blockchains for climate action, and in making standards for tokenized carbon credits. From the work of these groups, we are most interested in the work of standards for tokenized carbon credits, though each contributes more to the ecosystem.

The Crypto Climate Accord (CCA), an initiative to decarbonize blockchains and cryptocurrencies supported by various companies and nonprofits, has as its goal to "develop standards, tools, and technologies with CCA Supporters to accelarate the adoption of and verify progress toward renewably-powered blockchains by the 2025 UNFCCC COP30 conference."[71] It puts forward various solutions, including guidance for accounting and reporting electricity use and carbon emissions from cryptocurrencies.

The Climate Collective is a coalition of entrepreneurs, investors, non-profit organizations, and scientists, whose aim is to promote blockchains and cryptocurrencies (Web3 infrastructure) as a tool for climate action at scale.[72]

Finally, Gold Standard has launched some working groups with the aim to develop "an open, global collaboration on digital solutions for carbon market standards and monitoring, reporting, and verification (MRV)."[73,74] They consist of a digital assets working group, which "looks at the role of blockchain to track carbon credits in decentralised environments;" an open APIs and digital infrastructure working group, which "looks into how new digital methodologies can increase the robustness of carbon credit calculations;" and a digital MRV working group, which looks into the "details of how to turn earth observations into meaningful carbon metrics."

While we expect the token contracts of these carbon credits to all conform to established token standards, we do not yet have a standardization framework for methodologies substantiating carbon credits. Because methodologies can vary widely, as we saw in Section 3, we do not expect standards to be strictly prescriptive in the way that token standards are. However, standards on token metadata, data collection, or measurement practices could be useful as key guidelines to ensure that tokenized carbon credits are rigorously substantiated and can be effectively compared

ISSN 2379-5980 (online)
DOI 10.5195/LEDGER.2023.294

along various metrics.

8. Conclusion

Tokenized carbon credits vary in their implementation details and in what substantiates them (Section 3). As the goal of this research is to help maximize interoperability between tokens, we face the technical hurdle that carbon credits exist on various blockchains and with various token standards. Luckily, in practice most (non-fungible) tokenized carbon credits are pooled into a fungible token that conforms to established token standards. Thus by using inter-chain bridges, the technical hurdle itself for token interoperability is not particularly high.

Instead, as we saw, interoperability can be hampered by variations in what substantiates a token. In contrast to token standards, where it is productive to have all tokens conform to established standards, it is likely unproductive to fully standardize the data and methodologies that substantiate carbon tokens. Instead, we can drive innovation with an open and transparent marketplace for methodologies of data capture and processing that rewards accuracy and efficacy. In time, such an open marketplace could be supported by the various decentralized carbon data collection and availability schemes (Section 6), and reproducible or verifiable computation over them. Even so, organizations seeking to form some consensus around standardization could prove productive in providing a common framework for these methodologies (Section 7), which could include standard ways of structuring token metadata.

In some sense, however, this desire for a rich variability in the methodologies substantiating tokenized carbon credits stands in conflict with the nearly ubiquitous goal of having as much liquidity as possible on-chain by pooling carbon credits together (Section 4). This is because, as they exist, fungibility layers pool tokens by valuing them one-for-one, and so tokens can be pooled together insofar as they are valued equally to each other. This achieves fungibility by *discarding* differences between the constituent tokens in methodology, project type, vintage, *etc.* Because we *want* carbon credits to be able to vary in price depending on their characteristics, ideally where higher quality credits are valued more highly, we are inherently restricted in our ability to pool tokens and achieve higher levels of liquidity on-chain.

Ideally, we would be able to pool tokens in such a way that values distinct tokens differently according to some market price (*e.g.* a carbon credit worth twice as much as another would trade for twice as many pool tokens as the other) and allows for dynamic price discovery between the constituent tokens over time. This would achieve the goals stated above of high liquidity and fungibility, while still valuing carbon credits individually with their granular data, encouraging a rich landscape of tokenized carbon credits. It could also prove useful for interoperability as it relates to applications building on tokenized carbon credits (Section 5), achieving our goals of interoperability more broadly.

Conflict of Interest

Derek Sorensen is a member of the Cambridge Centre for Carbon Credts (4C).

ISSN 2379-5980 (online)
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