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Non-fungible token (NFT) markets on the Ethereum blockchain: Temporal development, cointegration and interrelations

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Abstract: The market for non-fungible tokens (NFTs), transferrable and unique digital assets on public blockchains, has received widespread attention and experienced strong growth since early 2021. This study provides an introduction to NFTs and explores the 14 largest submarkets using data from the Ethereum blockchain between June 2017 and May 2021. The analyses rely on (a) the number of NFT sales, (b) the dollar volume of NFT trades and (c) the number of unique blockchain wallets that traded NFTs. Based on the number of transactions and wallets, the Ethereum-based NFT market peaked at the end of 2017 due to the success of the CryptoKitties project. As of 2021, fewer transactions occur but the traded value is much higher. We find that NFT submarkets are cointegrated and feature various causal short-run connections between them. The success or adoption of younger NFT projects is influenced by that of more established markets. At the same time, the success of newer markets has an impact on the more established projects. The results contribute to the overall understanding of the NFT phenomenon and suggest that NFT markets are immature or even inefficient.

Keywords: NFTs; non-fungible tokens; cryptocurrency; cointegration; Granger causality

1 Introduction

On March 11, 2021, an exclusively digital piece of art in the form of a *non-fungible token (NFT)* was sold for the equivalent of $69 million (Christie's, 2021). This work of art by the artist *Beeple* can be freely viewed or accessed by anyone on the Internet. So why was such a large sum paid for it? Arguably because this particular piece of art is an NFT. NFTs are blockchain-based tokens that securely map ownership rights to digital assets. Analogous to owning a physical work of art (that visitors to a museum can also look at without owning it), NFTs provide a way to represent ownership or possession of digital assets such as art, music, games or collectibles (Ante, 2021a; Dowling, 2021a).

While the idea of NFTs existed long before blockchain technology (Protos, 2021a), Bitcoin's underlying technology is the first to offer a secure decentralized infrastructure to digitally map

non-fungible values. Blockchain technology represents a secure and transparent basis for the mapping and (peer-to-peer) transfer of values over the Internet (Steinmetz et al., 2020). Specifically, the blockchain is used to store metadata that represent ownership or other rights to an asset. Additionally, the technology provides a suitable infrastructure for the application of smart contracts, which are scripts that enable the automation of business logic (Ante, 2021b; Wang et al., 2019). Being largely autonomous, they execute predefined actions when triggered by blockchain transactions. All terms and conditions of smart contracts are transparently stored on the blockchain, ensuring that all network participants can validate the underlying information, which resolves trust issues between the parties. Using smart contracts, any type of business logic can be anchored and applied in a decentralized manner, enabling a wealth of different use cases. A key use case is the concept of tokenization, where a "digital container" is created via a smart contract that maps values decentrally and transparently on the blockchain, additionally making them programmable, transferable and tradable (Ante, 2021b; Cong and He, 2019).

A "classic" application of such blockchain-based tokens is for projects to issue tokens that convey particular rights, such as access to a decentralized protocol, financial claims (i.e. debt or equity) or even energy units. The tokens can also be of an exclusively monetary nature—be it a decentralized (volatile) cryptocurrency or a so-called stablecoin whose value is tied to other assets, such as the dollar or gold (Ante et al., 2021). Like Bitcoin or shares, all these types of blockchain tokens are fungible. There is basically no distinction between two Bitcoins or two shares—it is completely irrelevant which of the two you own. Both have the same characteristics and convey the same rights. As their name suggests, non-fungible tokens are a special form of blockchain-based tokens that are specifically non-fungible. Each NFT represents a unique value that cannot be fully replaced by a different token. A simple example is the digital work by the artist *Beeple*, which was sold for $69 million. The artist created a single NFT token that reflects the rights to the digital art asset. Just as physical art can be viewed in museums without owning it, internet users can also view the artwork. However, there is only one owner. Somewhat more complex examples comprise concert tickets (Regner et al., 2019), trading cards, or the allocation of liquidity at the decentralized exchange *Uniswap*. The same trading card can exist multiple times, but not the "exact same one". NFTs for concert tickets are distinguished by characteristics such as the seat or a simple barcode ID. In the example of the decentralized exchange *Uniswap*, NFTs represent the rights to allocated capital. While two parties can of course provide exactly the same amount of capital, they still represent independent rights or positions (Uniswap, 2021).

NFTs can provide a digital equivalent for unique or rare assets in the analogue world. The programmability of NFTs allows their properties to be customized. For example, this can mean that the creators automatically receive royalties from resales (Ethereum Foundation, 2021), NFTs can be traded in fractions (NIFTEX, 2021) or used as collateral (NFTFI, 2021), or new NFT projects can supplement existing ones. A prominent example of this is the *KittyHats* project, which allows *CryptoKitties* NFTs (i.e. digital cats) to be extended with hats, apparel and accessories (KittyHats, 2021).

With the application of smart contracts, standards have been developed to offer NFTs off-the-shelf. The first NFT project on the *Ethereum* blockchain was *Etheria*, which was demonstrated at an *Ethereum* conference in 2015. The project initially received little attention but was

"rediscovered" in 2021 as part of the rapid growth of the NFT market (Hakki, 2021). In 2017, projects such as *CryptoPunks* and *CryptoKitties* were launched. The *CryptoKitties* project in particular attracted a lot of attention, as usage of the NFT-based game resulted in so many blockchain transactions that the transaction costs of the network increased significantly and the challenge of *Ethereum*'s scaling capability became obvious (BBC, 2017). This very challenge of scalability and transaction costs has led NFT project *Axie Infinity* to switch to a so-called layer-2 scaling solution (Axie, 2021) and the NFT *project NBA Top Shot*—by *CryptoKitties* developer *Dapper Labs*—being launched on the proof-of-stake *FLOW* blockchain infrastructure that offers higher transaction throughput (Dapper Labs, 2021).

In 2021, the NFT market achieved significant growth and attention, which was associated with various high-profile NFT sales and the launch of many new projects. Besides the above-mentioned NFT by *Beeple*, for example, the first tweet ever was sold for 2.9 million (Valuables, 2021), the meme animation *Nyan Cat* was auctioned for about $0.6 million (Business Insider, 2021) and the band *Kings of Leon* sold their music rights as NFTs for the equivalent of $2 million (NME, 2021). NFTs have clearly become a relevant phenomenon that has yielded highly innovative approaches. For the first time, artists can monetize digital content, users or gamers can be owners of digital worlds, and rare collectibles can be (re)produced digitally. Various NFT ecosystems have developed on the Ethereum blockchain, which at this point still have a strong dependency and relationship with cryptocurrency markets (Ante, 2021a; Dowling, 2021a)—not least because NFTs are often traded against Ethereum's native cryptocurrency Ether. So far, there has been little academic research on the financial aspects of the NFT market or individual NFT markets. While Dowling (2021a) examines the pricing of three NFT markets (*Decentraland*, *CryptoPunks* and *Axie Infinity*) and their relationship to cryptocurrency markets, Ante (2021a) looks at the relationship between the overall *Ethereum*-based NFT market, *Bitcoin,* and *Ether*. Both studies identify a correlation or co-movement between NFT and cryptocurrency markets. Finally, Dowling (2021b) analyzes the pricing of the metaverse NFT project *Decentraland*, where users can trade digital parcels of *LAND*.

These studies provide important initial insights for the scientific understanding of NFT markets. Yet significant gaps remain in our knowledge of NFTs, their markets and implications. Rather than relating NFTs to the cryptocurrency market, this article considers the NFT market and its most relevant submarkets. Since NFT projects differ significantly depending on the assets they represent (e.g. trading cards, art, digital objects, music, etc.), we explore the question as to how strongly the individual markets are interrelated, cointegrated or influence each other. Nadini et al. (2021) analyze NFT markets in terms of their statistical properties. The authors look at market cycles, cluster NFT objects into categories, and predict NFT sales. While the present study also aims for a basic description of the NFT market and uses a similar data basis, it focuses on different research questions and methodological approaches. Accordingly, our approach of analysing specific NFT submarkets regarding their relationship, (co-)integration and causal connections complements the work by Nadini et al. (2021).

To address these questions, we collect daily market data on 14 major NFT projects on the Ethereum blockchain and complement it with aggregate daily data on all other available NFT projects on the same blockchain to identify the overall Ethereum-based market size—which at the time accounts for the majority of the overall market. Following a brief description of those

14 projects, we visualize and describe the corresponding data series on the number and volume of transactions, as well as on the number of wallets involved, to gain an understanding of the NFT market, the selected submarkets, and temporal characteristics. In the next step, we test whether the corresponding (log transformed) time series are stationary and determine the number of cointegrated vectors using the Johansen test (Johansen, 1991). Using a *vector error correction model (VECM)*, we calculate short-run Granger causalities between the individual NFT projects and visualize their relationships using *impulse response functions (IRFs)*, allowing us to identify the (causal) relationships between individual NFT projects and, thus, to better understand the market. The results provide a basis for the scientific discourse on NFTs and allow users/practitioners to understand and assess relevant characteristics of the market(s).

This article proceeds as follows. Section 2 describes the data collection, the resulting variables and the methodological approach. Section 3 provides an overview and descriptive evaluation of the 14 NFT markets studied and the NFT market as a whole. This includes a brief description of each project, descriptive statistics and the development of the NFT market over time. In Section 4, the basic parameters for the time series analysis are reviewed before postestimation results (Granger causalities and IRFs) of the VECM are presented. Section 5 discusses the results (5.1), followed by limitations and future research opportunities (5.2). Finally, Section 6 concludes.

2 Data and methodological approach

2.1 Data and variables

As with the above-mentioned studies on NFTs, we obtain our data from NonFungible.com. The website provides data on NFTs on the *Ethereum* blockchain; therefore, projects on other blockchains are not part of the analysis. On May 19, 2021, individual daily data series were collected for the 14 NFT projects whose cumulative trading volume was at least $10 million, as well as aggregate daily data on the total market. Note that other NFT projects may be "more relevant" according to other criteria, such as the number of sales. Specifically, for each NFT, we collected data on (1) the number of sales, (2) the USD amount spent on sales and (3) the number of unique blockchain wallets involved in the trades. These three metrics adequately capture the basic activity, monetary relevance, and the number of wallets (users) in NFT markets. Regarding the latter, note that one person may use several wallets, so the wallet count constitutes an upper limit on the number of NFT users. For the subsequent analyses of cointegration and causality, we use logged variables, where a constant of 0.0001 is added to all values prior to taking logs to accommodate the (few) days with zero activity.

One limitation to consider is that *Axie Infinity* switched from the Ethereum blockchain to a layer-2 scaling solution, so no comparable data is available from the time of the switch (end of April 2021), which makes any interpretation considerably more difficult.

2.2 Methodological approach

Investigating the interactions and causal relationships between the 14 NFT projects, we aim to distinguish between short-term and long-term effects. For that purpose, the three time series

described above are analysed by means of a (cointegrated) *vector autoregression (VAR)* model. In VAR models, vectors of variables are related both to their own lags and the lags of other variables. The optimal number of lags can be determined via the *Akaike information criterion (AIC)* (Hamilton, 1994; Hatemi-J, 2004; Scott Hacker and Hatemi-J, 2008). To specify the VAR model, the *augmented Dickey Fuller test (ADF)* is used to check whether the logged series follow a unit-root process, i.e. whether they are stationary. All non-stationary series are excluded from further analysis. We apply the Johansen test (Johansen, 1991) to the remaining variables to check for any cointegration among the series, i.e. any long-run equilibrium relationships. Such long-run connections make the VECM—the cointegrated VAR—a suitable model to study any short-run deviations from the equilibrium relationship(s) (Engle and Granger, 1987).

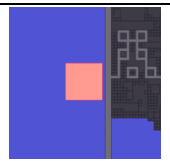
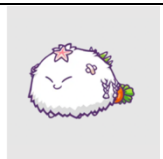
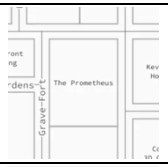
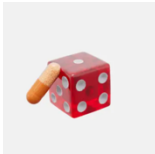
We present two postestimation results of the VECM: short-run Granger causalities between the variables and IRFs. Granger causality refers to the ability of a lagged time series to predict another time series (Granger, 1981). While the metric indicates whether such a causal relationship exists, its sign (positive or negative) cannot be determined. IRFs in turn provide a suitable complementary visualization of the interactions between the variables in the VECM model, showing how a shock of one standard deviation to variable A affects variable B over time. Given cointegration and the long-term relationship, short-term effects can be visualized, whose values drift back to the equilibrium relationship over time (Hamilton, 1994).

3 NFT markets

The 14 NFT projects studied are briefly described in Table 1, their descriptive statistics are shown in Table 2. The projects are sorted by their launch date. *CryptoPunks* is the oldest project with 1,428 daily observations between June 2017 and May 2021, *Meebits* is the youngest with 17 observations in May 2021. Besides a brief description of the project, the table also indicates the sector, the launch date on the Ethereum blockchain, and an example image of an NFT.

The descriptive statistics show that the projects differ significantly in terms of their basic characteristics. While *CryptoPunks* are traded 9.4 times per day on average by 10 unique wallets at a total value of $236,000 ($25,106 per NFT trade), the average for *CryptoKitties* is 2,251 transactions and 443 wallets per day, with an average trade being worth only $73.3. *CryptoKitties* is by far the project with most transactions per day, while the youngest project, *Meebits*, has the highest volume traded in a single day (over $85 million).

Table 1. Major NFT projects on the Ethereum blockchain.

Project	Sector	Launch	Description	Example
CryptoPunks	Collectibles	Jun 17	A collection of 10,000 unique collectable CryptoPunks on the Ethereum blockchain that have specific meta-attributes (e.g., *Zombie*, *Handlebars*, *Bandana*, *Cigarette*, *Earring* for the pictured example of *CryptoPunk #1190*, which sold for $1.4 million in May 2021).	
Decentraland	Metaverse	Sep 17	Virtual reality platform where users can create, experience and monetize their creations—be it 3D scenes or interactive games. Content is published on LAND, digital parcels of the metaverse. Users can trade LAND, estates, avatars or names. The example shows *Estate #4186*, which sold for $700k in May 2021.	
CryptoKitties	Collectibles	Nov 17	Collectable digital kittens that have various meta-attributes (e.g., *Gen*, *Exclusive*, *Fancy*, *orangesoda*, *chocolate,* etc. for the pictured example of *CryptoKitty #57*, which sold for $37.8k in May 2021). Kittens can be bred to create new CryptoKitties, enabling endless varieties and generations.	
Axie Infinity	Collectibles, Game	Feb 18	Collectable digital pets or fantasy creatures called Axie that can be trained, raised and used for battling other creatures. Creatures have attributes such as class, health, speed, skill etc. The example Axie, *Big Yak reptile*, sold for $693 in May 2021. In April 2021, Axie Infinity migrated to Ronin, an Ethereum sidechain (Axie, 2021).	
SuperRare	Art	Apr 18	Smart contract platform that allows the creation, trading and collection of digital art. The example NFT, *Five Eyes – Tastes like hairspray*, sold for $185k in May 2021.	
CryptoVoxels	Metaverse	Jun 18	A virtual metaverse where users can build, develop and trade properties. Ownership and land are permanently recorded on the Ethereum blockchain. Using the project's native token, parcels can be coloured. The example NFT, *55 Hook Street*, sold for $23k in May 2021.	
MakersPlace	Art	Jul 18	A platform for the creation of NFTs that represent digital artwork. The example NFT, *CHAOS #16 Sunset*, is part of a collection of 501 unique sculptures on the Ethereum blockchain, where physical objects are transferred to a digital equivalent via 3D scanning. It sold for $111.7k in May 2021.	

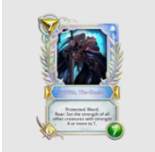
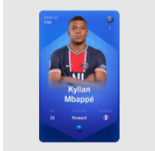
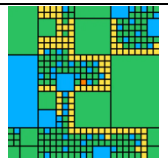
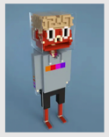
Gods Unchained	Collectibles, Game	Jul 18	A collectable card game where users can build decks to play the game against each other. Similar to games such as *Magic the Gathering* or *Hearthstone*. The example NFT card, *Griffith, The Chosen*, sold for $12k in May 2021.	
Sorare	Collectibles, Game	Jul 19	Fantasy soccer game where users can collect and trade official collectable cards of soccer players. They can manage their team to win prizes. The example card of PSG and French national player *Kilian Mbappé* sold for $55.9k in May 2021.	
Somnium Space	Metaverse	Sep 19	A virtual reality ecosystem where users can acquire land and create objects. Objects can be imported and traded, with players being able to shape the metaverse. The example parcel, *Medium #4722*, sold for $9k in May 2021.	
The Sandbox	Metaverse	Dec 19	A metaverse where users can trade and use LAND in which to host their creations. The creations in the user-built world can themselves be traded. The example LAND sold for $3.9k in May 2021.	
Art Blocks	Art	Nov 20	A platform and marketplace for the creation of (random) programmable artworks on the Ethereum platform. The NFT *Chromie Squiggle #2079* by artist *Snowfro* sold for $151k in May 2021.	
Hashmasks	Art, Collectibles	Feb 21	Crypto art collectable project where Hashmasks are (randomly) designed/layered based on various inputs from artists. The exemplary Hashmask, *The Ethereal King*, sold für $147k in May 2021.	
Meebits	Collectibles	May 21	3D collectable and provably scarce avatars from the creators of CryptoPunks. The avatars possess diverse meta-attributes, such as type, hair style, shirt or pants. The pictured *Meebit #10761* sold for $2.67 million in May 2021.	

Table 2. Descriptive statistics on sales per day, daily sales volume in million USD and daily unique wallet of NFTs on the Ethereum blockchain. The 14 projects with the largest all-time trading volume (> $10 million) are presented individually. In each case, the data cover the period from the launch date until May 19, 2021.

NFT market	Days recorded	NFT sales			NFT volume			NFT wallets		
		Mean	SD	Max	Mean	SD	Max	Mean	SD	Max
CryptoPunks	1,428	9.4	24.4	329	0.236	1.139	21.200	10.0	21.4	234
Decentraland	1,329	93.6	399.0	6,573	0.045	0.156	2.872	36.3	76.7	1,406
CryptoKitties	1,276	2,250.8	4,270.4	52,451	0.034	0.165	2.436	442.5	1,078.7	12,867
Axie Infinity	1,190	276.0	285.8	2,269	0.017	0.043	0.340	135.9	183.9	1,092
SuperRare	1,144	19.3	25.6	152	0.068	0.234	2.692	27.1	35.0	202
CryptoVoxels	1,080	8.1	12.6	101	0.009	0.029	0.409	7.2	7.1	49
MakersPlace	1,046	15.4	22.6	189	0.019	0.079	1.303	18.1	27.0	227
Gods Unchained	1,045	543.9	1,645.9	15,868	0.021	0.511	16.500	74.0	134.7	767
Sorare	686	480.9	763.3	6,624	0.085	0.199	1.971	318.3	513.6	2,725
Somnium Space	618	5.8	24.3	406	0.016	0.051	0.585	4.4	6.9	104
The Sandbox	535	167.6	910.4	13,947	0.039	0.170	3.457	32.7	77.7	875
Art Blocks	174	283.3	347.7	1,858	0.151	0.191	0.988	147.6	190.0	1,530
Hashmasks	112	226.7	698.3	5,297	0.572	1.031	6.755	131.6	201.0	1,390
Meebits	17	753.1	2,336.4	9,770	8.181	20.500	85.200	368.8	740.9	3,137
Others	1,238	1,010.8	1,006.8	24,383	0.076	0.185	3.478	n/a	n/a	n/a
All	1,428	4,002.6	4,456.8	52,457	0.702	3.397	102.000	1,222.6	970.5	12,874

Figure 1 illustrates the temporal development of the NFT market on Ethereum in terms of the number of NFT sales and their value in USD. The metrics distinguish between the 14 largest NFT projects and the rest of the market (other). The number of active wallets cannot be summed up because a unique wallet in one project may simultaneously be a unique observation in another project. The largest absolute number of NFT trades on the Ethereum blockchains occurred in the fourth quarter of 2017 and was mostly attributable to the *CryptoKitties* project. Subsequently, the market share of *CryptoKitties* transactions declined by about 5 to 10% per quarter.

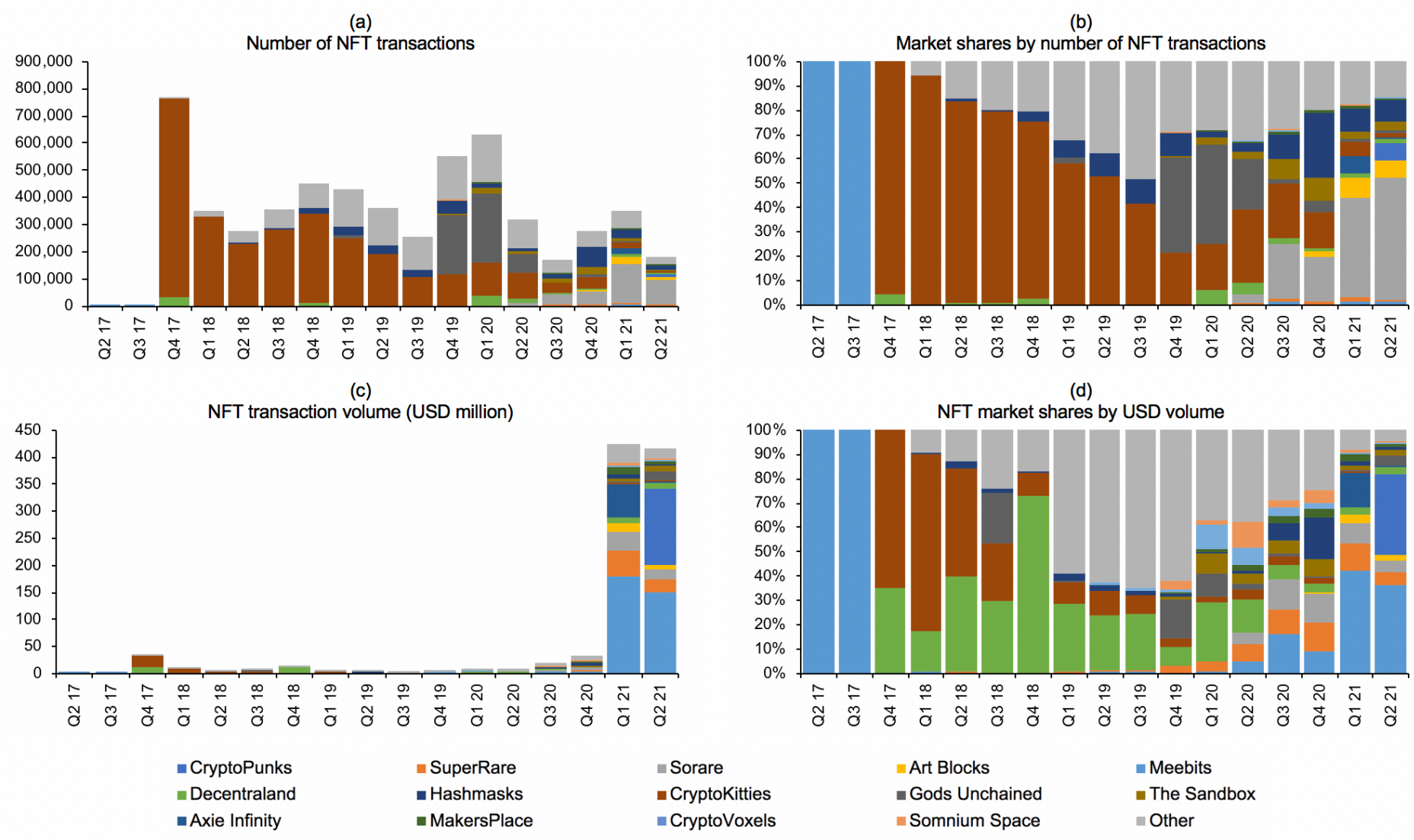


Figure 1. Absolute and relative prevalence of Ethereum-based NFT submarkets by quarters. Note that "Q2 2020" only covers less than two months (April 1 to May 19, 2021).

In terms of the number of trades, the *Gods Unchained* project gained a significant market share immediately following its launch in 2018 but lost its prominence soon thereafter. By contrast, the soccer trading card game *Sorare* has been growing steadily from Q2/2020 and now accounts for around half of all transactions. The volume of the NFT market has been growing at a staggering rate in 2021. The Q1/2021 volume exceeded $400 million, and this value was almost reached again in the short period between April 1 and May 19, 2021. Most of this volume is shared by the collectable projects *CryptoPunks* and *Meebits*, while *Decentraland* accounted for most of the (much smaller) market throughout most of 2018 and 2019. Clearly, looking at the number of transactions versus the volume yields a very different picture of the NFT market and its individual projects.

In sum, we find that, telling by the number of transactions, the NFT market peaked in 2017. In terms of traded volume in USD, however, the market has downright exploded in 2021—the volume was $36 million in 2018, $24 million in 2019, $66 million in 2020, and it already stands at $841 million as of May 2021. Whether that growth will continue is of course anyone's guess (Protos, 2021b).

4 Results

4.1 Model specification

We test the stationarity of the various (log-transformed) time series using the ADF test. For the calculations, we select the optimal lag length based on the AIC. The results are shown in Table 3. We find that the bulk of the time series are stationary, while for some comparatively recent projects with fewer observations, this is not the case. In the subsequent analyses we focus exclusively on the stationary variables and drop the non-stationary ones for statistical reasons. For example, for the variable NFT sales, the projects *Sorare*, *Hashmasks* and *Meebits* are excluded, so the analysis hereafter refers to the remaining 11 projects.

Table 4 reports the results of the Johansen test (Johansen, 1991) for cointegration, i.e. long-term correlation between several time series. The Johansen test can be regarded as a multivariate generalization of the ADF test, where linear combinations of variables are examined for unit roots. For n variables, a maximum of $n-1$ cointegrating vectors exist. On the basis of eigenvalues, Trace test and Maximum Eigenvalue test estimates are used to identify the cointegrating vectors. The corresponding estimates for the number of cointegrating vectors are shown on the right side of the table, relevant test statistics for the Trace test are marked in bold. We find that for all three types of variables, the series are cointegrated. NFT sales have three integrated vectors, NFT volume has six integrated vectors, and NFT wallets have four integrated vectors. Therefore, rather than on a standard *Vector Autoregression (VAR)* model, our further analysis must rely on a VECM (the cointegrated VAR), where we use an error-correction term based on the known cointegrating relationships to fit the model. The optimal lag length of the variable is determined by the AIC (4 days).

Table 3. Unit root tests. Results of the Augmented Dickey-Fuller (ADF) test for unit root on the log-transformed series of NFT sales, NFT volume and NFT wallets.

NFT market	NFT sales		NFT volume		NFT wallets	
	ADF	*p*-value	ADF	*p*-value	ADF	*p*-value
CryptoPunks	-9.459	0.000***	-7.406	0.000***	-9.510	0.000***
Decentraland	-4.119	0.000***	-3.899	0.002***	-3.812	0.003***
CryptoKitties	-3.174	0.021**	-4.055	0.001***	-2.986	0.036**
Axie Infinity	-3.498	0.008***	-3.841	0.003***	-3.489	0.008***
SuperRare	-4.354	0.000***	-3.859	0.002***	-4.544	0.000***
CryptoVoxels	-8.178	0.000***	-6.887	0.000***	-8.041	0.000***
MakersPlace	-3.980	0.002***	-3.372	0.012**	-4.154	0.001***
Gods Unchained	-3.090	0.027**	-3.511	0.008***	-3.271	0.016**
Sorare	-0.880	0.795	-0.846	0.805	-0.860	0.801
Somnium Space	-6.207	0.000***	-5.835	0.000***	-6.134	0.000***
The Sandbox	-4.795	0.000***	-3.985	0.002***	-4.686	0.000***
Hashmasks	-2.560	0.102	-1.885	0.339	-2.559	0.102
Art Blocks	-6.952	0.000***	-1.705	0.429	-3.081	0.028**
Meebits	-1.148	0.696	-1.251	0.651	-1.086	0.721

***, ** or * indicate that the null hypothesis of a unit root in the time series can be rejected at the 1, 5 or 10 per cent level. Lags were determined by the AIC.

Table 4. Johansen cointegration test.

	NFT sales					NFT volume					NFT wallets				
#	EVI	Trace	5% CI	L_{Max}	5% CI	EVI	Trace	5% CI	L_{Max}	5% CI	EVI	Trace	5% CI	L_{Max}	5% CI
0		364.3	277.7	101.8	68.8		357.9	233.1	91.8	62.8		395.4	277.7	88.3	68.8
1	0.46	262.6	233.1	60.3	62.8	0.16	266.1	192.9	69.2	57.1	0.41	307.1	233.1	73.8	62.8
2	0.30	202.2	192.9	59.2	57.1	0.12	196.9	156.0	46.6	51.4	0.36	233.3	192.9	69.8	57.1
3	0.30	**143.0**	**156.0**	50.2	51.4	0.08	150.3	124.2	43.5	45.3	0.34	163.6	156.0	51.9	51.4
4	0.26	92.8	124.2	32.4	45.3	0.08	106.8	94.2	37.6	39.4	0.27	**111.7**	**124.2**	34.2	45.3
5	0.18	60.4	94.2	22.6	39.4	0.07	69.3	68.5	32.4	33.5	0.18	77.5	94.2	28.7	39.4
6	0.13	37.8	68.5	13.4	33.5	0.06	**36.9**	**47.2**	20.2	27.1	0.16	48.8	68.5	20.5	33.5
7	0.08	24.5	47.2	10.4	27.1	0.04	16.7	29.7	12.0	21.0	0.12	28.3	47.2	14.6	27.1
8	0.06	14.0	29.7	7.9	20.9	0.02	4.7	15.4	4.1	14.1	0.08	13.7	29.7	8.4	21.0
9	0.05	6.2	15.4	5.4	14.1	0.01	0.7	3.8	0.7	3.8	0.05	5.4	15.4	4.4	14.1
10	0.03	0.8	3.8	0.8	3.8	-	-	-	-	-	0.03	1.0	3.8	1.0	3.8

4.2 Granger causality and impulse response functions

The results of the actual cointegrated VAR are not easy to interpret, especially given the large set of variables, so we present only postestimation results. These are, first, short-run Granger causalities and, in a second step, IRFs. Given that the series are cointegrated, a longer-term relationship among them has already been established. Short-run Granger causality examines whether changes in various lags of one time series are associated with changes in another series. Note that while Granger causality can reveal a causal relationship, the result does not indicate whether this relationship is positive or negative. The visualization of IRFs is in turn useful to determine and interpret the causal relationship, both in the short and the long term. While IRFs for traditional VARs always run towards zero, this is not the case for the IRFs of cointegrated VARs—because the series have a long-term relationship. More precisely, an IRF models how a standard deviation shock to one variable affects another variable over time. We plot the response over an interval of 30 days, which allows us to identify both short-term and longer-term effects. Since the combination of all examined projects would yield 11x11 or 10x10 matrices (depending on the variable used), we refrain from displaying all IRFs graphically, instead focusing on those combinations for which we found significant Granger causalities.

Granger causalities are shown in Table 5 while IRFs are visualized in Figure 2 (NFT sales), Figure 3 (NFT volume in USD), and Figure 4 (active wallets). To interpret the results, note that the time series have different lengths (see Table 2). Regarding the number of NFT sales, we find that CryptoPunks has a significant impact on several projects (*CryptoKitties, CryptoVoxels, Somnium Space, The Sandbox* and *Art Blocks*). Conversely, *Decentraland, CryptoKitties* and *CryptoVoxels* Granger-cause the number of *CryptoPunks* transactions. While the relationship between the two collectable projects *CryptoPunks* and *CryptoKitties* is mutually positive, we identify a negative impact of *Decentraland* transactions on those of *CryptoPunks*. The NFT transactions of *Somnium Space* Granger-caused five other NFT projects, with all effects except the one on *CryptoVoxels* being negative. This may indicate that NFT users are more likely to migrate to *Somnium Space* than to use the project as an alternative to other NFT projects.

Three NFT projects—*Axie Infinity, SuperRare* and *MakersPlace*—do not significantly Granger-cause any of the other projects. Only one of the 11 NFT projects is not influenced by any of the other projects: *Decentraland*. In sum, although we do find some significant correlations between the NFT projects regarding the number of transactions, it is hardly possible to interpret them clearly in their entirety. Detailed case studies or clustered analyses of NFT markets by sector may yield a more comprehensive picture. However, the focus of this article is not on examining individual relationships, but rather on taking an overall look at the NFT market, which is largely made up of the submarkets under consideration.

Table 5. Short-run Granger causality test statistics for the VECM model. Rows correspond to dependent variables, columns to independent variables.

Project	Sector	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Number of NFT sales												
(1) CryptoPunks	Collectibles	-	2.37	12.48***	1.21	5.97	18.06***	2.15	7.48*	12.91***	9.24**	1.86
(2) Decentraland	Metaverse	6.39*	-	2.74	1.25	10.34**	0.40	7.64*	1.09	9.19**	3.99	8.49**
(3) CryptoKitties	Collectibles	7.65*	1.04	-	2.39	1.92	0.12	2.74	4.29	6.02	4.72	16.12***
(4) Axie Infinity	Collectibles; Game	1.44	1.64	1.64	-	2.12	0.88	1.25	1.61	0.67	0.60	4.29
(5) SuperRare	Art	4.03	2.40	4.48	5.42	-	1.22	0.60	5.38	1.99	0.81	0.73
(6) CryptoVoxels	Metaverse	9.30**	2.06	1.68	1.53	3.32	-	1.60	1.02	4.60	4.67	5.87
(7) MakersPlace	Metaverse	3.50	1.43	5.55	4.46	0.08	4.01	-	2.88	1.46	0.60	3.10
(8) Gods Unchained	Collectibles; Game	0.03	4.50	7.60*	7.33*	5.71	3.41	6.58*	-	0.15	0.70	2.95
(9) Somnium Space	Metaverse	6.14	2.32	10.80**	6.96*	13.06***	14.89***	4.75	13.72***	-	3.21	20.79***
(10) The Sandbox	Metaverse	3.14	1.25	3.86	0.92	0.75	5.69	7.60*	2.09	5.58	-	1.15
(11) Art Blocks	Art	2.70	3.31	6.54*	3.50	0.99	2.00	4.54	2.76	12.57***	3.55	-
NFT transaction volume (USD)												
(1) CryptoPunks	Collectibles	-	0.51	1.89	0.96	3.12	4.53	1.64	0.49	4.17	3.58	-
(2) Decentraland	Metaverse	1.21	-	8.15**	2.50	2.20	8.57**	7.63*	0.93	3.08	6.61*	-
(3) CryptoKitties	Collectibles	4.93	4.56	-	2.67	0.39	0.77	3.39	25.87***	8.48**	2.65	-
(4) Axie Infinity	Collectibles; Game	3.36	1.78	1.96	-	7.66*	3.78	6.29*	8.77**	0.58	2.02	-
(5) SuperRare	Art	3.17	1.54	11.71***	7.75*	-	4.13	2.01	1.83	7.13*	1.66	-
(6) CryptoVoxels	Metaverse	7.20*	1.18	1.40	3.39	1.37	-	6.15	1.73	3.69	2.78	-
(7) MakersPlace	Metaverse	1.00	4.35	5.43	6.20	5.24	5.84	-	3.49	13.71***	5.66	-
(8) Gods Unchained	Collectibles; Game	0.13	2.11	5.72	14.67***	1.91	4.81	1.67	-	1.23	5.02	-
(9) Somnium Space	Metaverse	9.61**	0.79	5.84	7.25*	3.36	20.30***	45.46***	1.60	-	4.91	-
(10) The Sandbox	Metaverse	9.22**	5.57	2.60	0.35	9.91**	0.41	3.82	4.77	2.10	-	-
Number of unique wallets buying or selling NFTs												
(1) CryptoPunks	Collectibles	-	1.90	3.32	0.82	6.04	10.16*	1.87	2.01	16.24***	5.05	1.72
(2) Decentraland	Metaverse	6.51*	-	6.79*	3.02	4.96	3.18	4.83	3.63	4.46	11.99***	3.86
(3) CryptoKitties	Collectibles	8.32**	0.90	-	1.39	3.04	1.04	4.33	23.15***	6.49*	1.95	6.37*
(4) Axie Infinity	Collectibles; Game	1.05	0.58	3.08	-	1.34	2.54	0.30	2.43	0.42	0.44	3.67
(5) SuperRare	Art	5.43	2.87	2.17	5.44	-	0.41	0.51	5.92	4.28	0.97	1.37
(6) CryptoVoxels	Metaverse	10.44**	6.70*	1.37	1.23	3.29	-	0.60	1.54	8.02**	2.72	2.65
(7) MakersPlace	Metaverse	3.55	2.36	1.90	3.81	0.23	2.63	-	2.01	2.60	1.27	2.87
(8) Gods Unchained	Collectibles; Game	1.14	7.35*	9.27*	7.52**	13.79***	2.24	7.10*	-	4.30	0.45	8.13**
(9) Somnium Space	Metaverse	9.08**	15.87***	1.47	7.86**	10.38**	2.63	2.79	5.88	-	1.73	10.72**
(10) The Sandbox	Metaverse	4.21	1.34	1.15	2.16	3.86	4.05	3.15	1.48	6.74	-	1.36
(11) Art Blocks	Art	4.02	1.94	0.97	2.50	2.89	1.27	6.11	12.72***	15.49***	2.69	-

***, ** or * indicate that the null hypothesis of no Granger causality can be rejected at the 1, 5 or 10 per cent level.

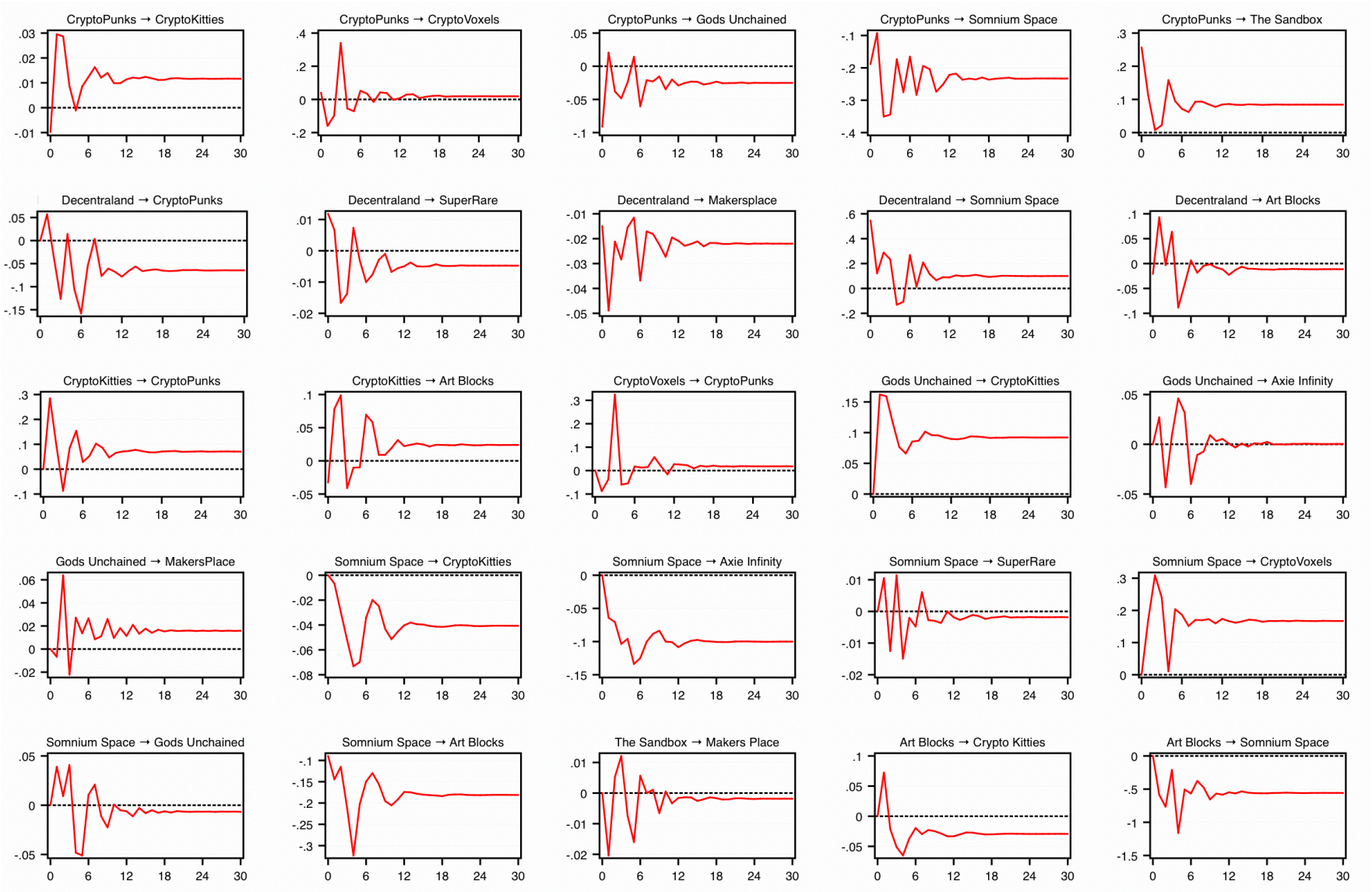


Figure 2. Selected impulse response functions based on the VECM on the number of NFT sales.

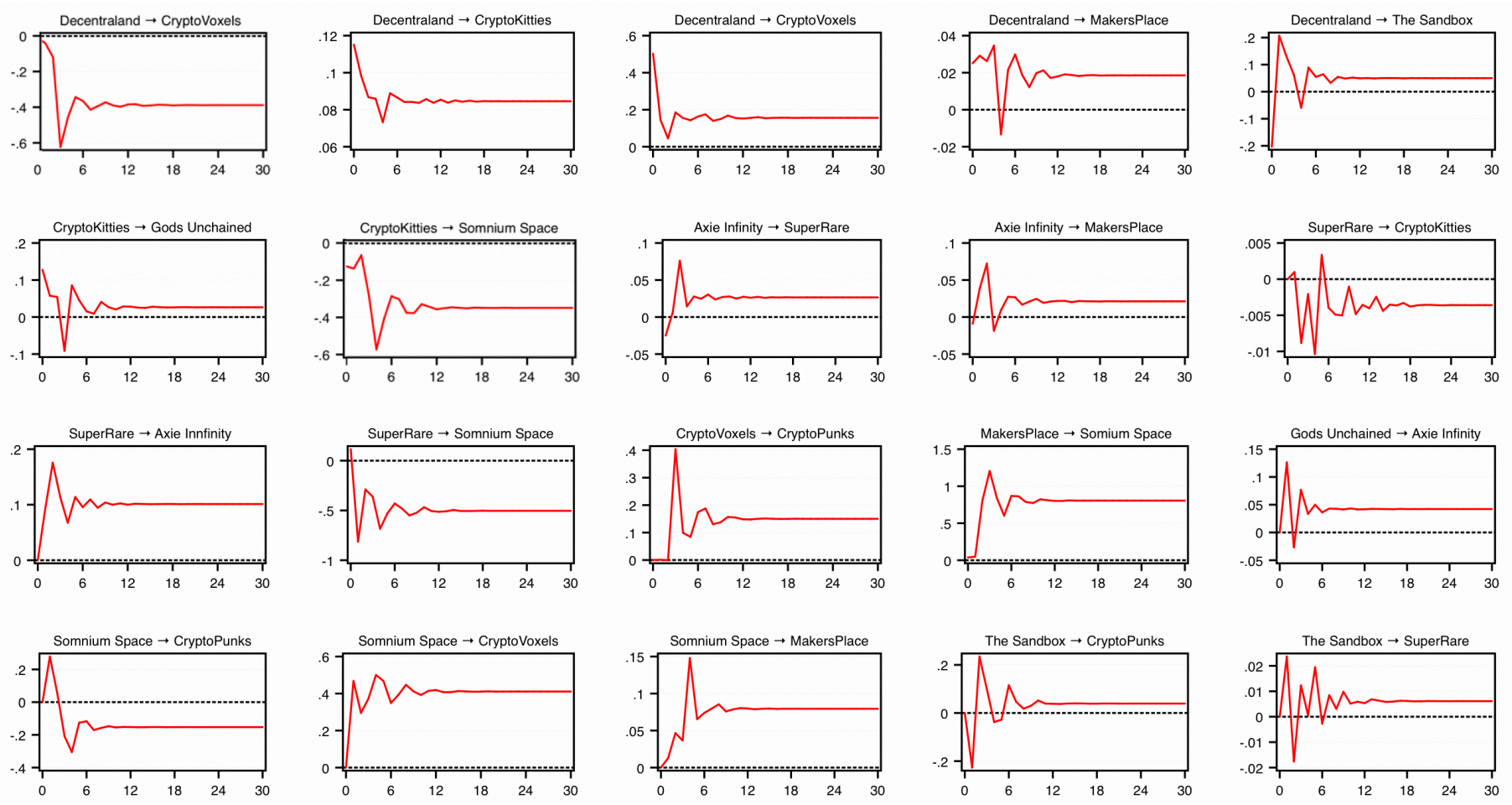


Figure 3. Selected impulse response functions based on the VECM on the NFT transaction volume in USD.

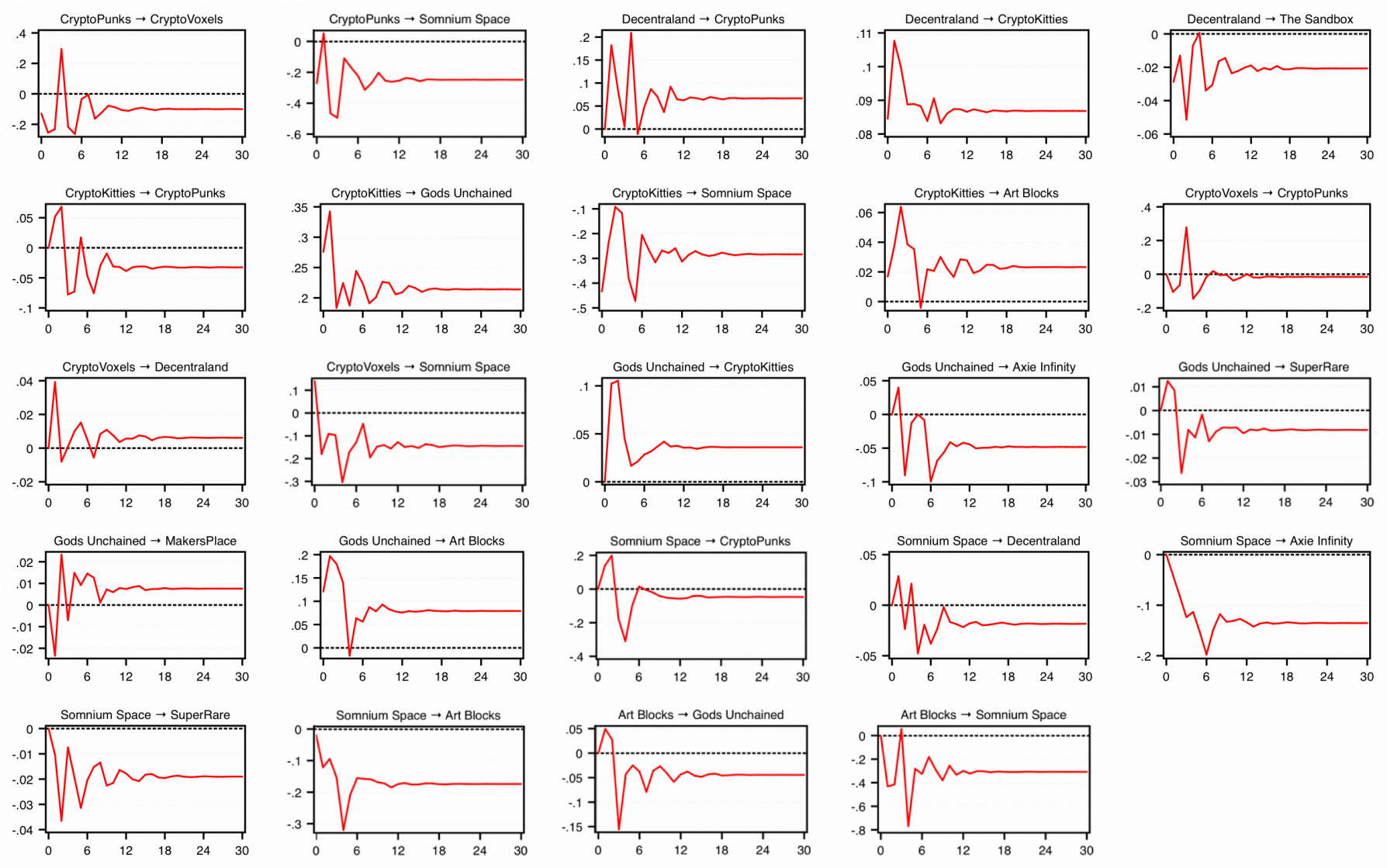


Figure 4. Selected impulse response functions based on the VECM on the number of active NFT wallets.

Looking at the traded volume in USD, we find that *CryptoPunks* does not Granger-cause any of the other projects but is itself Granger-caused by the two youngest projects in the sample. However, this relationship may be spurious, reflecting merely the rapid recent market growth (cf. Figure 1). By contrast, the second oldest project, *Decentraland*, appears to have greater market "relevance" or "lead", with significant influences on *CryptoKitties, CryptoVoxels* and *The Sandbox* (all positive based on the IRFs). As already indicated by the results on NFT transactions, *Somnium Space* seems to play a leading role in the NFT ecosystem. It has a positive effect on *CryptoPunks* in the short term (3 days) but a negative effect in the longer term, and a strongly positive effect on the traded USD volume of *CryptoVoxels* and *MakersPlace*—both of which are also metaverses.

The significant role of *Somnium Space* is also reflected in the number of unique wallets that bought or sold NFTs: We find that *Somnium Space* significantly Granger-causes *CryptoPunks, Decentraland, Axie Infinity* and *Art Blocks*. The IRFs show that, beyond the first few days, the effects are always negative. These results thus also suggest that *Somnium Space* draws NFT users away from other projects. This impression is reinforced by the fact that shocks to *CryptoPunks, CryptoKitties* and *CryptoVoxels* tend to depress the number of *Somnium Space* wallets, with significant Granger causality. At less than two years, *Somnium Space* is much younger than *CryptoPunks* and *CryptoKitties*. One implication of the results is that a shock to younger NFT projects invigorates older projects. Conversely, an increase in the number of active wallets of older projects seems to be negatively related to younger projects in the longer term.

5 Discussion

5.1 Reflections on main results

The NFT market is a very young phenomenon, which in turn emerged from similarly recent technological phenomena (blockchain around 2009 and smart contracts around 2015). Within this short period of time, the market has already experienced several peaks, including the great success of *CryptoKitties* (from late 2017) and the market boom that began in 2021 in the form of an extreme growth in trading volume. Our results and visual analysis indicate that the NFT market should be viewed from diverse angles (revenue, activity, users). Given that the NFT market is highly dependent on the larger cryptocurrency markets (Ante 2021a), the question naturally arises to what extent the huge NFT trading volume in early 2021 has merely been due to rising cryptocurrency prices. Accordingly, it would be worthwhile to investigate the pricing of NFTs in relation to the price of Ether or Bitcoin, and to what extent the cryptocurrency market drives the token prices in the much smaller NFT markets, which in turn drive NFT sales, volume and wallet activity.

The present study's financial focus on the NFT market is quite novel. It complements Nadini et al. (2021), who also map the NFT market but focus more on the interaction between NFT objects, traders and sectors, rather than on individual projects. In looking at individual NFT projects, our study is also related to Dowling (2021a), who examines the pricing of three NFT submarkets but focuses on the relationship with the cryptocurrency market (Bitcoin and Ethereum), similarly to Ante (2021a).

Our results suggest that NFT markets are driven by other NFT markets. The largest projects are currently assignable to the collectibles, metaverse, gaming, and art sectors. NFT projects with widely diverging content can nevertheless have a significant influence on each other—which initially seems counterintuitive. For example, the metaverse project *Decentraland* Granger-causes the art marketplace *SuperRare* in terms of trading volume. However, this is most likely related to the fact that *SuperRare* joined the *Decentraland* marketplace so that *Decentraland* users can use their native digital currency MANA within *SuperRare* (Decentraland, 2020). It can be a sensible strategy for younger NFT projects to offer the native tokens or currencies of larger NFT projects (or cryptocurrency projects) on their platforms or to integrate their own produce or services within the larger platforms to attract additional existing users with an affinity to NFTs. This strategy is particularly valid if the partner projects differs in terms of content, i.e. it does not constitute direct competition.

The high degree of interrelation within the NFT market is also evidenced by the fact that the younger project *Somnium Space* Granger-causes several other projects, though this effect seems to be negative. More sales of *Somnium Space* NFTs (digital parcels) lead to fewer NFT sales of other projects, which suggests that NFT users are "poached". The occurrence of both negative and reinforcing relationships between the projects suggests that pairwise relationships should be considered in more detail. A holistic assessment of the interaction within the market should only be made with caution.

Arguably, what we have seen so far in terms of the range of applications of NFTs is but the tip of the iceberg. Additional sectors that stand to benefit from this technology include financial markets (e.g, Uniswap, 2021), tourism (e.g., Regner et al., 2019), and sports (e.g., fan tokens). Irrespective of any speculative bubbles, the unique and secure mapping of digital rights is likely to remain in demand. A major obstacle to the wider adoption of NFTs, however, is the lack of technical and legal standards that would allow established companies to develop or use NFTs and provide legal certainty for end users. While technical standards already exist for the decentralized anchoring of NFTs on the blockchain, such as the ERC-721 NFT standard on Ethereum (Entriken et al., 2018), many other legal and technical issues of NFTs remain open. For example, in the case of digital art, it is completely unclear how and where the actual image must or should be stored (e.g., a centralized server or the *InterPlanetary File System (IPFS)*), and the legal rights to NFTs are insufficiently clarified. Can a NFT owner really enforce her rights? And does this differ by jurisdiction? A salient example of this is an incident in the context of the sale of tweet NFTs. The platform *Valuables* allows users to auction off tweets, as in the sale of the first-ever tweet for $2.9 million in March 2021 (Valuables, 2021). In another case, however, an author of an auctioned tweet deleted the actual tweet after the sale, losing the digital asset in its original form (Bitcoin.com, 2021).

Since NFTs represent a young phenomenon and there are large differences between projects in terms of technical and legal security, we assume a high level of uncertainty among users/investors. Accordingly, it is no surprise that we have identified a high level of co-movement in the NFT market. NFTs or NFT projects are highly unproven applications and assets whose long-term benefits are subject to much uncertainty. While the *Beeple* image mentioned in the introduction, which was auctioned for $69 million, is likely to offer high technical and legal certainty, the same often cannot be said of cheaper and less prominent

projects or artworks. If something goes wrong in an individual case, this can rebound on the entire NFT industry, which could be an explanation for the high level of co-movement.

5.2 Limitations and future research

A key academic and practical challenge for the NFT market is to identify to what extent the observed transactions are "genuine", as oppose to representing critical market phenomena such as wash trading, tax evasion or money laundering. In this study, we have used unique blockchain wallets as a proxy for actual users. However, due to the pseudonymous nature of the Ethereum blockchain, a single person may use any number of wallets. In the context of wash trading, a common phenomenon in the cryptocurrency market (Le Pennec et al., 2021), individual market participants could trade NFTs between their own wallets to artificially inflate liquidity and thereby raise the attractiveness of the tokens to uninformed traders. Likewise, NFTs could be sold "cheaply" and bought back at a high price in order to evade taxes or launder money. At this point, we do not know how prevalent these phenomena are in the NFT market. While we have consistently described and analysed the NFT market, we cannot say how much of that activity is "real".

For a more holistic overview of the NFT market, future studies should draw their data not just from Ethereum but also from other blockchain infrastructures. A cross-blockchain view would also enable an investigation of the impact of the transaction costs and scalability of blockchains on the adoption of NFTs or NFT projects. It remains unclear, for example, whether *CryptoKitties* would have achieved significantly more users or trading volume in 2017 if the limited transaction processing capabilities of the Ethereum blockchain had not made trading the NFTs very expensive. NFT projects are increasingly launching on other blockchains or migrating away from Ethereum ("chain swap") to enjoy cheaper or faster blockchain infrastructures. This phenomenon offers an exciting basis for scientific investigation, as the projects face an interesting trade-off. While the Ethereum blockchain is deemed to have the highest number of NFT-savvy users, making it an ideal launch platform, its technical constraints severely limit subsequent project growth, which suggest the transition to another blockchain. At this point, it is by no means clear what exactly drives these decisions, what their effects are, and how old and new users will react.

It is also important to remember that the three characteristics that we have investigated are not the only means by which NFT projects can be differentiated. For example, NFTs may simply serve as a digital proof on wallets to gain access to a system or to participate in voting. Likewise, NFTs can be linked to future events, which could (but must not) mean that no transactions are even possible or meaningful before a certain date. This implies the limitation that the projects examined in this study need not be the most "relevant" NFT projects on Ethereum. Future research could look in more detail at the actual rights conveyed by each token to enable a more accurate assessment of the extent to which those rights explain metrics such as sales or transactions, and the extent to which the "market relevance" of NFT projects can be meaningfully captured or interpreted. NFTs may include other characteristics such as revenue-sharing or voting rights, which can significantly influence the frequency of transactions or the trading volume. In addition, future studies may examine the impact of project-specific

cryptocurrencies on adoption and trading—for example the extent to which the price development of the digital currency MANA is related to activity around *Decentraland* NFTs.

Future research may want to analyse the identified relationships between NFT projects in more detail or to examine their persistence over time. For example, one could investigate whether the *SuperRare* marketplace indeed benefitted from offering its services on *Decentraland*. Furthermore, the impact of the launch of a new (successful) NFT project on other (similar) projects could be investigated. For example, our results show that the *CryptoPunks* project did not regain a significant market share until the NFT market took off in 2021, suggesting that the recent "success" of the project is mostly due to the growth of the overall NFT market. While our results show that various characteristics of *CryptoPunks* are driven by those of younger projects, which supports this assumption, further substantiation is required.

NFTs may include other characteristics such as revenue-sharing or voting rights, which can significantly influence the frequency of transactions or the trading volume. In addition, future studies may examine the impact of project-specific cryptocurrencies on adoption and trading—for example the extent to which the price development of the digital currency MANA is related to activity around *Decentraland* NFTs.

6 Conclusion

This study provides researchers and practitioners with a substantial basis from which to understand and further pursue the topic of NFTs. We have examined data on the overall NFT market as well as 14 of the most significant submarkets on the Ethereum blockchain, finding that the number of NFT transactions peaked in late 2017, whereas trading volume and the number of active wallets has experienced an unprecedented and ongoing surge in the first half of 2021. Following an exemplary description of those 14 projects, the daily time series data on NFT transactions, NFT volume (in USD) and NFT wallets (a proxy for users) were examined for unit roots. The stationary series were then checked for cointegration, which we identified with regard to all three metrics. The NFT submarkets exhibit a long-run equilibrium relationship, which is why we used a VECM model as part of the VAR methodology, presenting Granger causality and IRFs as postestimation results. We found numerous Granger causalities, so in addition to the long-run relationships, there are also significant short-run relationships between the projects. We use IRFs to visualize both short-run and long-run relationships between selected projects. Most NFT submarkets are driven by other NFT submarkets.

In sum, this study provides a comprehensive overview of the development of the NFT market on the Ethereum blockchain. The focus is on individual significant projects, where "significance" was defined as a cumulative trading volume of at least $10 million for each project's NFTs. The success of younger NFT projects has allowed older and virtually inactive projects to successfully participate in the market again. At the same time, older projects have an impact on younger projects (both positive and negative). The results suggest that while still immature, the market is developing at a rapid pace.

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Declarations

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on request.

Conflicts of interest

Not applicable.

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About the Blockchain Research Lab

The Blockchain Research Lab promotes independent science and research on blockchain technologies and the publication of the results in the form of scientific papers and contributions to conferences and other media. The BRL is a non-profit organization aiming, on the one hand, to further the general understanding of the blockchain technology and, on the other hand, to analyze the resulting challenges and opportunities as well as their socio-economic consequences.

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