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Decentralized lending and its users: Insights from compound☆

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ABSTRACT

Permissionless blockchains offer an information environment where users can interact privately without fear of censorship. Financial services can be programmatically coded via smart contracts to automate transactions without the need for human intervention or knowing users' identities. This new paradigm is known as decentralized finance (DeFi). We investigate Compound – a leading DeFi lending protocol – to show how it works in this novel information environment, who its users are, and what factors determine their participation. On-chain transaction data shows that loan durations are short (31 days on average), and many users borrow to support leveraged investment strategies (yield farming). We show that systemic risk in DeFi can arise from concentration and interconnection and how traditional risk management practices can be challenging for DeFi.

1. Introduction

Decentralized finance (abbreviated as *DeFi*) refers to an alternative financial system built on a permissionless blockchain that promises openness, efficiency, transparency, interoperability, and decentralization (Harvey et al., 2021; Schär, 2021), where users can anonymously interact in a digital environment while preserving the benefits of cash such as privacy. DeFi involves a system of computer algorithms called a *DApp* (decentralized application) or *protocol* replicating traditional financial services such as lending, exchange, and asset management. In addition, these algorithms can create new transferable data known as *tokens*, which can be freely connected as an open network. Furthermore, the transparency of blockchain allows developers to incorporate existing components into their design.[2] This interoperability is often termed *composability*, and DeFi money is called *Lego money* for this reason.

Traditional lending intermediaries raise funds in various forms, such as deposits, bills of exchanges, or shareholder equity, and lend them in exchange for interest income. In doing so, they take on several risks, such as interest rate risk (fixed versus variable rates), asset-liability mismatch risk (market value and maturity), and credit risk (ability and willingness to repay). In other words, lending

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[2] This freedom is not absolute, however, as owners of smart contracts that create the tokens can program restrictions, prohibiting specific addresses from interacting with the contract and effecting banning transfers. An example is the Tether USD (USDT) stablecoin, which contains an "addBlackList" function. Thus, the degree of freedom depends on the standpoint of the developer. See https://etherscan.io/address/0xdac17f958d2ee523a2206206994597c13d831ec7#writeContract for details of the function.

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intermediaries not only connect but transform the needs of suppliers and borrowers of capital while monitoring borrowers (Diamond, 1984) and creating liquidity as deposits (Gorton and Pennacchi, 1990; Kashyap et al., 2002).

Nakamoto (2008), the anonymous inventor of the Bitcoin blockchain, intends to build a system that allows "any two willing parties to transact directly with each other without the need for a trusted third party," such as banks. However, we show that DeFi financial services still require intermediaries despite the ability to transact directly with one another on-chain. In this environment, financial services can be automatically intermediated via pre-programmed codes, often called smart contracts. Furthermore, the ability to freely create new accounts and anonymously transact necessitates a different mechanism design. As a result, some risk management practices, such as customized lending terms or exposure limits to avoid concentration risk, are impossible.

We illustrate these points via Compound, one of the earliest and largest lending protocols built on the Ethereum blockchain. Compound does not take on any interest rate or asset-liability mismatch risk and faces minimal credit risk. Unlike how a modern bank operates, Compound is more similar to a mutual lender, where depositors mutually own the economic benefits of the protocol, like how a mutual insurance company operates. This limited risk exposure allows Compound to intermediate funds in this information environment.

Between May 2019 and June 2020, Compound supplied more than $61.1 billion in loans to almost 23,000 borrowers. Depositors and borrowers in Compound are concentrated, as the top 100 addresses account for 75% of all deposits, and the top 100 borrower addresses 78% of all loans. This concentration is more significant than in a traditional bank. For example, Juelsrud (2021) finds that the top 5% of depositors in Norway in 2018 accounted for 53% of all deposits. We document the factors that influence aggregate depositing and borrowing activities, particularly how the reward distribution can affect users' incentives to borrow, as the total return from collateralized borrowing can be positive even after accounting for borrowing costs.

Because DeFi protocols do not restrict the use of proceeds, loans can be used to finance spending and capital investments or fund leveraged investment positions. Using DeFi protocols to maximize rewards has come to be known as *yield farming*, which can be amplified by leverage, resulting in *leveraged yield farming* investment strategies. With address-level and loan-level data retrieved directly from the blockchain, we find evidence more consistent with leveraged investments than financing, such as shorter durations for certain types of addresses and recursive interactions with the protocol to maximize rewards.

Further investigations of address-level activities and new information on the identity of the address owners (for example, failed crypto businesses such as Three Arrows Capital, Celsius Network, Alameda Research, and FTX), we find that on-chain transactions before the collapse of the crypto asset market in May 2022 can reveal potential sources of vulnerabilities that built up as systemic risk and threatened the crypto asset market.[3] Aramonte et al. (2021) show that following forced DeFi liquidations, crypto asset prices fall sharply, and volatility spikes follow. Given that leverage is procyclical, liquidation risk can amplify the instability of the DeFi ecosystem. In addition, Acemoglu et al. (2015) show that dense interconnections can propagate shocks rather than enhance financial stability, and on-chain data shows that this is indeed the case for DeFi. The systematic risk arising from interconnections has been highlighted by many, including The Financial Stability Oversight Council (FSOC),[4] and lending protocols can contribute to such risk.

DeFi is an emergent field with growing research on how the protocols are structured and the potential risks involved. Several papers explain how DeFi lending protocols and crypto shadow banking work (Bartoletti et al., 2021; Gudgeon et al., 2020; Perez et al., 2020; Kozhan and Viswanath-Natraj, 2021; Li and Mayer, 2021; Castro-Iragorri et al., 2021), with Perez et al. (2020) and Castro-Iragorri et al. (2021) explicitly investigating Compound. However, most papers approach the issue at a conceptual level or rely on aggregate flow data. In contrast, our paper uses transaction-level blockchain data to provide a more microscopic view.

The rest of this paper is organized as follows. Section 2 provides an overview of what DeFi means and how Compound works. Section 3 outlines data sources, research hypotheses, and empirical methodologies. Finally, we present the results of aggregate-level and address-level analyses of Compound's usage in Section 4 and conduct further investigations into concentration, connectivity, and systemic risk in the context of the crypto asset market collapse in 2022 in Section 5.

2. How Compound works

2.1. Properties of decentralized finance

In this section, we describe the properties and operational rules of DeFi so readers can understand the context and why financial services offered on permissionless blockchains operate differently.

While there had been many interpretations of what the *decentralized* part of DeFi means, by 2022, the general definition has converged toward the ability to offer financial products and services without relying on a *trusted central intermediary* such as a bank or a payment processor (Aramonte et al., 2022; Carapella et al., 2022). Financial records, including money, can be represented by data. Therefore, a central authority who is the gatekeeper to the information system may abuse this database privilege, so an alternative environment where users are not subjected to this authority may be desired.

This definition is consistent with the objective of the Bitcoin white paper, where Nakamoto (2008) expresses a desire to build "a peer-to-peer electronic cash system" to preserve the privacy and convenience of money that physical cash provides in the context of an increasingly digitized world. Such a system would allow users to remain anonymous and retain the ability to transact without censorship, which requires a different information environment than the ones used by the financial system leading up to 2008.

[3] Source: https://www.nytimes.com/2022/05/12/technology/cryptocurrencies-crash-bitcoin.html, accessed November 28, 2022.
[4] Source: https://home.treasury.gov/system/files/261/FSOC-Digital-Assets-Report-2022.pdf, accessed November 28, 2022.

Blockchain technology is required to ensure that users accept the states and flows of information recorded, obviating the need for a centralized, trusted third party as a gatekeeper of the system. This interpretation is consistent with Cong and He (2019), who describe blockchain technology as providing *decentralized consensus*.

A blockchain with decentralized consensus potentially allows any entity running the blockchain software (a *node*) to hold the authority to record new data as a block and append it to the pre-existing data blocks as a ledger. Other nodes would then agree and update their ledger accordingly. As each node records the exact version of the ledger, blockchain technology is often called *distributed ledger technology* (DLT). The node chosen by the consensus algorithm (for example, proof-of-work or proof-of-stake) is rewarded with data known as *native coins* (such as Bitcoin) as compensation for their efforts.

The openness of this information environment entails the transparency of information recorded on the blockchain and the freedom to interact with other users on the same blockchain, leading to adjectives such as *permissionless* and *censorship-resistant* associated with this environment. The censorship resistance property of the blockchain depends on how decentralized the nodes are, and the amount of data recorded in each block is constrained by the minimum capability of an entity that can become a node in this environment; in other words, the more decentralized the environment is, the less efficient the blockchain would be. Block space is a scarce resource in a permissionless blockchain network.

The early blockchains have limited capabilities as they were intended for internal remittances and the self-custody of funds.[5] For example, the Bitcoin blockchain and its variants only allow existing Bitcoin (BTC) transfers between accounts. The accounts are known as *addresses* because users can freely create them without requiring personally identifiable information. Thus addresses are destinations to send the coins to, not persons. This objectification of data where ownership is proven by possession (like bearer instrument) rather than the owner's identity is the distinction between token money and account-based money described by Brunnermeier et al. (2019).

Later versions of blockchains allow more information to be recorded, including programming codes which would then be executed by the network of computers running the blockchain software. These are *programmable blockchains*, and the Ethereum blockchain is the most prominent example. In programmable blockchains, users are required to pay transaction fees using the native coins (so, Ether is used to pay for transactions in the Ethereum blockchain) to incentivize nodes to compute and record new information onto the blockchain and prevent network spamming because decentralized computing power and block space are limited resources in such blockchains. This transaction fee is known as *gas*, analogous to fuel for the blockchain network.

When addresses contain codes, they are called *smart contracts*, which can be used to compute and record new data onto the blockchain, thus allowing a more comprehensive range of possibilities beyond transfers and payments. Smart contracts can also create new numerical data and design how users interact with them. Such data is referred to as *tokens*, while *coins* are often used to describe numerical data created natively by blockchain software, and each blockchain is designed to have a single coin. Thus, Bitcoin and Ether are also known as native coins.

In principle, addresses can interact directly in a peer-to-peer manner. However, anonymity makes communication difficult and can introduce counterparty risk for intertemporal transactions. Address owners can voluntarily identify themselves or be flagged by others (hence, addresses are often described as *pseudonymous* rather than anonymous), but new addresses can always be freely created. Consequently, for agreements to be enforceable, DeFi service providers (often called *protocols*) would create smart contracts to hold relevant tokens for a transaction in a pool to reduce delivery risk.

Because of blockchain transparency, users can see the availability of tokens in the pool, and the computing network can check whether a desired transaction can be performed. Then, developers can write mathematical functions to allow users to interact with the pool to exchange or borrow tokens, depending on the protocol's purpose. The outcome of the mathematical calculations (such as exchange rate and interest rate) are updated and recorded every time a new block is added to the blockchain. Details of how the main types of DeFi protocols operate are provided in the Appendix.

In sum, smart contracts created as part of protocols by developers become a new type of intermediary, operating as instructed by computer codes rather than by human discretion. Based on this environment, decentralization in the context of DeFi means financial intermediation via smart contract pools in a permissionless (decentralized) blockchain that can be offered by anyone to anyone without the need to know their identity.

2.2. An overview of Compound

Founded in 2017, Compound launched its *money market* protocol in September 2018. The protocol's mission is to generate an efficient system for earning interest, achieved by a dynamic interest rate algorithm that automatically adjusts borrowing and saving rates as a function of available liquidity. Because it needs to generate income to pay depositors, Compound can also be viewed as a lending protocol.

Users must deposit accepted tokens into Compound's cToken contracts, which return the cToken as depository receipts. For example, if a user deposits DAI (a stablecoin), she would receive a cDAI token in return. The cToken is often called a *wrapped* token, as it is created by wrapping DAI by a cDAI contract to create a linked token.

The cToken contracts set the exchange rates between the tokens according to accrued saving rates, giving users more deposited tokens when redeemed. This design means interest payment is made upon redemption like discount loans, so users will pay gas costs

[5] For more on the limitations of such early blockchains, see John et al. (2022).

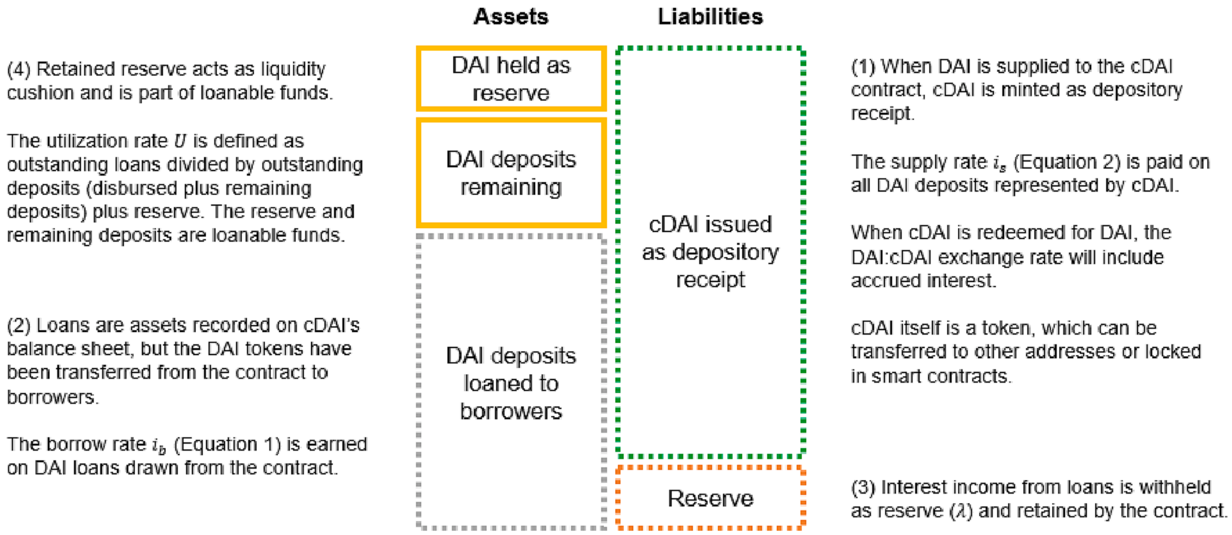


Fig. 1. Balance sheet view of Compound cToken contract. DeFi protocols can be represented as a business entity with assets and liabilities. The solid lines represent tokens held in the address, while dotted lines represent financial relationships between addresses. Tokens are transferable objects in blockchains: if an address holds some tokens, they are the address' assets. However, other assets, such as loans, are financial contracts representing the repayment obligations of the borrowers. In this case, the borrowed tokens will be transferred to the borrower's address, but the lender and borrower are tied by a promise which may or may not be tokenized. Similarly, when a user deposits DAI, the cDAI contract will hold the tokens. However, the cDAI contract will issue cDAI tokens as depository receipts, which the depositor holds. In this sense, the depositor can also be considered a creditor of the cToken contract, so the cDAI token could be considered tokenized debt. Like bank deposits are considered a debt to the bank, the cDAI token can also be classified as a tokenized deposit. Details of the contract can be viewed at https://etherscan.io/address/0x5d3a536E4D6DbD6114cc1Ead35777bAB948E3643.

only when they decide to withdraw. To see how this works, let us consider an example. When a user first deposits DAI to the cDAI contract, the exchange rate may be 46.2896 cDAI to 1 DAI. One day later, the exchange rate may move to 46.2859, so deposited 1 DAI will now be redeemed for 46.2896 / 46.2859 = 1.0000081 DAI after one day, equivalent to 3% annually. The flexible interest rate is set automatically via computer code, to be described later.

There are multiple ways to design a lending protocol. For example, one smart contract can be used to receive tokens and deposits and disburse them as loans, but creating a depository receipt like a cToken requires a separate contract for each linked token. As protocols develop, their smart contract designs can change. For example, Compound's original smart contract (Compound v1), created in 2018, operated a shared lending pool before migrating to a segregated cToken design (Compound v2) in May 2019. The cToken design makes analyzing the assets and liabilities positions denominated in each token easier. Fig. 1 provides a high-level overview of how the cDAI contract operates through the lens of a traditional balance sheet.

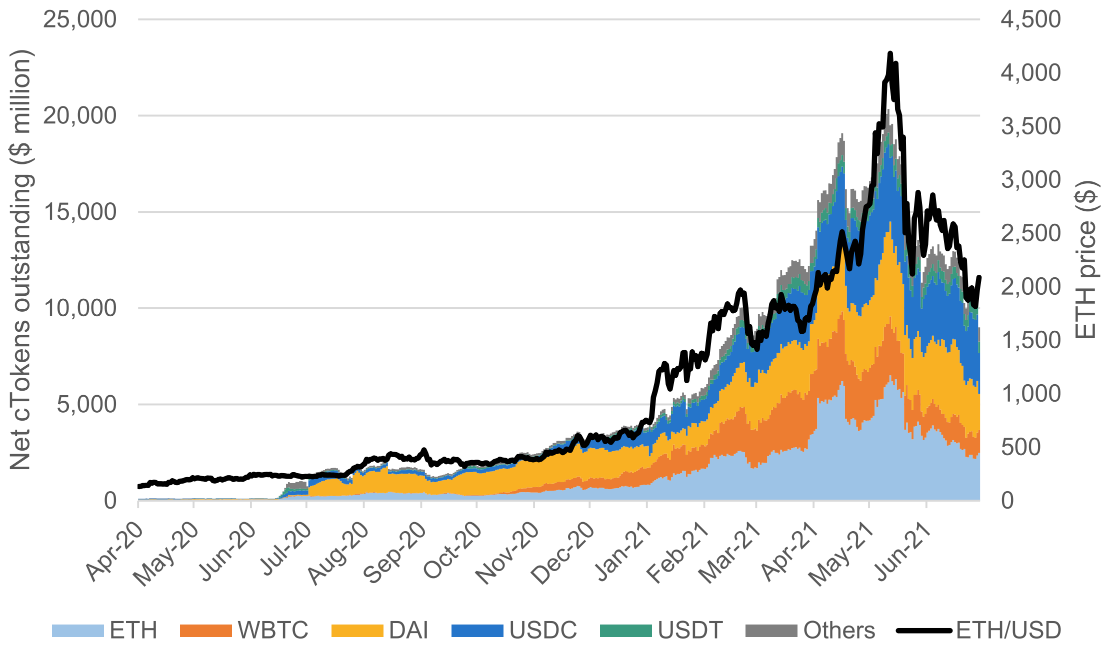
When it began, Compound initially accepted four tokens, which were Ether (ETH), 0x Protocol (ZRX), Basic Attention Token (BAT), and Augur (REP). As of July 2021, the list stood at twelve tokens, including stablecoins such as DAI, USD Coin (USDC), and Tether (USDT), and its governance token, COMP, whose properties will be described later. Stablecoins are tokens designed with mechanisms to stabilize their exchange rate to a pre-determined value, such as national currency, providing users with lower exchange risk compared to other crypto assets.[6] As of July 26, 2021, the most popular deposited tokens in Compound were USDC ($5 billion), followed by DAI ($4.3 billion) and ETH ($3.3 billion).[7] Fig. 2 Panel A shows the daily value of outstanding token deposits against ETH price. While most of the dollar value of deposits is in stablecoins, net outstanding value tracks movements in ETH price well.

The deposited tokens become part of the liquidity pool that can be loaned to users. Like its traditional money market fund counterpart, Compound follows the intermediation banking model (Kashyap et al., 2002), where loanable funds are deposited tokens minus loaned tokens. This model contrasts with how modern banks can create new money as deposits (McLeay et al., 2014). With the pseudonymity of participants in the ecosystem, lenders cannot ensure borrowers honor their obligations. Users who want to borrow must first deposit accepted tokens as collateral and maintain sufficient overcollateralization, or their pledged collateral will be foreclosed for repayment. Consequently, DeFi loans are more like repurchases than credit agreements. However, even with over-collateralization, defaults with credit loss can still occur. Details of how default risk is managed will be further explained in Section 2.4.

Each blockchain is a different information environment, and smart contracts can only perform on their native blockchain. This limitation restricts the choice of acceptable collaterals. For example, tokens that represent claims on off-chain assets such as tokenized real-world assets (for example, real estate or vehicles) present additional enforcement costs and counterparty risk, or heterogenous

[6] See Klages-Mundt et al. (2020) for the different mechanisms behind the creation and price stabilization of stablecoins.
[7] Source: https://compound.finance/markets, accessed on July 26, 2021.

Panel A: Daily net cToken outstanding in $ million



Panel B: Monthly loans originated in $ million

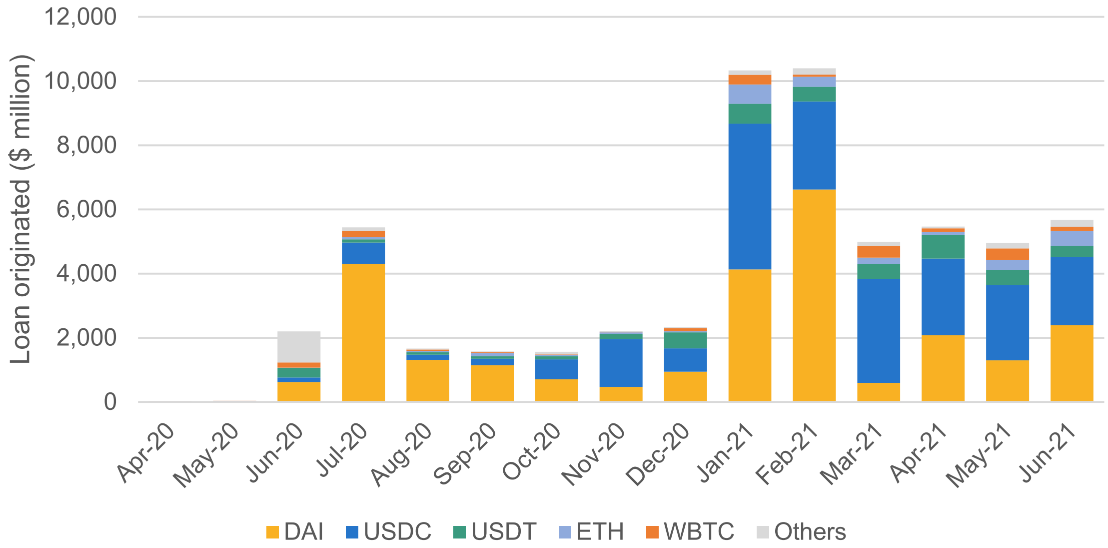


Fig. 2. Compound activities. Panel A plots the daily dollar value of outstanding token deposits between May 2019 and June 2021 and the daily ETH price (right-hand side scale). The top-five tokens are ETH, WBTC (wrapped Bitcoin), DAI, USDC, and USDT. Panel B plots the dollar value of monthly token loans drawn from cToken contracts during the same period.

tokens that represent unique claims such as virtual assets represented by non-fungible tokens, or fungible tokens which are inactively traded or are traded in limited venues are examples of less desirable collateral. Corporate finance research shows that collateral quality can influence debt contracts in various ways. For example, Benmelech and Bergman (2009) show that collateral redeployability can affect credit spreads and loan-to-value ratios. For Compound, differences in collateral quality are reflected solely in collateralization requirements, and not all crypto assets are accepted as collateral.

Fig. 2 Panel B shows the dollar value of token loans originated by Compound in each month. While loans can be drawn in any token Compound accepted as collateral, most users borrowed stablecoins, with DAI at the most popular, followed by USDC.

A governance token is a token issued by the protocol's smart contract containing voting rights. These protocol-issued tokens are sometimes called native tokens, different from native coins issued by the blockchain's software to incentivize the blockchain network's operation. For example, the governance token of Compound is known as COMP, and the contract was created on March 4, 2020, with a fixed supply of 10 million.[8] Holders of COMP can vote on protocol-related issues, such as adjusting interest rate models. Compound is backed by high-profile venture capital funds, such as Andreessen Horowitz (a16z), Polychain Capital, and Bain Capital Ventures,[9] majority holders of their governance tokens, COMP. As of July 26, 2021, the three VC firms own a combined voting power of 32.85%.[10]

Issuance of equity-like governance tokens via initial coin offering (ICO) has received interest in the past, and several papers have argued that they can be an optimal financing method for digital platform start-ups (for example, Li and Mann, 2018; Cong et al., 2021; Gryglewicz et al., 2021; Lee et al., 2022). However, while an ordinary share is a legally recognized (and often standardized) agreement that contains a bundle of economic and legal rights, a token created by a smart contract is a piece of digital information that may or may not have legal definitions. Thus, a governance token issued by different protocols may contain different rights.[11] Researchers often divide the rights of equity holders into cash flow rights and voting rights. In the case of Compound, while its business model earns more income than expenses, the surplus is retained as reserves (see Fig. 1), but there has been no detailed plan to distribute the reserves. Thus, a COMP holder is entitled to only voting rights, not cash flow rights.

While Compound is not the first protocol to reward its participants with its native token, it is often attributed as the force behind the *DeFi Summer* of 2020, where interest in DeFi began to accelerate.[12] Within one week of its launch on June 15, 2020, the price of COMP doubled. The event is said to have kickstarted the *yield farming* phenomenon where participants interact with DeFi protocols' liquidity pools by providing them with tokens (also referred to as "staking") with the expectation of receiving token rewards in return. The reward distribution rate is often presented as an annualized percentage rate and referred to as APY. Thus, the *yield* nomenclature was adopted. However, in practice, Compound would allocate a fixed quantity of COMP to a cToken contract, which would then split equally to depositors and borrowers, to be shared pro-rata. Consequently, if there are fewer borrowers than depositors, the yield for borrowers would be higher. Compound reports this yield as APY, and users are presented with these percentage rates as they interact with protocol.[13]

The brief DeFi Summer of 2020 began in June and ended in September before gaining interest again at the end of 2020. As of July 26, 2021, COMP had a circulating supply of 5,373,538.37 and had already distributed 973,535 with a current distribution rate (also referred to as "emission" rate) of 2,312 per day.[14] As of February 20, 2022, 26.7% of the supply is held in the Compound Reservoir address (treasury) and 1.39% in the Compound Comptroller address used to distribute COMP rewards.[15] Because of this design, we can infer the amount of COMP reward claimed by each address.

2.3. Compound's interest rate model

Many mathematical equations can be used to calculate interest rates (Gudgeon et al., 2020). A sustainable lending operation requires the protocol to earn enough interest from borrowers to pay depositors and perhaps keep some as reserves for default risk or profits. Because an interest rate is the price of money, one way to endogenously achieve market equilibrium of the supply and demand of tokens is to allow prices to move freely to clear the market.

In DeFi, deposit rates are often referred to as *supply rates* and lending rates as *borrow rates*. Developers can decide whether to have fixed or floating rates in their protocol. For Compound, the developers choose variable rates for both rates, eliminating interest rate mismatch risk, but some protocols offer fixed rates. For example, Aave on the Ethereum blockchain offers a choice to borrow at a fixed rate, while Anchor on the Terra blockchain fixes the supply rate.

Let i_b denote the borrow rate, i_s the supply rate, U the utilization rate, defined as outstanding loans divided by outstanding deposits plus reserve, and λ the reserve factor. We can write Compound's interest rate model as follows:

$$i_b = \begin{cases} a + bU & if U \le U^* \\ a + bU^* + c(U - U^*) & if U > U^* \end{cases} \tag{1}$$

$$i_s = i_b(1 - \lambda)U \tag{2}$$

Under this specification, the borrow rate described by Equation (1) is a kinked linear function in U with a as the base rate. As U exceeds some threshold U^* representing the optimal or target utilization rate, the slope of i_b with respect to U changes from b to c, a

[8] The contract creation event can be viewed here: https://etherscan.io/tx/0xe87715364f1733c893b4dca5c8e932627e5ddcc2076f8fc69a9d38c5563c4ed1.

[9] Source: https://fortune.com/2019/11/14/crypto-interest-startup-compound-decentralized-finance/, accessed on October 15, 2022.

[10] Source: https://compound.finance/governance, accessed on July 26, 2021.

[11] It is unclear whether the venture capital funds invested in Compound as a protocol or as a business entity. However, ownership of COMP tokens represents protocol-specific benefits rather than claims on the company that develops the protocol.

[12] Source: https://www.coindesk.com/business/2020/10/20/with-comp-below-100-a-look-back-at-the-defi-summer-it-sparked/, accessed on October 15, 2022.

[13] See https://compound.finance/governance/comp for how reward distribution and APYs are reported.

[14] Source: https://coinmarketcap.com/currencies/compound/, https://compound.finance/governance/comp, accessed on July 26, 2021.

[15] Source: https://etherscan.io/token/0xc00e94cb662c3520282e6f5717214004a7f26888#balances, accessed on February 20, 2022.

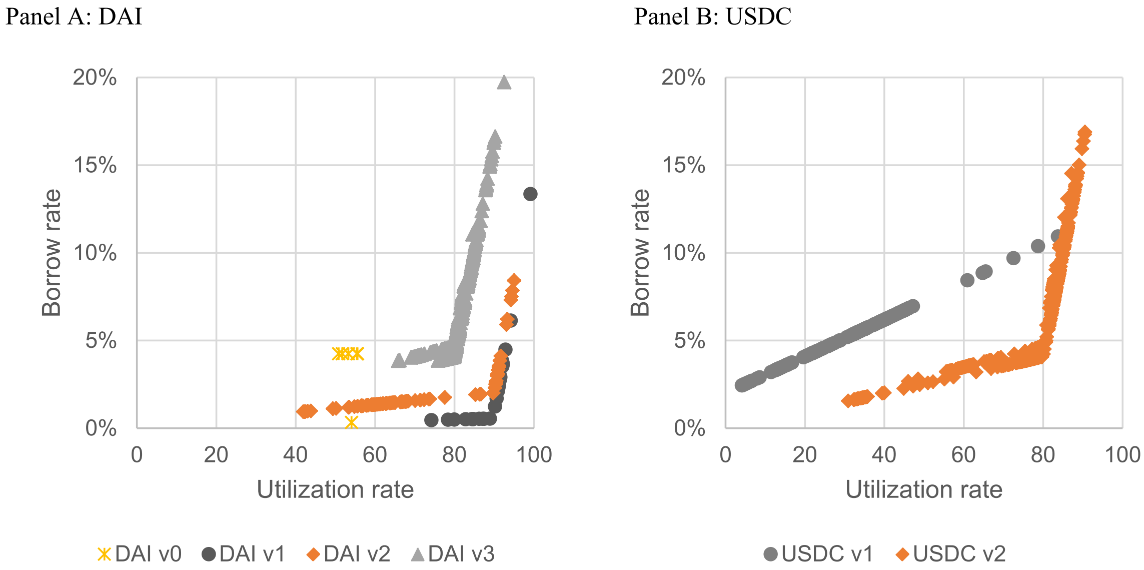


Fig. 3. The kinked interest rate model. Each panel plots the daily borrow rates for selected tokens against utilization rates as scatter plots. The utilization rate, computed as outstanding loan divided by outstanding deposit plus reserves, is plotted on the horizontal axis. Data is obtained from Compound's API. Compound uses a kinked interest rate model, where the interest rate is linear in utilization rate and the slope changes when the utilization rate reaches the optimal level. The model is applied to the borrow rate, and the supply rate is further adjusted based on the utilization rate to ensure the cToken contract generates enough interest income to pay depositors and maintains sufficient liquidity. Compound adjusts the formula interest calculation several times during its operation. Data points corresponding to different interest rate regimes are marked with different colors. During the sample, the cDAI contract operated under four different interest rate models (v0 to v4), while the cUSDC contract operated under two models (v1 and v2).

higher rate. The transaction will fail if the pool has insufficient tokens for a loan request. This increased sensitivity discourages borrowers from taking on new loans and encourages depositors to supply additional capital, ensuring that the lending operation will not halt. Because of the pseudonymity and high-speed nature of blockchain transactions, negotiation and communication between the borrower and the lender cannot be relied on, so a failed transaction in a system that is supposed to operate autonomously may cause confusion among users and induce a panic bank run (Dijk, 2017; Kiss, Rodriguez and Rosa-Garcia, 2022). To ensure continuity, protocols design the mechanism to prevent such states from occurring. For Compound, the automatic interest rate adjustment that attracts deposits and discourages loans provides that self-stabilizing mechanism.

The supply rate described by Equation (2) is moderated by U (and hence no longer linear in U) to ensure sufficient income to pay depositors. A fraction of λ (*reserve factor*) is set aside as a buffer for potential default risk or retained as profits. As the supply and demand of tokens in the pool change in each block, interest rates are adjusted accordingly.

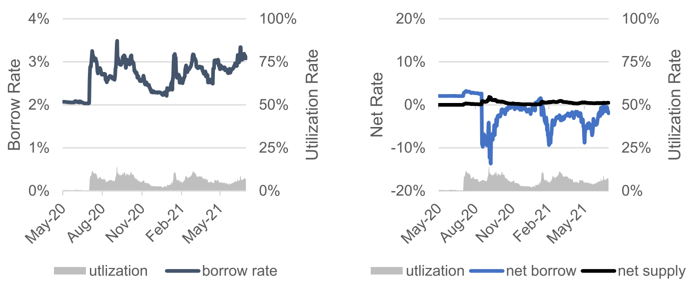
The parameters of interest rate models can be changed over time. For example, DAI underwent three changes: the first on April 7, 2020; the second on May 2, 2020; and the third on July 28, 2020. USDC underwent a single change on September 21, 2020, and USDT on August 21, 2020. The changes would be proposed to the community and voted on by COMP holders, reflecting the governance role of the token.[16] Fig. 3 plots the supply rates for DAI and USDC under several regimes marked using different colors and symbols. The distribution of data points suggests that they belong to different interest rate regimes.

Fig. 4 plots the daily rates for selected tokens computed using data obtained from Compound's API. The plots on the left show that borrow rates fluctuate with utilization rates, which is a direct consequence of the interest rate model. As Compound began distributing COMP as a reward for both suppliers and borrowers, the effective rates received and paid by users were subsidized by Compound. The plots on the right of Fig. 4 display the net borrow and supply rates, computed by subtracting or adding the COMP reward rates for each activity, making supplying tokens more lucrative and borrowing less costly.

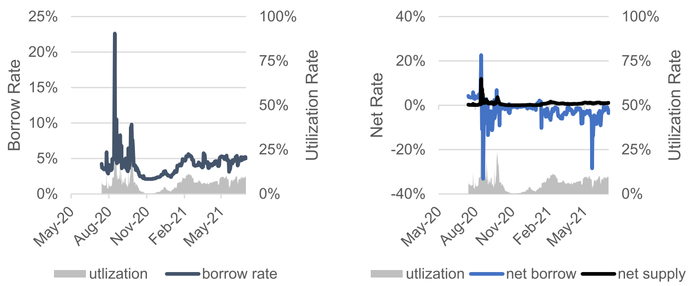
The differences between the net supply rate and the net borrow rate are mostly positive. However, the net borrow rate for tokens with low utilization rates, such as ETH and WBTC, are also mostly negative, as Compound disproportionately subsidizes borrowers by providing an equal number of COMP to be shared among suppliers and borrowers in the same cToken contract, so whenever there are fewer borrowers than suppliers, COMP borrow reward rates are higher.

[16] The first Compound governance proposal was to add USDT support. The proposal was initiated by Geoffery Hayes, the founder and CTO at Compound, on April 27, 2020, and received majority support. Details of the proposal and the votes can be found here: https://compound.finance/governance/proposals/1. The second change to the DAI interest rate model was the second proposal, proposed on April 27, 2020, and executed on May 2, 2020.

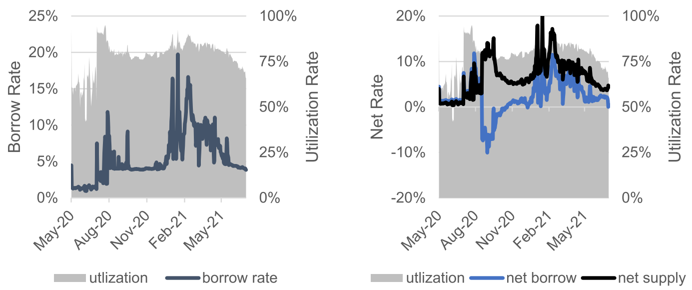
Panel A: ETH rates



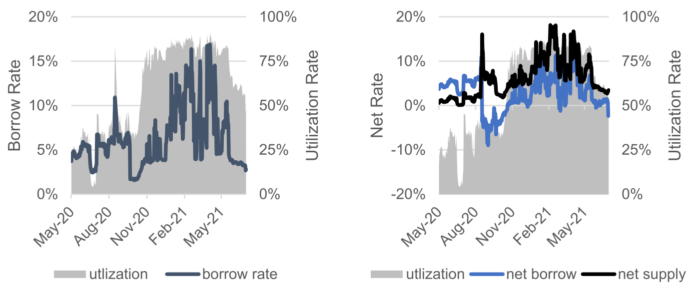
Panel B: WBTC rates



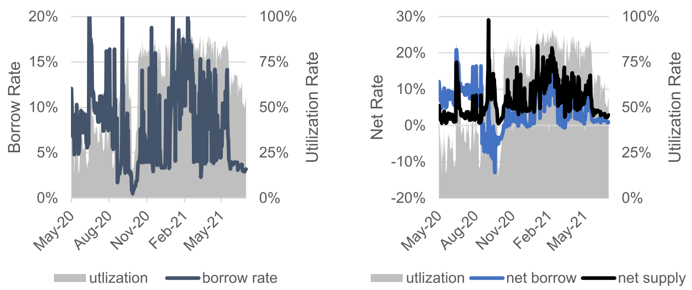
Panel C: DAI rates



Panel D: USDC rates



Panel E: USDT rates



(caption on next page)

Fig. 4. Pool interest rates and utilization rates for selected tokens. In each panel, the time series data of daily rates for selected tokens are plotted with utilization rate (computed as outstanding loan divided by outstanding deposit plus reserves). On the left, daily borrow rates are plotted against the utilization rate. Daily net borrow and net supply rates (computed by subtracting or adding the COMP reward rates for each activity) are plotted against the utilization rate on the right. Data is obtained from Compound's API.

2.4. Compound's loan liquidation

Because borrowers are pseudonymous, credit risk assessment cannot be reliably made on information related to the borrower, so the most helpful discriminant is the collateral quality. Thus, credit risk management must rest entirely on the foreclosure of collateral because the borrower is not reachable.

Compound calculates each borrower's credit line (the "borrow limit") using the following logic. Let $\left(1-\gamma_j\right)$ be the collateral factor for token j, Q_j the amount of deposited token collateral and P_j the price of token j. Token prices may vary according to trading venues, some of which are not reflected on the blockchain. A set of codes, known as a price oracle or a blockchain oracle, can import external (off-chain) data. The oracle will specify the data source(s), and the final price used for calculation may involve processing such as averaging across sources or time.

The dollar value of the outstanding loan drawn in token i must be within the borrow limit $\sum_j(1-\gamma_j)P_jQ_j$, computed across all cToken deposits. Some protocol calculates the borrow limit based on one token only. In that case, it would be known as a single-collateral protocol. The multi-collateral protocol design of Compound allows for greater diversification. Because scheduled payment is not required to minimize gas cost, γ_j is set to ensure that the borrower can maintain the ability to repay, while the smart contract's ability to enforce transactions automatically ensures the borrower's willingness to pay. If P_j is volatile, γ_j for that token may be set to a higher rate, reflecting the heterogeneity in collateral quality as discussed earlier. For example, as of September 13, 2021, $\gamma_{DAI}=25\%$ (or alternatively, $(1-\gamma_{DAI})=75\%$), while $\gamma_{COMP}=40\%$.

Let L_i be the quantity of loan drawn in token i and P_i the price of token i (which could, in principle, be the same as some j; in other words, one could borrow the same token as the collateral). At any point in time, the borrower must ensure that Inequality 3 holds and the ability to satisfy this condition depends on the relative movements between P_i and P_j.

$$\sum_j(1-\gamma_j)P_jQ_j - P_iL_i > 0 \tag{3}$$

Compound refers to the expression on the left-hand side of Inequality 3 as *account liquidity*, which, when negative, permits third-party users to partially repay the loan on the borrower's behalf and receive a share of the borrower's overcollateralized tokens. Without gas cost, this transaction would likely be profitable unless collateral prices change sharply over a short horizon. However, because gas cost does not vary according to transaction value, it is possible that small loans are not liquidated because arbitrage profits are not sufficient. To ensure that liquidators are sufficiently motivated, Compound adds liquidation incentives to make liquidation more profitable. During the sample period, Compound was operating under v2, and the incentive was paid from excess collateral from the liquidated accounts and shared between Compound's reserves and the liquidator. In Compound v3, the accumulated reserves can now be used to subsidize the liquidation of undercollateralized positions. Fearing liquidation, borrowers tend not to draw loans up to their total credit limits, making them highly overcollateralized.

It is worth noting that Compound can design a mechanism that centralizes the ability to liquidate to trusted authorities (like its developers). However, Compound does not proactively monitor and manage the credit risk of its loan positions. Instead, it outsources the task to liquidators, allowing users to participate in as many aspects of the protocol as possible.

Because of the collateral factors in Inequality 3, liquidation is allowed when the loan is still comfortably overcollateralized. Consequently, Compound ultimately faces little to no credit risk. Only a severe drop in P_j or a sharp rise in P_i would threaten Compound with credit loss. More technical details of how Compound's liquidation mechanism works are explained by Perez et al. (2020). The combination of cToken design, self-stabilizing interest rates, selective permissible collateral, and account liquidity requirements reduce Compound's asset-liability mismatch risk.

With the account liquidity in Inequality 3 and the net rates example for ETH from Fig. 4, users can use a long-short strategy of the same token to earn arbitrage profit and never be liquidated. Inequality 3 can be viewed as a degree of asset-liability mismatch, so the mismatch is eliminated when both the collateral (asset) and borrowed token (liability) are the same. The borrowed token can be redeposited as collateral, and this process can be repeated without fear of liquidation risk. By receiving the yield from the COMP reward, this position can earn a positive return even when the net cost of leverage is positive (and there were many periods when the net cost of leverage was negative). This recursive strategy allows the user to increase leverage beyond the collateral factor, making the position appear undercollateralized relative to the initial position.[17]

[17] In late 2021, Abracadabra.Money protocol was built to automate this repeated leverage process. The protocol uses interest-bearing, stablecoin-like depository receipt (similar to cDAI) as collateral to their stablecoin loans issued as native tokens called Magic Internet Money (MIM). This makes Abracadabra operate more like credit creation banking (McLeay et al., 2014) since MIM "deposits" are issued by the protocol, while Compound lends the tokens received as deposits, making it operate more like intermediary banking with deposits as optimal security with high liquidity (Gorton and Pennacchi, 1990). But while this recursive interaction can quickly increase funds locked in the protocol, it could promptly unravel in a bank run-like fashion when trust in the collateral value is lost, as Saengchote et al. (2022) documented.

Table 1

Summary statistics. Panel A reports the summary statistics of daily net deposits (deposits minus withdrawals) between May 2019 and June 2021 by token. During this period, Compound accepts twelve tokens. The dollar values are calculated using daily prices obtained from CoinGecko. DAI, TUSD, USDC, and USDT are classified as stablecoins, and other tokens are broadly classified as cryptocurrencies (cryptos). Panel B reports the summary statistics for daily token loans drawn from the twelve cToken contracts during the same period. Finally, panel C reports the summary statistics of the supply rate, borrow rate, supply reward, borrow reward, and utilization rate.

Panel A: Daily net deposits in $ million

	Average	Std Dev	Min	P5	P50	P95	Max
cETH	0.00	0.03	−0.12	−0.06	0.00	0.06	0.12
cWBTC	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cBAT	1.71	13.32	−14.46	−3.84	0.00	5.84	99.10
cCOMP	0.00	0.01	−0.03	−0.01	0.00	0.02	0.05
cLINK	0.08	0.26	−0.14	−0.11	0.00	0.67	1.24
cREP	0.00	0.05	−0.28	0.00	0.00	0.00	0.26
cUNI	0.05	0.55	−1.42	−0.61	−0.01	0.93	3.03
cZRX	0.11	1.71	−6.19	−1.54	0.00	1.64	9.76
cDAI	6.53	108.43	−491.10	−122.97	4.42	143.71	348.64
cUSDC	9.43	114.68	−439.27	−70.20	3.16	100.62	611.14
cUSDT	0.81	15.99	−56.73	−20.40	0.01	26.08	64.33
cTUSD	3.03	12.79	0.00	0.00	0.00	30.69	59.50
All	13.20	214.80	−2,125.02	−224.94	13.06	204.12	954.97
Stablecoins	12.63	212.91	−2,126.06	−219.77	10.30	195.69	956.14
Cryptos	0.57	58.30	−990.28	−4.58	0.02	6.66	537.09

Panel B: Daily token loans drawn in $ million

	Average	Std Dev	Min	P5	P50	P95	Max
cETH	5.46	19.00	0.00	0.01	0.79	19.00	200.42
cWBTC	4.41	15.12	0.00	0.00	0.22	20.97	156.48
cBAT	2.21	15.54	0.00	0.00	0.00	6.14	278.13
cCOMP	0.48	3.51	0.00	0.00	0.00	1.20	47.93
cLINK	0.20	1.08	0.00	0.00	0.00	0.23	9.63
cREP	0.64	6.80	0.00	0.00	0.00	0.01	108.86
cUNI	1.16	6.31	0.00	0.00	0.00	4.82	105.04
cZRX	0.19	1.78	0.00	0.00	0.00	0.26	29.06
cDAI	62.53	203.45	0.00	0.04	9.07	263.93	1,792.90
cUSDC	50.22	160.93	0.00	0.04	8.88	162.81	1,515.29
cUSDT	10.40	21.06	0.00	0.00	3.86	50.24	185.71
cTUSD	0.23	3.88	0.00	0.00	0.00	0.09	80.00
All	138.12	299.88	0.05	0.54	47.61	578.01	3,096.37
Stablecoins	123.37	294.82	0.02	0.22	37.81	553.65	3,066.71
Cryptos	14.75	35.23	0.00	0.04	3.45	82.64	341.39

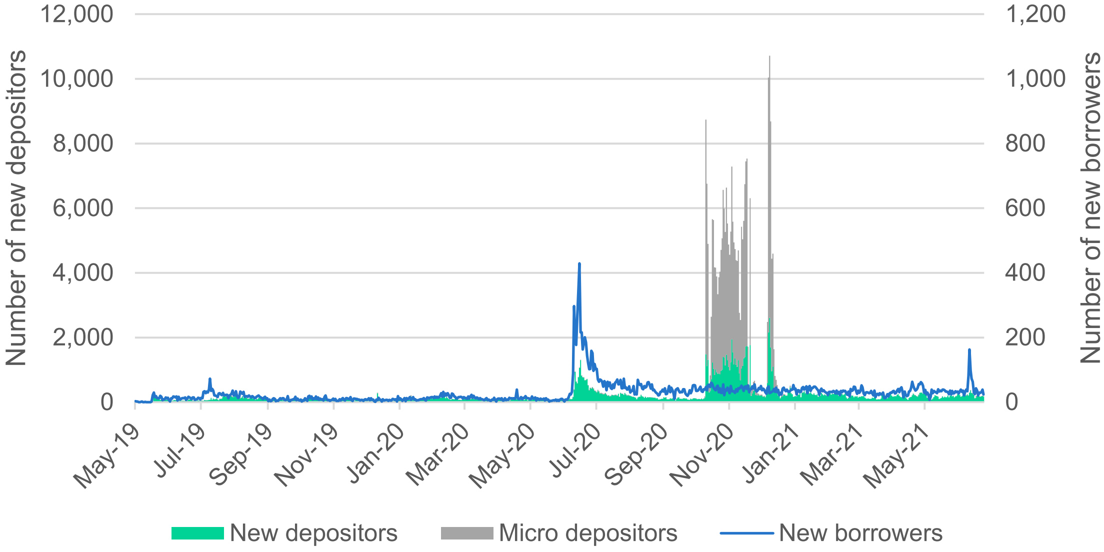
Panel C: Rates and utilization in percentages

	Supply Rate		Borrow Rate		Supply Reward		Borrow Reward		Utilization Rate	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
cETH	0.13	0.08	2.65	0.35	0.27	0.27	4.27	3.47	5.55	3.12
cWBTC	0.29	0.71	4.11	1.72	0.44	0.47	6.31	4.36	6.47	5.25
cBAT	1.46	3.76	6.83	6.60	1.30	1.94	7.96	22.12	14.28	19.26
cCOMP	1.98	3.83	8.69	5.92	2.35	1.41	10.31	5.33	25.43	10.99
cLINK	1.52	2.78	7.63	4.33	3.64	5.76	15.53	6.93	19.48	14.87
cREP	0.01	0.07	10.27	8.12					24.04	23.58
cUNI	1.24	2.15	7.53	4.57	0.77	0.45	7.04	4.22	15.76	13.10
cZRX	1.63	1.51	9.87	3.19	1.07	0.90	4.92	3.88	24.03	10.00
cDAI	3.96	2.50	5.52	3.34	2.59	2.26	3.22	2.83	78.35	9.03
cUSDC	3.84	3.08	6.17	3.18	2.12	1.61	3.27	2.90	60.03	24.80
cUSDT	4.70	3.94	7.74	4.49	2.07	1.86	2.90	2.65	64.15	23.41
cTUSD	0.48	1.02	1.13	1.35					19.47	23.18

Data oracles present a potential source of risk (as highlighted in the case of Iron Finance in Saengchote, 2021a), and there are service providers specialized in building trust in the data import process. A mistake can ultimately be exploited, and the protocol can do little to stop it. For example, suppose the data oracle references a price feed from an illiquid market. In that case, a malevolent user can manipulate the price of a token used as collateral to artificially increase the borrow limit and drain a lending pool of its loanable funds. The borrower would be liquidated, but the repossessed collateral would be worth less than the drawn loans. This vulnerability is another reason a protocol's developer may restrict the choice of tokens permissible as collateral.

Thus, Compound does not take on any interest rate or asset-liability mismatch risk and faces minimal credit risk. In a traditional business sense, Compound's developers need not put any equity into their lending business since depositors fully fund loans. With variable claims directly tied to the lending income, Compound can be considered a mutual lender, where depositors mutually own the

Panel A: New depositors and borrowers



Panel B: Cumulative depositors and borrowers

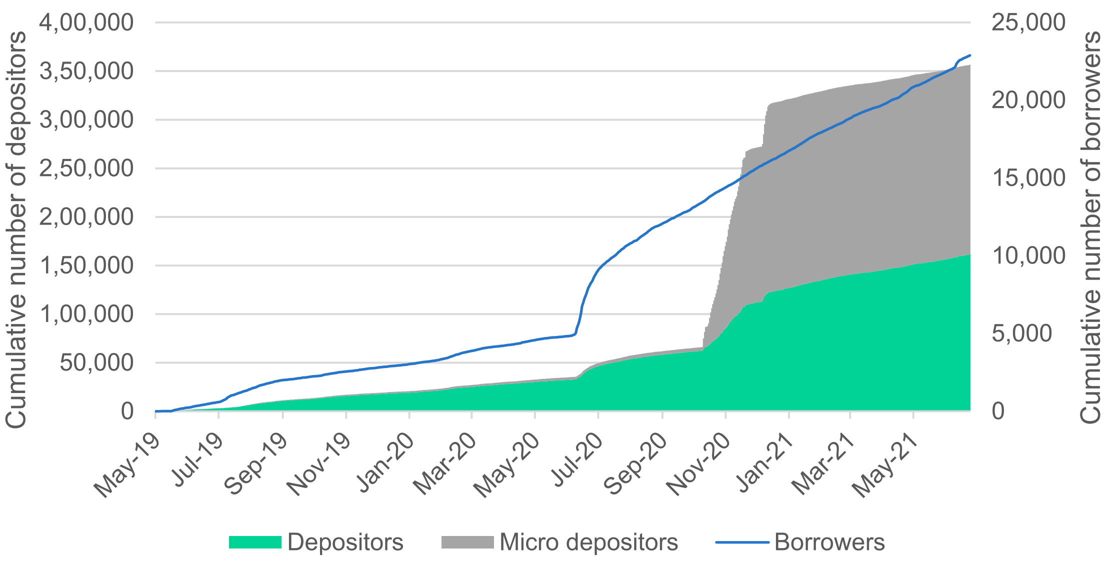


Fig. 5. User acquisition timeline of Compound. Panel A plots the number of new unique addresses that deposit tokens into or take loans out of cToken contracts each day. Of 356,800 addresses, there are about 195,200 addresses that made exactly one stablecoin deposit of $3 or less, with 183,000 addresses that made precisely a $3 deposit. The addresses are classified as micro depositors and are excluded from the address-level analysis. About 161,500 depositors and 22,300 borrowers are in Compound over the sample period. Figure B plots the number of users on a cumulative basis.

economic benefits of the protocol. This model resembles how a mutual insurance company (where policyholders share ownership and benefits) operates.

3. Data and empirical methodology

3.1. Data

The Ethereum blockchain data used in this paper is obtained from Google BigQuery, hosted and listed on Google Cloud Marketplace. We retrieve Compound's transactions between May 2019 and June 2021, covering over 8 million deposits, 3.56 million withdrawals, 0.16 million loan draws, 0.13 million loan repayments, and 5,036 liquidations of 356,800 unique addresses. The Ethereum blockchain's information unit is an address that can be used as a container of tokens or programmed as a smart contract, as described in Section 2.1. While blockchain addresses are designed to be anonymous, owners of public smart contracts typically identify themselves and provide their source codes for community audit on websites such as Etherscan.io to increase their credibility. However, this is not mandatory, and many smart contracts are unintelligible to a human reader. While blockchain content is transparent, it is in binary data that cannot be easily parsed and reverse-engineered.

Most private addresses are not identified or labeled by Etherscan.io, so researchers must make judgment calls on classifying them. First, we manually inspect the content of each address to classify whether it is part of a DeFi protocol, an unidentified smart contract, or a simple address. For example, the address '0x5d3a536E4D6DbD6114cc1Ead35777bAB948E3643′ is the Compound DAI (cDAI) contract that accepts DAI for cDAI from depositors and lends out DAI to borrowers.

Because of the laborious nature of the task, we classify only some of the addresses. For each transaction, we observe the source and target of the token transfer. We inspect the top 100 sources and targets of the twelve cToken contracts based on the token amount and transaction frequencies, resulting in 466 manually identified addresses. They are divided into seven categories: (1) large address, (2) small address, (3) yield aggregator protocol, (4) on-ramp, (5) decentralized exchange protocol, (6) asset management protocol, and (7) unidentified contract.

Large addresses do not contain any programming code and do not belong to an identified protocol. Further, smart contracts of protocols are classified according to the criteria described in the Appendix. Other remaining addresses are classified as small addresses. We supplement the token transaction data with states of cToken contracts, such as interest rates retrieved from Compound's API and token price data from CoinGecko's API. In analyses at daily frequency, a day begins at midnight of Coordinated Universal Time (UTC). The net deposits are aggregate token flows to and from cToken contracts. The dollar value of token transactions is obtained by multiplying the token quantity by the daily token prices obtained from CoinGecko's API.

Table 1 reports the aggregate summary statistics from May 2019 to June 2021 of daily net deposits (deposits minus withdrawals) and daily token loans drawn in $ million in each of the twelve cToken contracts. DAI, USDC, USDT, and TUSD are classified as stablecoins, and other tokens which are diverse in their purposes are broadly classified as cryptocurrencies for simplicity.[18] Most of the activities in both deposit and lending are in stablecoins, corresponding to the pattern observed in Fig. 2. While average daily net deposits are small, with medians close to zero, the maximum and minimum values can be very high. For loans, stablecoins are more popular, with as much as $3 billion in stablecoin loans drawn in one day.

Transaction-level data retrieved from the Ethereum blockchain allows us to glean further insights into the behaviors of different types of users. However, before providing summary statistics of the 356,800 addresses that interacted with Compound, we find that approximately 195,200 addresses made exactly one stablecoin deposit of $3 or less, with 183,000 addresses depositing precisely $3. Therefore, we classify these addresses separately as *micro addresses*. Fig. 5 plots the numbers of new depositors and borrowers between May 2019 and June 2021. The spike in the number of new micro addresses began in October 2020 and again in December 2020, and there was no noticeable change in new borrower addresses around those dates.

The micro addresses do not further interact with Compound and leave their funds deposited throughout the sample period. Our best conjecture regarding these peculiar interactions is that the addresses were created in anticipation of COMP token distribution from Compound as a reward for interacting with the protocol. In September 2020, Uniswap (a decentralized exchange protocol that operates by requiring users to participate as market makers by depositing tokens into liquidity pools) began distributing UNI, its governance token. Users who provided liquidity to the protocol before the distribution date would receive at least 100 UNI, priced at $3.50 soon after the distribution.[19] This reward mechanism is known as an "airdrop" in the DeFi community, and the airdrop of UNI was an unanticipated but welcomed surprise for Uniswap's users.

Around the same time, users on Compound's community discussion board began discussing whether COMP should also be distributed as an airdrop,[20] and again in late November,[21] which coincides with the spike in micro addresses' activities. Because blockchain allows new addresses to be freely generated, these 195,200 micro addresses could belong to a much smaller number of users who essentially hold free real options on airdrops with little downside risk because of the stablecoin deposit. Compound has yet

[18] ETH and WBTC are native coins of the Ethereum and Bitcoin blockchain, BAT and LINK are cryptocurrencies/utility tokens of Brave (web browser) and Chainlink (blockchain oracle), and COMP and UNI are governance tokens of Compound and Uniswap.

[19] Source: https://www.coindesk.com/markets/2020/09/17/uniswap-recaptures-defi-buzz-with-uni-tokens-airdropped-debut/, accessed on October 15, 2022.

[20] Source: https://www.comp.xyz/t/distribution-of-comp-token-to-early-users-pre-comp-distribution-period/, accessed on October 15, 2022.

[21] Source: https://www.comp.xyz/t/should-compound-retroactively-airdrop-tokens-to-early-users/595, accessed on October 15, 2022.

Table 2
Summary statistics of Compound users. Panel A reports the summary statistics of cToken deposits by address type. Address type classification methodology is outlined in the Appendix. While more than 356,800 unique addresses made deposits, there are about 195,200 addresses that made exactly one stablecoin deposit of $3 or less, with 183,000 addresses that made precisely $3 deposits identified in Fig. 5. These addresses are excluded from our analysis. Total deposits by address type in $ million, average deposits per address in $ million, and median deposits in $ are reported. For each address type, the share of addresses that only made stablecoin deposits and addresses that have at least once deposited ETH or WBTC – the two most popular cryptocurrencies – are reported. Panel B reports the number of unique addresses borrowed via cToken contracts, the number of closed loans by token type, and the dollar value of loans in $ million. A closed loan is defined by a complete borrow-repayment cycle for each address; a closed loan can include more than one drawdown and repayment. The average dollar value in $ million and the average duration in days are also reported.

Panel A: Depositors.

	Total deposits ($ m)	Number of unique addresses	Av. depositsper address ($ m)	Standard Deviation ($ m)	Median value of deposits ($)
Large address	50,725.9	256	198.1	467.3	46,700,000
Small address	26,712.8	161,103	0.2	2.2	92
Yield aggregator	13,018.8	41	317.5	737.7	30,100,000
On-ramp	5,852.2	32	182.9	771.5	11,600,000
Decentralized exch.	3,305.3	14	236.1	476.4	36,800,000
Asset management	721.1	14	51.5	139.5	4,618,128
Unidentified contract	66,226.5	109	607.6	3,922.1	16,400,000
All types	166,562.5	161,569			

	Share of deposits (dollar)	Share of addresses (number)	Deposited stablecoins only	Deposited ETH	Deposited WBTC
Large address	30.5%	0.2%	11%	75%	49%
Small address	16.0%	99.7%	40%	49%	4%
Yield aggregator	7.8%	0.0%	61%	24%	15%
On-ramp	3.5%	0.0%	31%	66%	25%
Decentralized exch.	2.0%	0.0%	50%	50%	43%
Asset management	0.4%	0.0%	29%	14%	14%
Unidentified contract	39.8%	0.1%	25%	60%	35%

Panel B: Borrowers.

	Number of unique addresses	Stablecoin loans (num)	Crypto loans (num)	All loans (num)	Stablecoin loans ($ m)	Crypto loans ($ m)	All loans ($ m)
Large address	217	1,441	614	2,055	28,659.5	3,762.6	32,422.1
Small address	21,986	32,220	12,230	44,450	8,164.3	1,912.9	10,077.2
Yield aggregator	8	55	60	115	4,224.7	145.9	4,370.6
On-ramp	24	4,062	973	5,035	2,026.6	425.6	2,452.2
Decentralized exch.	1	7		7	3.8		3.8
Asset management	2	2		2	256.6		256.6
Uniden. contract	51	796	310	1,106	11,345.3	5non-st14.8	11,860.0
All types	22,289	38,583	14,187	52,770	54,680.7	6,761.9	61,442.6

	Average value of loans ($ m)			Average loan duration (days)		
	Stable	Crypto	All	Stable	Crypto	All
Large address	19.89	6.13	15.78	23.6	15.2	21.1
Small address	0.25	0.16	0.23	40.6	26.6	36.7
Yield aggregator	76.81	2.43	38.01	2.4	2.9	2.7
On-ramp	0.50	0.44	0.49	0.6	0.3	0.6
Decentralized exch.	0.54		0.54	0.0		0.0
Asset management	128.32		128.32	81.6		81.6
Uniden. contract	14.25	1.66	10.72	9.0	6.5	8.3
All types	1.42	0.48	1.16	33.8	23.2	31.0

to distribute any airdrop, but the real option does not have a maturity date in this context. Coupled with the rapid rise in ETH price from around $350 in October 2020 to more than $1,000 by January 2021 and more than $4,000 by May 2021, the gas cost of transferring the stablecoins out of the addresses likely exceeds the option value of leaving their tokens with the protocol. Fig. 5 suggests that such practice was no longer widespread by mid-2021.

Because of exceptional circumstances surrounding the micro addresses and the small dollar contribution, we exclude them from our analyses. Table 2 presents the summary statistics of the remaining 161,569 addresses, classified into seven categories described earlier.

Small addresses account for 99.7% of all addresses but only 16% of the dollar value deposited, while the 256 large addresses (0.2%) account for 30.5% of the dollar value deposited. Smart contracts that are part of DeFi protocols tend to make more significant deposits, but 109 unidentified contracts account for most deposits and have the highest average deposits per address. As posited in the Appendix, using smart contracts suggests a higher level of sophistication than simple addresses. The average transaction size suggests they may belong to large investors such as crypto hedge funds. The top 100 addresses account for 75% of all deposits, which is more concentrated than the traditional financial system. For context, Juelsrud (2021) finds that the top 5% of depositors in Norway in 2018 accounted for 53% of all deposits, while OECD data shows that the top 5% of US households owned 68% of total wealth in 2018.[22]

There are 22,289 unique addresses for borrowers, with 52,770 closed loans. This complete borrow-repayment cycle allows us to calculate loan duration. Most of the dollar value comes from the 217 large addresses, followed by the 51 unidentified contracts. 89% of the loans are drawn in stablecoins, and the top 100 addresses account for 78% of all loans. The average loan duration is 31 days and longer for stablecoins (33.8 days) than cryptocurrencies (23.2 days). Large addresses tend to borrow for a shorter duration than small addresses, and asset management protocols have the highest average loan value and most extended duration. The asset management protocols in this sample operate like exchanged traded funds (ETFs), borrowing USDC for leverage, so the duration is consistent with usage.

Yield aggregators have the second-highest average loan value but the shortest duration. Larger loan size benefits from economies of scale for gas cost, reducing the friction from fixed adjustment costs and providing greater flexibility in investment strategies. However, their short loan duration may result from yield farming rewards that become less lucrative as pool size increases. For example, an analysis in mid-2021 by Nansen, a DeFi analytics service, finds that 42% of users who entered a liquidity pool on the first day of its launch exited within the first 24 h. By the third day, 70% would have withdrawn from the pool.[23] For yield aggregators built to automate these strategies, their demand for leverage is likely to be more transient, which also likely applies to large addresses.

The summary statistics for unidentified contracts are closer to yield aggregators than large addresses. Their durations are shorter for the remaining 11% of the loans in cryptocurrencies. Overall, the short loan durations make it more likely that Compound loans are used for leveraged investment strategies rather than traditional purposes such as financing.

3.2. Hypothesis development and empirical methodology

As discussed in Section 2.2, Compound follows the intermediation banking model that connects depositors and lenders via mathematical equations. Therefore, our first and most basic hypothesis is that users respond to interest rates algorithmically determined by the interest rate model and automatically enforced by smart contracts.

H1: Demand for deposits and loans in Compound is influenced by supply and borrow rates.

For daily net deposits (deposits minus withdrawals, which represent net inflows), the variable could be negative, representing net withdrawals. Thus, the dependent variable is measured in $ million, as reported in Table 1 Panel A. The primary determinant is the lagged supply rate (*SupplyRate*) described in Equation (2). Rate variables need to be lagged because they are, in turn, determined by the utilization rate, which depends on the net flows into and out of the cToken contracts, leading to reverse causality.

We control for the size of the cToken contract with the log of deposits and the three variables for market conditions: past 1-day return (price change), past 7-day return, and past 30-day volatility of the crypto market, represented by the vector X_t. The correlations between ETH and other tokens are between 0.73 and 0.92, while the correlation between ETH and BTC is 0.80. Because the dominant deposited tokens are stablecoins, ETH and WBTC, and the protocol is built on the Ethereum blockchain, we use ETH-based control variables only to avoid multicollinearity.

Compound started distributing COMP on June 15, 2020, to promote the protocol. Two weeks after the introduction, Compound team was "surprised by how powerful the impact of the distribution was on incentives, and so was the community,"[24] which is corroborated by a sharp rise in borrowing activities, as illustrated in Fig. 3. To analyze how users' sensitivity to supply and borrow rates are affected, we include an interaction term to allow the coefficients on lagged supply rate to change after COMP distribution and include lagged COMP distribution reward for suppliers (*SupplyReward*) computed as annual percentage rate (APY) in the regression. For periods prior to COMP distribution, SupplyReward takes a value of zero. If borrowers are attracted by COMP distribution, the coefficient on SupplyReward should be positive.

H2: Demand for deposits and loans in Compound is influenced by COMP reward distribution.

The daily net deposit regression follows Equation (4), where the subscript *i* for cToken *i* is suppressed for brevity. Finally, standard errors are estimated using the Newey-West procedure with a one-day lag to control for serial correlation in the data.

$$NetDeposit_t = \alpha + \beta_0 Post_{t-1} + \beta_1 SupplyRate_{t-1} + \beta_2 Post_{t-1} \times SupplyRate_{t-1}$$

$$+ \beta_3 SupplyReward_{t-1} + \beta_4 \log(PoolSize_t) + \gamma X_t + \varepsilon_t \tag{4}$$

Stablecoins offer a more stable store of wealth in nominal dollars during uncertain times, which can lead to increased demand similar to flight to safety (Baele et al. 2020). We refer to this as the safety demand hypothesis. Under the safety demand hypothesis, we should observe a positive relationship between net deposits and past 30-day volatility.

H3: During periods of high volatility, demand for stablecoin deposits increases.

We repeat similar analyses for token loans, replacing the supply rates with borrow rates (*BorrowRate*, described in Equation (1), and *BorrowReward*) and the dependent variable with the log of 1 plus loan amount since all values are non-negative. The loan regression

[22] Source: OECD Wealth Distribution Database (WDD), https://stats.oecd.org/Index.aspx?DataSetCode=WEALTH, accessed on October 15, 2022.
[23] Source: https://www.nansen.ai/research/all-hail-masterchef-analysing-yield-farming-activity, accessed on October 15, 2022.
[24] Source: https://www.coindesk.com/tech/2020/06/30/compound-changes-comp-distribution-rules-following-yield-farming-frenzy/, accessed on October 15, 2022.

Table 3
Determinants of net deposits. This table reports the result from the regressions of daily net deposits (deposits minus withdrawals) in $ million between May 2019 and June 2021 for the 12 accepted tokens. In columns 1 to 8, the results for cryptocurrencies are reported, followed by stablecoins from columns 8 to 12. Explanatory variables include lagged supply rate, its interaction with an indicator for periods post COMP distribution, lagged supply COMP reward rate, the log dollar value of deposits in $ million, 1-day ETH return, 7-day ETH return, and 30-day ETH volatility (measured in percentage point). Standard errors are computed using the Newey-West procedure with a one-day lag and reported in parenthesis. Stars correspond to the statistical significance level, with *, **, and *** representing 10%, 5%, and 1%, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
VARIABLES	cETH	cWBTC	cBAT	cCOMP	cLINK	cREP	cUNI	cZRX	cDAI	cUSDC	cUSDT	cTUSD
Post COMP distribution	−6.63	5.62*	0.257			−0.401***		0.051	−34.31	−18.46	2.95	
	(5.90)	(2.90)	(0.440)			(0.130)		(0.380)	(28.28)	(14.42)	(2.69)	
Lagged supply rate	−14.35	1.80***	0.685***	0.024	−1.98	−1.96***	−0.110	−0.021	−7.14	−2.86	1.88**	5.00
	(19.36)	(0.260)	(0.180)	(0.020)	(1.33)	(0.360)	(0.690)	(0.120)	(5.43)	(2.21)	(0.880)	(8.85)
Post * lagged supply rate	63.72	4.74	−0.780***					−0.185	11.14*	4.80	−0.978	
	(59.98)	(6.12)	(0.230)					(0.200)	(6.29)	(3.45)	(0.910)	
Lagged supply reward	1.11	−3.66	0.168*	0.312*	1.00		1.22	0.124	2.10	7.55	0.017	
	(13.21)	(4.08)	(0.10)	(0.18)	(0.66)		(1.46)	(0.080)	(3.29)	(5.84)	(0.410)	
log(pool size)	−0.002	−0.00	−0.006	−0.006*	−0.064	−0.020**	−0.002	−0.001	−0.005	−0.004	−0.009	−0.408
	(0.000)	(0.000)	(0.010)	(0.000)	(0.060)	(0.010)	(0.010)	(0.000)	(0.010)	(0.010)	(0.010)	(0.270)
ETH return (1d)	20.76	−64.07	−3.94	−6.89	2.18	−0.646	−20.69	−0.792	18.97	−40.55	−33.13*	−25.71
	(52.57)	(39.26)	(2.58)	(6.31)	(16.61)	(0.480)	(16.18)	(1.00)	(133.04)	(144.62)	(17.55)	(34.90)
ETH return (7d)	5.28	28.40	0.444	−2.50	3.98	−0.439**	2.40	0.661	87.13	−7.18	8.32	−4.02
	(25.61)	(19.84)	(1.15)	(2.07)	(14.09)	(0.170)	(3.19)	(0.690)	(64.69)	(72.60)	(7.77)	(7.19)
ETH SD (30d)	−27.53	−42.44	−0.408	3.20	65.29	−1.68	21.79	−0.300	−15.07	31.84	86.10	−279.81
	(225.17)	(152.05)	(6.56)	(14.35)	(44.16)	(1.12)	(34.25)	(3.48)	(392.15)	(501.76)	(59.86)	(415.90)
Constant	3.78	−1.21	0.06	0.145	0.087	0.506***	−1.205	0.231	21.91	5.06	−8.94***	51.60
	(9.12)	(5.27)	(0.490)	(0.530)	(4.46)	(0.170)	(1.74)	(0.280)	(19.30)	(19.24)	(2.88)	(40.23)
Observations	426	351	426	256	39	426	270	426	426	426	425	40
Adj R-squared	−0.007	−0.010	0.305	0.053	−0.070	0.041	−0.006	−0.010	0.008	−0.008	0.080	0.217

follows Equation (5). For both net deposits and loans, rather than aggregating the tokens into two broad categories or relying on a panel data estimation technique, we separate each token and analyze the data as time series because their underlying properties and roles in the DeFi ecosystem are different, so the sensitivities and determinants can be different.

$$\log(1+Loan_t) = \alpha + \beta_0 Post_{t-1} + \beta_1 BorrowRate_{t-1} + \beta_2 Post_{t-1} \times BorrowRate_{t-1} + \beta_3 BorrowReward_{t-1} + \beta_4 \log(PoolSize_t) + \gamma X_t + \varepsilon_t \tag{5}$$

The loan demand in DeFi could be driven by (1) idiosyncratic demand for liquidity without necessitating a sale that triggers capital gains tax, (2) demand for leverage for long positions in cryptocurrencies, (3) demand for shorting via repurchase agreement, or (4) demand for yield farming. For channels (1) and (2), loan demand would be higher in bullish market conditions, and they would more likely be drawn in stablecoins. For channel (3), loans would more likely be drawn in cryptocurrencies since token depreciation would lower borrowing costs, and demand would be higher in bearish market conditions. For channel (4), loan demand would be responsive to the borrow reward rate.

Without detailed financial positions of each borrower, it is difficult to discern the demand channels, except for yield farming, where we can gain more accurate insights. Because Compound offers internal yield farming opportunities, we can identify them by looking for users who redeposit borrowed tokens to Compound to recursively earn COMP, which is possible with blockchain transaction data.

For loan demand, ETH's volatility has a different interpretation. Most cryptocurrencies exhibit positive co-movements, so stablecoin loans will likely face the most liquidation risk. While we cannot observe the token collaterals that back each loan, if one assumes that borrowers are more likely to rely on cryptocurrencies as collateral than stablecoins, then when ETH's price is more volatile, borrowers would be less likely to borrow in stablecoins. Consequently, we expect a negative coefficient on ETH's past 30-day volatility.

H4: During periods of high volatility, demand for stablecoin loans decreases.

We further investigate yield farming via the long-short arbitrage strategy described in Section 2.4, where borrowers would redeposit their borrowed tokens into the cToken contract, observable in the data. In addition to univariate analyses, we fit a logistic regression of redeposits on the same control variables, adding the log of loan size and fixed effects for each address type. The regressions are estimated for the top five tokens in dollar value: ETH, WBTC, DAI, USDC, and USDT, and standard errors are clustered by addresses.

4. Results

4.1. Determinants of net deposits and loan demand

Fig. 5 shows that COMP distribution might affect the demand for deposits and loans as new borrowers and depositors joined after June 15. To investigate the hypotheses more systematically, we turn to the multivariate regressions. The result of each cToken contract is displayed in a separate column, beginning with the eight cryptocurrencies, followed by the four stablecoins.

Table 3 reports the determinants of net deposits. The adjusted R-squared values are close to zero or negative for most tokens. There is no clear pattern across the tokens, corroborating the view that tokens are heterogeneous assets. Net deposits are only positively related to supply rates for WBTC, BAT, and USDT, while the relationship is negative for REP. This lack of pattern is true even for stablecoins, as each stablecoin can serve a different role in the DeFi ecosystem.

The introduction of COMP reward also seems to have minimal effect, with only BAT and COMP reporting a positive but statistically weak relationship to supply rewards. This finding is consistent with the pattern observed in Fig. 5. There is also no systematic relationship between market conditions and net deposits, suggesting that the safety demand deposit hypothesis cannot be substantiated.[25]

Next, we aggregate net deposits by address type, focusing on the top five tokens identified in Fig. 2 (ETH, WBTC, DAI, USDC, and USDT). The results are reported in Table A1 of the Appendix. We find that some patterns emerge: for example, net deposits for small addresses tend to respond positively to supply rates more (WBTC, USDC, and USDT), which could be interpreted as saving demand, while yield aggregator and asset management protocols' ETH net deposit is positively related to market conditions (7-day return, 30-day volatility), which may be a result of fund inflows during the bull market. However, the adjusted R-squared values remain low, and no clear pattern emerges. In conclusion, the aggregate behavior of depositors does not seem to exhibit any clear systematic relationship.

While many idiosyncratic reasons exist for depositing, the circumstances surrounding loan demands are more defined. However,

[25] In a previous version of this paper, two clear patterns that emerged are (1) net deposit in cDAI contract is positively and strongly related to the net increase in DAI stablecoins issued by MakerDAO, resulting in very high adjusted R-squared, and (2) net deposit in cBAT contract is negatively related to the net increase in DAI, which could be due to competition from MakerDAO which began accepting BAT as collateral to mint DAI in late 2019. Compound is an attractive place to deposit DAI, as Compound provides a higher yield from both supply rate and supply reward, and the deposits can be used as collateral for subsidized loans. Thus, much of MakerDAO's DAI likely ended up in Compound for this reason. We remove these findings from this version of the paper because of the tokens' specificity. Still, the results highlight the potential rivalry between DeFi protocols for users' liquidity and the different roles that each token may have in the DeFi ecosystem.

Table 4

Determinants of loans drawn. This table reports the result from the regressions of log cToken loan between May 2019 and June 2021. In columns 1 to 8, the results for cryptocurrencies are reported, followed by stablecoins from columns 8 to 12. Explanatory variables include lagged borrow rate, its interaction with an indicator for periods post COMP distribution, lagged borrow COMP reward rate, the log dollar value of deposits in $ million, 1-day ETH return, 7-day ETH return, and 30-day ETH volatility (measured in percentage point). Standard errors are computed using the Newey-West procedure with a one-day lag and reported in parenthesis. Stars correspond to the statistical significance level, with *, **, and *** representing 10%, 5%, and 1%, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
VARIABLES	cETH	cWBTC	cBAT	cCOMP	cLINK	cREP	cUNI	cZRX	cDAI	cUSDC	cUSDT	cTUSD
Post COMP distribution	3.36**	−2.57***	0.504			−1.84		−2.21	−2.39***	0.875	3.06***	
	(1.57)	(0.910)	(0.650)			(2.34)		(3.13)	(0.46)	(0.580)	(0.950)	
Lagged borrow rate	2.66***	0.131*	0.276***	0.070*	−0.185	0.858	0.085	0.342***	0.064	0.093	0.285***	−3.29***
	(0.490)	(0.070)	(0.030)	(0.040)	(0.260)	(0.880)	(0.080)	(0.120)	(0.060)	(0.100)	(0.080)	(0.780)
Post * lagged borrow rate	−1.29**	0.147	−0.050			−0.750		−0.170	0.002	−0.104	−0.252***	
	(0.610)	(0.14)	(0.060)			(0.880)		(0.230)	(0.060)	(0.100)	(0.080)	
Lagged borrow reward	0.061*	0.089**	0.019***	0.006	0.203**		0.440***	0.187*	0.110***	0.032	0.096**	
	(0.030)	(0.04)	(0.000)	(0.18)	(0.100)		(0.090)	(0.110)	(0.030)	(0.030)	(0.040)	
log(pool size)	0.756***	0.524***	0.854***	−3.01***	−0.533	0.491***	−0.767*	0.297	1.23***	1.19***	1.10***	0.497***
	(0.080)	(0.12)	(0.230)	(0.74)	(1.87)	(0.150)	(0.420)	(0.370)	(0.08)	(0.080)	(0.120)	(0.110)
ETH return (1d)	1.14	−3.42*	−2.52	1.33	−8.80	−0.426	6.22	−1.12	0.542	−0.074	−1.80	2.38
	(1.43)	(2.07)	(4.91)	(5.51)	(6.02)	(1.84)	(4.87)	(3.81)	(1.44)	(1.08)	(1.36)	(3.46)
ETH return (7d)	−0.310	1.50	−3.56	6.27**	9.87***	−3.33***	−3.80	−2.62	0.302	0.484	1.71**	−0.195
	(0.670)	(1.07)	(2.22)	(2.65)	(3.01)	(0.920)	(2.35)	(2.21)	(0.670)	(0.530)	(0.700)	(1.84)
ETH SD (30d)	4.61	30.25***	−21.92	14.96	15.36	−8.55*	–23.66	−10.90	−0.540	−16.31***	−21.61***	−110.11*
	(5.45)	(9.72)	(16.31)	(19.87)	(38.64)	(4.50)	(18.09)	(14.85)	(4.64)	(3.77)	(5.28)	(62.09)
Constant	1.40	9.04***	4.75***	16.68***	12.95	1.53	11.65***	1.76	9.43***	8.76***	7.48***	22.75***
	(1.20)	(0.80)	(0.78)	(1.69)	(8.88)	(2.33)	(1.95)	(1.22)	(0.47)	(0.61)	(0.88)	(6.14)
Observations	426	351	426	256	39	426	270	426	426	426	425	40
Adj R-squared	0.552	0.209	0.255	0.395	0.194	0.373	0.065	0.101	0.583	0.727	0.657	0.688

the regression results also seem to be puzzling. Table 4 reports the determinants of loan demands. Contrary to the typical interpretation of interest rate as loan price, for six out of the twelve tokens, the relationship with lagged borrow rate is positive, with only TUSD reporting a negative relationship. To make sense of this result, we must consider loan demands in conjunction with the borrow reward. The coefficients on borrow reward rates are unanimously positive, with eight out of the ten tokens that receive COMP distribution showing statistically significant coefficients.

Compound's interest rates instantaneously increase when the utilization rate is low, or loan demand is high. Under this interpretation, borrowers are willing to pay high rates as loanable funds deplete, which is puzzling. Nevertheless, as described in Section 2.4, executing a profitable leveraged strategy is possible when the COMP reward is considered. Even though the net cost of leverage is positive on the short side, the income and rewards from the long side can make the long-short position profitable.

This practice is known as *leveraged yield farming*.[26] In as short as one week after the introduction of COMP reward in June 2020, an article remarked that this potential for recursive interaction "triggered a gold rush of yield arbitrage, sending its assets under management and price to new heights."[27] This demand for leveraged yield farming would also explain why the demand for TUSD, a stablecoin which not eligible for COMP reward, is negatively related to the borrow rate as one might expect. Furthermore, for the case of leveraged yield farming outside Compound, this also holds: as long as the borrowed funds can be deployed in more profitable strategies, the borrow rates do not matter. Consequently, as users borrow more, borrow rates increase, which can result in the positive correlation observed in the data. The loan demand drives the interest rate, and the increased interest rate is insufficient to dampen loan demand.

As discussed in Hypothesis 4, stablecoin loans face greater liquidation risk during volatile times. Hence, we see the negative relationship between loan demands and the past 30-day standard deviation of ETH for USDC, USDT, and TUSD. The adjusted R-square values for the stablecoin loans are also higher than cryptocurrency loans.

In Table A2 in the Appendix, we separate addresses by type and find that the positive relationship to borrow rates and borrow rewards still holds, but primarily for large and small addresses. Protocols and unidentified contracts exhibit a positive relationship to borrow rates, but the relationship with borrow rewards is unclear. Stablecoin loans by large and small addresses are also lower during volatile markets. We assume that actions taken by addresses are more likely to be manual while protocols' actions are automated. Under the liquidation risk hypothesis, this finding is consistent with the view that addresses are more averse to liquidation risk and less likely to take stablecoin loans during volatile times. It may come as a surprise that protocols do not respond very strongly to borrow reward rates (in fact, negatively for USDC). More profitable rewards may be obtained in other protocols or complex deployable strategies. In this case, their objectives may be to use Compound to gain leverage, not for its reward. Thus, leveraged yield farming likely explains the positive relationship between the borrow rate and loan demand.

From the results in this section, DeFi yield farming is most likely Compound's primary use case and driver of growth. Therefore, the following section investigates leveraged yield farming within Compound from address-level activities.

4.2. Recursive interactions

In subsequent analyses, we use transaction data to investigate users' interactions more granularly. However, understanding the full financial positions of each address requires manually parsing all on-chain transactions and understanding the protocols' structure. Therefore, we limit the scope of our analysis to interactions with Compound only.

Leveraged yield farming within Compound entails redepositing borrowed tokens. To identify such addresses, we reaggregate the data by address-loan-day, aggregating all loans drawn from a token by an address daily. Since the loans are not required to be closed like in Table 2, and each closed loan may involve multiple draw spread over multiple days, there are more loan day observations (98,717) than closed loans (52,770). The summary statistics of loan days and their redeposit rates are reported in Table 5.

We analyze the number of loans, not the dollar value. On average, 11.4% of cToken loans are redeposited within one day and 10.5% within the same day, with ETH (20.6%) and BAT (28.5%) as the most redeposited tokens followed by COMP (18.5%) and UNI (15.9%). Of the four stablecoins, DAI is the most redeposited (14.7%), followed by USDC (7.4%). Across address types, yield aggregators, and unidentified contracts are most likely to redeposit, consistent with their objectives outlined in the Appendix. This evidence may seem contradictory to the earlier loan demand analysis result. However, the difference is that this analysis is conducted on loan counts, not dollars. Excluding on-ramps and decentralized exchanges, small addresses are the least likely to redeposit, possibly due to their lower level of sophistication or relatively smaller position sizes that make the benefits not worth the gas cost.

Next, we use the logistic regression. The dummy takes the value of one if the address redeposits the borrowed token within one day. We pool all types of addresses and control for the cross-category differences in redeposit rates observed in Table 5 with address-type fixed effects. Because leveraged yield farming strategies earn rewards from supplying and borrowing, we include the determinants from Equations (4) and (5) and the log of loan size. Table 6 reports the estimated coefficients of the regressions for the five primary tokens.

First of all, it is worth noting that there are far more stablecoin loans than cryptocurrency loans, and their pseudo R-squared values are also larger. The relationships for cryptocurrency loans are statistically weaker, and only the supply rewards, not borrow rewards,

[26] A description of leveraged yield farming strategy in Compound can be found at https://defiprime.com/defi-yield-farming, accessed on November 11, 2022.

[27] Source: https://cointelegraph.com/news/compound-reward-farming-results-in-six-fold-increase-of-lending-activity, accessed on November 11, 2022.

Table 5

Redeposited loans. Panel A reports the number of loan day by token and address type. A loan day is defined as a day that an address takes out a token loan, which may involve multiple draws within the same day. Because of this, the number of loan days is higher than the number of closed loans reported in Table 2, which are defined as a complete borrow-repayment cycle. Panel B reports the share of loan days where the borrower immediately redeposits the borrowed tokens to the cToken contract on the same day. Finally, panel C reports the share of loan days where a redeposit occurs within one day.

Panel A: Distribution of daily loans by token

	cETH	cWBTC	cBAT	cCOMP	cLINK	cREP	cUNI	cZRX	cDAI	cUSDC	cUSDT	cTUSD	Total
Large address	348	167	141	45	30	20	72	36	2,817	1,859	1,048	10	6,594
Small address	8,026	2,280	2,827	418	214	371	765	772	31,177	27,934	14,344	327	89,539
Yield aggregator		37							2	9	2		50
On-ramp										180			180
Decentralized exchange									3				3
Asset management	32	5	21			6	11	15	113	112	38		357
Unidentified contract	50	117	50	8	8	19	25	32	1,045	444	187		1,994
All types	8,456	2,606	3,039	471	252	416	873	855	35,157	30,538	15,619	337	98,717

Panel B: Share of daily loans that are redeposited on the same day

	cETH	cWBTC	cBAT	cCOMP	cLINK	cREP	cUNI	cZRX	cDAI	cUSDC	cUSDT	cTUSD	Total
Large address	13.5%	22.2%	49.6%	33.3%	40.0%	10.0%	13.9%	16.7%	14.3%	9.8%	1.2%	10.0%	12.1%
Small address	19.1%	10.5%	24.6%	17.0%	9.8%	4.3%	15.3%	8.4%	12.5%	6.0%	2.5%	0.3%	9.7%
Yield aggregator		97.3%							0.0%	0.0%	0.0%		72.0%
On-ramp										0.0%			0.0%
Decentralized exchange									100.0%				100.0%
Asset management	12.5%	0.0%	23.8%			0.0%	0.0%	0.0%	55.8%	8.9%	0.0%		23.0%
Unidentified contract	34.0%	20.5%	54.0%	0.0%	62.5%	52.6%	16.0%	12.5%	47.5%	42.8%	1.6%		39.1%
All types	18.9%	12.9%	26.3%	18.3%	15.1%	6.7%	15.0%	8.8%	13.8%	6.8%	2.4%	0.6%	10.5%

Panel C: Share of daily loans that are redeposited within one day

	cETH	cWBTC	cBAT	cCOMP	cLINK	cREP	cUNI	cZRX	cDAI	cUSDC	cUSDT	cTUSD	Total
Large address	16.4%	24.0%	51.1%	33.3%	43.3%	20.0%	16.7%	25.0%	15.7%	10.8%	2.0%	10.0%	13.5%
Small address	20.7%	12.2%	26.8%	17.2%	10.7%	5.4%	16.1%	10.1%	13.3%	6.6%	3.0%	0.3%	10.5%
Yield aggregator		97.3%							0.0%	0.0%	0.0%		72.0%
On-ramp										0.0%			0.0%
Decentralized exchange									100.0%				100.0%
Asset management	12.5%	0.0%	38.1%			0.0%	0.0%	0.0%	57.5%	11.6%	0.0%		25.2%
Unidentified contract	34.0%	21.4%	58.0%	0.0%	62.5%	63.2%	16.0%	15.6%	48.9%	44.1%	3.2%		40.6%
All types	20.6%	14.5%	28.5%	18.5%	16.3%	8.7%	15.9%	10.8%	14.7%	7.4%	2.9%	0.6%	11.4%

Table 6

Determinants of redeposited loans. This table reports the result from the logistic regression of redeposit dummy variable (which takes the value of 1 when the address redeposits borrowed tokens within one day) on the log of loan size in $, lagged supply rate, lagged borrow rate, their interactions with an indicator for periods post COMP distribution, lagged supply COMP reward rate, lagged borrow COMP reward rate, 1-day ETH return, 7-day ETH return, 30-day ETH volatility (measured in percentage point), and address type fixed effects. Only the five primary tokens (ETH, WBTC, DAI, USDC, and USDT) are analyzed. Standard errors are clustered by address and reported in parenthesis. Stars correspond to the statistical significance level, with *, **, and *** representing 10%, 5%, and 1%, respectively.

	(1)	(2)	(3)	(4)	(5)
	ETH	WBTC	DAI	USDC	USDT
Log(loan size in $)	−0.024*	0.066**	0.224***	0.235***	0.066**
	(0.010)	(0.030)	(0.020)	(0.020)	(0.030)
Post COMP distribution	2.36	−1.14	−0.946***	−1.11**	−0.927
	(2.84)	(2.21)	(0.15)	(0.440)	(0.620)
Lagged supply rate	−3.71	0.392	−0.338***	−0.008	−0.084
	(4.66)	(0.91)	(0.10)	(0.18)	(0.06)
Lagged borrow rate	2.01	−0.307	0.296***	−0.065	0.204***
	(1.27)	(0.590)	(0.090)	(0.14)	(0.07)
Post * lagged supply rate	−6.378	−2.601	1.809***	−0.502**	0.082
	(5.47)	(1.69)	(0.30)	(0.24)	(0.24)
Post * lagged borrow rate	−0.471	0.503	−1.26***	0.449**	−0.167
	(1.36)	(0.62)	(0.22)	(0.20)	(0.18)
Lagged supply reward	1.48*	1.05*	−3.77***	0.217***	−0.087
	(0.850)	(0.610)	(0.390)	(0.080)	(0.200)
Lagged borrow reward	−0.076	−0.032	3.01***	−0.104	0.139
	(0.050)	(0.040)	(0.300)	(0.060)	(0.130)
ETH return (1d)	−0.174	0.995	0.105	−0.273	−3.58**
	(0.500)	(1.09)	(0.320)	(0.350)	(1.50)
ETH return (7d)	0.186	−0.584	−0.606***	−0.422**	−0.987
	(0.240)	(0.550)	(0.190)	(0.200)	(0.760)
ETH SD (30d)	−0.848	9.85	−15.15***	−0.987	−14.77
	(2.09)	(6.07)	(2.05)	(1.67)	(10.19)
Address type fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	8,514	1,874	35,378	30,601	15,704
Pseudo R-squared	0.030	0.048	0.116	0.084	0.212

are positively related to deposits. From Table 1 Panel C, the borrow rewards for ETH and WBTC are high due to low utilization. The long-short strategy described in Section 2.4 would offer a risk-free arbitrage for much of the sample period.[28] Thus, changes in reward rates would likely have little impact on whether borrowed tokens are more likely to be redeposited.

For stablecoin loans, the redeposits of DAI and USDC are more responsive to rates, both the borrowing spread and rewards. USDT redeposit, on the other hand, is only positively related to the borrow rate. Larger addresses are also more likely to redeposit borrowed tokens, consistent with how the profitability of leveraged yield farming would be attenuated by gas cost, which does not vary much by transaction size.

Finally, in Table 7, we analyze the behavior of the addresses that sent instructions to claim COMP rewards. There are only 16,968 COMP claimers from the 161,569 addresses in our sample. While most interactions with Compound are eligible for the reward, the gas cost can make claiming and monetizing COMP uneconomical for small transactions. While 873,652 COMP were claimed during this period, more than 1.9 million were deposited into the cCOMP contract (labeled as internal yield farming in Table 7). Almost 0.42 million COMP were sent to other yield aggregators or asset management protocols (labeled as external yield farming). This discrepancy arises because the deposits can be made from COMP that were claimed or bought in secondary markets. Relative to their claimed amount, there are many more internal and external yield farming activities by small address, indicating more considerable turnover than other address types.

On a per-address basis, unidentified contracts claim almost as much as large addresses and much more than yield aggregators. It is possible that these contracts are part of protocols but are not explicitly labeled or identified to users. In Panel B, we restrict the analysis to addresses that redeposit borrowed tokens into the relevant cToken contract. 2,551 addresses that redeposit account for 28.2% of loans drawn from Compound. While they are just 15% of COMP claimers, they represent 76.3% of all COMP claimed. With this restriction, the proportion of addresses engaged in yield farming increases from 13% to 19% for internal and 5.7% to 7.8% for external. Evidence from our loan-level and address-level analyses suggests that yield farming is prevalent, and the dollar value is concentrated among less than 1% of users.

[28] In fact, this is a strategy employed by Yearn, a yield aggregator protocol. A description of Yearn's GenLevCompV2 strategy in WBTC yVault reads, "Supplies and borrows yvWBTC on Compound Finance simultaneously to earn COMP. Earned tokens are harvested, sold for more yvWBTC which is deposited back into the strategy. Flashloans are used to obtain additional yvWBTC from dYdX to boost the APY." This also explains why yield aggregator addresses redeposit 97.3% of WBTC in Table 5. Source: https://yearn.watch/vault/0xA696a63cc78DfFa1a63E9E50587C197387FF6C7E/0x619Dde92f9fD8Af679025A2fD7e9ED2269e4c0c8, accessed November 11, 2022.

Table 7

COMP activities. Panel A reports the number of addresses that claimed COMP rewards by address type. Next, COMP claimed (in units), sent for internal yield farm by depositing into cCOMP contract, and sent for external yield farming to yield aggregator or asset management protocols are reported, first as aggregate by address type and then again as average per address. Finally, the proportion of addresses that yield farm their COMP tokens is reported. Finally, panel B repeats the summary statistics for addresses that redeposit their borrowed tokens into cToken contracts.

Panel A: All addresses									
	Number of addresses	Total COMP activities			Average COMP activities			% yield farming	
		Claimed	Internal	External	Claimed	Internal	External	Internal	External
Large address	192	475,048	842,865	238,255	2,474.2	4,389.9	1,240.9	34.4%	15.1%
Small address	16,661	242,605	1,016,698	178,836	14.6	61.0	10.7	12.7%	5.5%
Yield aggregator	23	10,665	48,754	131	463.7	2,119.7	5.7	8.7%	17.4%
On-ramp	8	1,995	6,351	2,434	249.4	793.8	304.3	25.0%	37.5%
Decentralized exchange	1	547	0	0	546.9	0.0	0.0	0.0%	0.0%
Asset management	24	8,625	1,278	0	359.4	53.3	0.0	16.7%	0.0%
Unidentified contract	59	134,166	14,833	262	2,274.0	251.4	4.4	13.6%	5.1%
All types	16,968	873,652	1,930,779	419,919	51.5	113.8	24.7	13.0%	5.7%

Panel B: Addresses that redeposit borrowed tokens only									
	Number of addresses	Total COMP activities			Average COMP activities			% yield farming	
Redeposits only		Claimed	Internal	External	Claimed	Internal	External	Internal	External
Large address	66	385,665	574,021	229,457	5,843.4	8,697.3	3,476.6	36.4%	22.7%
Small address	2,435	155,673	273,961	50,917	63.9	112.5	20.9	18.6%	7.6%
Yield aggregator	2	613	0	0	306.5	0.0	0.0	0.0%	0.0%
On-ramp	1	547	0	0	546.9	0.0	0.0	0.0%	0.0%
Decentralized exchange	9	4,245	439	0	471.7	48.7	0.0	22.2%	0.0%
Unidentified contract	38	119,962	11,033	233	3,156.9	290.3	6.1	10.5%	2.6%
All types	2,551	666,705	859,453	280,607	261.4	336.9	110.0	19.0%	7.8%

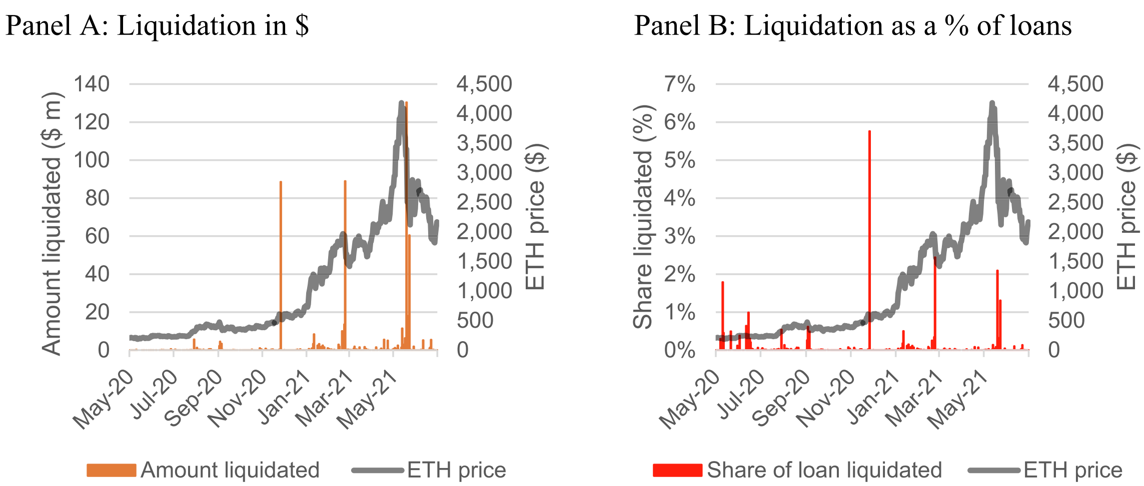


Fig. 6. Compound liquidations. This figure plots daily loan liquidations in Compound against ETH price. In Panel A, the dollar value in $ millions of liquidations is plotted. In Panel B, liquidations are computed as a percentage of outstanding loans.

4.3. Liquidations

Compound manages its credit risk by allowing third-party users to liquidate loans with negative account liquidity partially. Fig. 6 plots daily loan liquidations across all cTokens against ETH price. During periods of rapid price declines, liquidations increase. There were three major episodes of liquidations: November 16, 2020; February 22 – 23, 2021; and May 19 – 23, 2021. Daily liquidations reached $130 million on May 19, 2021, as the market crashed. However, liquidations on that day represented only 2.1% of outstanding loans, as evident in Fig. 7 Panel B, as Compound requires users to maintain ample collateralization, and liquidation is only partial.

Table 8 summarizes the loans by token and address type. We require that loans be at least $100 so liquidation can be economically viable with gas costs. Of the 44,423 loans, 6.1% are liquidated, representing less than 0.75% of loans drawn. Liquidated stablecoin loans account for 89% of the dollar value, and liquidations of large and small addresses account for 98.3% of all liquidations. Despite their higher frequency, the dollars of liquidated loans drawn by yield aggregators and unidentified contracts account for less than 0.1% of the loan value. If they follow the arbitrage strategy in Sections 2.4 and 4.2, this would explain the low liquidation.

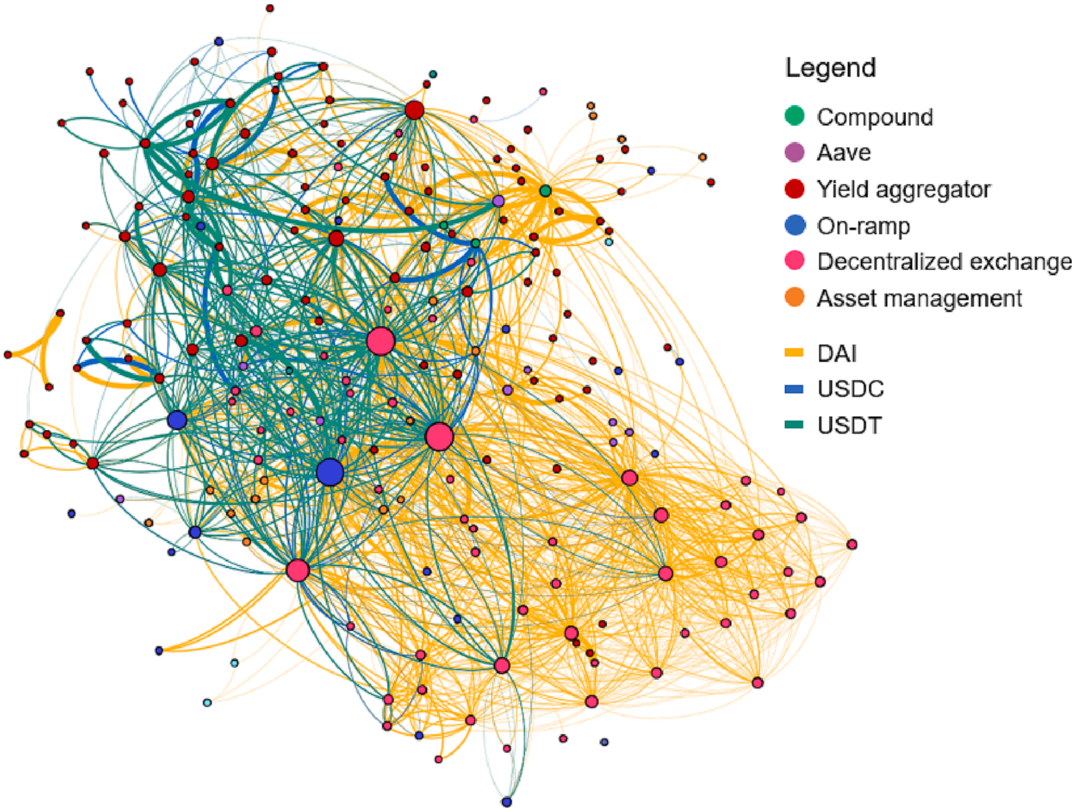


Fig. 7. Network diagram of DeFi stablecoins. This figure plots the stablecoins flows (DAI, USDC, and USDT) between smart contracts identified as part of Compound, Aave (a lending protocol), yield aggregator protocols, on-ramps, decentralized exchange (DEX) protocols, asset management protocols, and other smart contracts that exist between May 2019 and June 2021.

Next, we analyze the relationship between the tokens used as collateral and tokens drawn as loans. Table 9 reports the dollar values of the 5,036 liquidations between May 2019 and June 2021 by loan-collateral pairs. 86.4% of liquidated loans are in stablecoins and are predominantly collateralized by cETH and cWBTC, as the two tokens account for 73.9% of collaterals foreclosed by liquidators. Borrowers may post multiple tokens as collateral, and Compound allows liquidators to choose the collateral they wish to receive. Consequently, the diagonal entries such as DAI-cDAI (cDAI collateralizes the liquidated DAI loans, which should be liquidation-free) are not empty.

The results highlight the importance of the price mismatch between the collateral and borrowed tokens. Conceptually, a multi-collateral design like Compound should reduce the volatility of collateral value, and borrowers further delta-hedge their positions. However, because most tokens are positively correlated (the correlation between ETH and other tokens is between 0.73 and 0.92), especially during market downturns, and most borrowings are in stablecoins, liquidations are likely to occur during such periods.

Liquidations can lead to a fire sales spiral, which has occurred in many financial settings, as summarized by Shleifer and Vishny (2011) and documented in DeFi by Saengchote et al. (2022). Aramonte et al. (2021) show that following forced liquidations of DeFi derivatives positions and loans, sharp price falls, and spikes in volatility follow. Given that leverage is procyclical, liquidation risk can amplify the instability of the DeFi ecosystem. In the next section, we discuss how the connectivity between DeFi protocols can be a source of systemic risk and how participants that are part of the events that unfolded from May 2022 interacted with Compound in February before the crash.

4.4. Concentration, Connectivity, and systemic risk

As discussed in the Introduction, one of the hallmarks of DeFi is that it is built to allow interoperability. Compound did not create DAI, but it can incorporate the stablecoin into its cDAI contract as a main component. This interoperability can be visualized by the flows between addresses. We focus on stablecoins since they are closest to money and can threaten the monetary system (Arner et al., 2020) and limit the complexity of the network diagram. We aggregate the transfers of DAI, USDC, and USDT between smart contracts during the sample period and color code the contracts (nodes) and token flows (lines).

As explained in Fig. 1, when a user deposits into a cToken contract, she receives a cToken in return as a depository receipt. The cTokens function as bearer instruments allowing holders to redeem corresponding contract tokens. Thus, cTokens are valuable and can be considered a new asset, often referred to as interest-bearing tokens, as discussed in the Appendix for yield aggregator. Because of

Table 8

Liquidation statistics. Panel A reports the number of outstanding and closed loans as of June 2021 by tokens. Loans are required to be at least $100 so liquidation can be economically viable with gas costs. The number of loans and their dollar value, the dollar value of loans repaid by liquidators (liquidation), and the proportions of loans liquidated in frequencies and dollars are reported. Panel B reports similar statistics by address type.

Panel A: Liquidation by token

Token	Num loans	Loan value ($ m)	Liquidation ($ m)	% of loans liquidated	% of $ liquidated
ETH	5,681	2,796.1	6.9	6.0%	0.2%
WBTC	1,738	1,900.6	26.3	3.2%	1.4%
BAT	1,973	962.9	1.7	3.9%	0.2%
COMP	278	215.8	8.1	5.8%	3.7%
LINK	138	86.5	0.0	0.7%	0.0%
REP	345	275.4	0.0	10.1%	0.0%
UNI	524	581.1	13.2	4.0%	2.3%
ZRX	585	86.7	0.4	5.6%	0.5%
DAI	14,055	31,693.0	246.9	7.3%	0.8%
USDC	12,233	24,923.5	115.0	6.5%	0.5%
USDT	6,703	5,218.0	95.8	4.8%	1.8%
TUSD	170	96.7	0.1	5.3%	0.1%
All tokens	44,423	68,836.2	514.4	6.1%	0.7%

Panel B: Liquidation by address type

Address type	Num loans	Loan value ($ m)	Liquidation ($ m)	% of loans liquidated	% of $ liquidated
Large address	1,383	30,345.1	210.1	5.7%	0.7%
Small address	42,005	22,696.8	295.6	6.3%	1.3%
Yield aggregator	36	3,309.9	0.4	13.9%	0.0%
On-ramp	2	256.6	0.0	0.0%	0.0%
Decentralized exchange	7	3.8	0.0	0.0%	0.0%
Asset management	176	888.8	0.3	0.6%	0.0%
Unidentified contract	814	11,335.2	8.1	1.5%	0.1%
All types	44,423	68,836.2	514.4	6.1%	0.7%

this, they are also accepted by other DeFi protocols. For example, Curve.fi's crvCOMP contract allows cDAI and cUSDC to be exchanged in the swap pool. By depositing tokens into a protocol, users would often receive another token issued by the protocol as a depository receipt. Nevertheless, as seen in Fig. 1, tokens can represent the liabilities of the issuing contracts. Hence, the chains of interactions illustrated by Fig. 7 are similar to the debt-on-debt network of financial liabilities that stem from the original asset, such as ETH that secures WETH, which, in turn, secures cWETH, and so on.

Dang et al. (2020) argue that short-term debt that is information insensitive (such as bank deposits or T-bills) can serve as a medium of exchange. In the context of DeFi, certain classes of stablecoins are examples of such short-term debt. When there is doubt about the value of the collateral backing the short-term debt, users may begin acquiring private information, shifting the state from information-insensitive debt to information-sensitive debt, which can, in turn, result in financial crises when the credit chain collapses. Saengchote (2021b) demonstrates that composability in DeFi could lead to tacit leverage via webs of depository receipt creation that is not easy to recognize or monitor. In addition, off-chain lenders such as crypto banks may provide explicit leverage that further amplifies the financial connectivity in the ecosystem. When the price of the initial collateral declines, the whole credit chain will be affected.

In May 2022, the failure of TerraUSD stablecoin had a ripple effect throughout the crypto asset market, with Bitcoin falling to its lowest price since 2020.[29] Several crypto businesses, such as Three Arrows Capital (a crypto hedge fund), Celsius Network (a crypto bank), and Voyager Digital (a crypto brokerage/bank), filed for bankruptcy in the ensuing months.[30] Moreover, the effect of the May collapse continued to reverberate. In November, FTX (one of the world's biggest crypto exchanges) filed for bankruptcy, and Alameda Research (a crypto hedge fund) related to FTX was reported insolvent.[31] All of the examples earlier are not purely DeFi providers, as not all of their activities are entirely on-chain. However, because they interact with DeFi protocols, on-chain data can provide insights into what happened before the May crash.

Before proceeding further, we remind the reader that the following analysis is an attempt in an earlier version of our paper to investigate the concentration risk of DeFi by looking at who are the main depositors and borrowers in Compound before May 2022. However, many of the addresses that were anonymous to us on February 11, 2022, have now been identified by the DeFi community, and various familiar names have emerged. Therefore, we report the top ten holders of cETH, cDAI, cUSDC, and cUSDT as of June 30, 2021, and February 11, 2022, in Table A3, and the top twenty borrowers over the sample period in Table A4.

On February 15, 2022, the then pseudonymous, independent investigative journalist named Dirty Bubble Media released a publication titled "Celsius Network's unsustainable DeFi strategy could be costing them millions."[32] Celsius Network allows users to deposit their crypto assets and earn yield, and Celsius Network would then deposit them into DeFi lending protocols such as Compound

[29] Source: https://www.nytimes.com/2022/05/12/technology/cryptocurrencies-crash-bitcoin.html, accessed November 28, 2022.

[30] Source: https://www.businessinsider.com/why-crypto-celsius-three-arrows-voyager-filed-bankruptcy-2022–7, accessed November 28, 2022.

[31] Source: https://www.nytimes.com/2022/11/11/business/ftx-bankruptcy.html, accessed November 28, 2022.

[32] Source: https://dirtybubblemedia.substack.com/p/celsius-networks-unsustainable-defi, accessed November 28, 2022.

Table 9

Liquidated loans by collateral. This table reports the total dollar value in $ millions of loans repaid by liquidators between May 2019 and June 2021. The rows are denominations of liquidated cToken loans, while the columns are the corresponding cToken collaterals seized. For example, the DAI row and cETH column represent $124.9 million DAI loans repaid where liquidators choose to claim cETH as collateral.

	cETH	cWBTC	cBAT	cCOMP	cLINK	cREP	cUNI	cZRX	cDAI	cUSDC	cUSDT	cTUSD	Loan	Share
ETH		1.1	0.1	0.1	0.0	0.0	0.1	0.2	2.8	2.3	0.0		6.5	1.2%
WBTC	36.7	7.0	0.0	0.0			0.0	0.0	0.1	0.2	0.0		44.1	7.9%
BAT	0.4	0.6		0.0			0.0	0.0	0.0	2.8			3.9	0.7%
COMP	0.0	0.7	0.0	7.1					0.3	0.0			8.1	1.4%
LINK	0.0								0.0	0.0			0.1	0.0%
REP	0.0							0.0	0.0	0.0			0.0	0.0%
UNI	0.6	11.1		0.2				0.0	0.0	1.5			13.3	2.4%
ZRX	0.1	0.0	0.1	0.0					0.1	0.0			0.3	0.1%
DAI	124.9	15.5	2.9	2.3		0.0	4.0	0.7	65.9	17.9	0.0		234.3	41.8%
USDC	99.2	13.0	1.0	0.6		0.0	1.2	1.2	11.7		0.0		128.0	22.8%
USDT	92.1	11.3	0.7	0.9			6.6	5.1	0.5	4.9			122.0	21.8%
TUSD	0.0	0.0	0.0	0.0			0.0		0.0				0.1	0.0%
Collateral	354.2	60.3	4.7	11.1	0.0	0.0	12.1	7.2	81.4	29.7	0.0	0.0	560.7	100.0%
Share	63.2%	10.8%	0.8%	2.0%	0.0%	0.0%	2.2%	1.3%	14.5%	5.3%	0.0%	0.0%	100.0%	

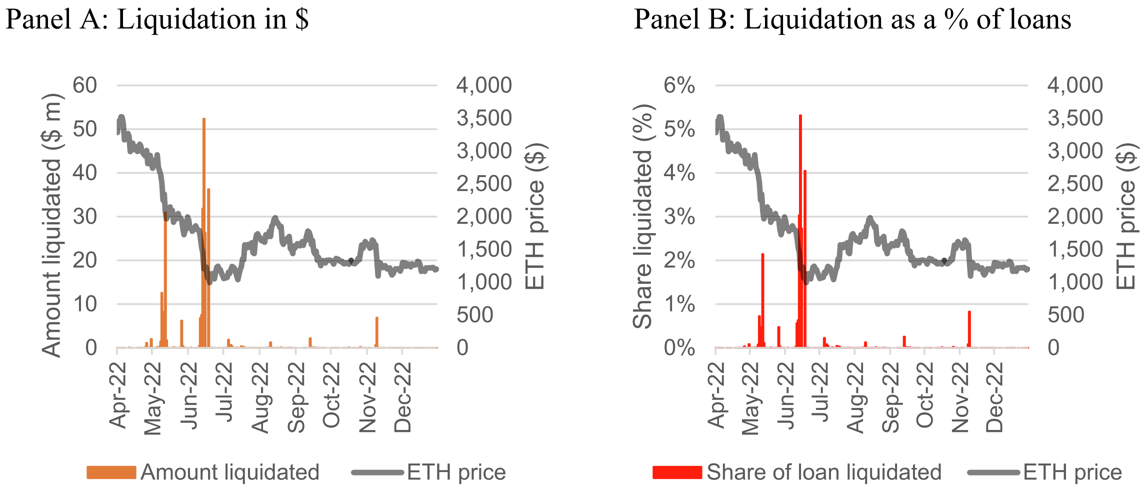


Fig. 8. Compound liquidations in 2022. This figure plots daily loan liquidations in Compound against ETH price. In Panel A, the dollar value in $ millions of liquidations is plotted. In Panel B, liquidations are computed as a percentage of outstanding loans.

and Aave. The author analyzed the yield generated by the protocols and raised questions regarding its ability to generate revenue and long-term viability:

"These deposits generate some interest. However, you'll note that the APY for these deposits is quite low; lower, in fact, than many "tradfi" savings accounts. This means there is a significant gap between what Celsius is paying and what they are receiving as interest on these deposits. Based on a conservative estimate of the average APY Celsius offers customers on these crypto assets, they face an annual deficit of ~$86 million in interest payments to depositors.

The author then released a follow-on publication, highlighting that investments in ETH and related crypto assets account for more than 65% of its assets under management, most of which are held by a single address.[33] The potential vulnerability of Celsius Network's business model, its concentrated position in certain crypto assets, and potential contagion that can occur from a fire sales spiral are ingredients for a systemic crash that can be hard to contain given most providers are unregulated and no backstops to prevent runs like those studied by Diamond and Dybvig (1983) exist.

In Panel A of Table A3, the top holder of cETH in June 2021 and February 2022 was indeed Celsius Network, held via the same address reported in the publication. During this period, their holding increased from 13.77% to 21.01%. In fact, for all four tokens, the concentration of the top ten holders increased, and for cDAI, the top ten addresses account for almost 90% of the deposits. In addition, yield aggregators became more prevalent in February 2022, with Yearn becoming the dominant protocol and the majority holder of cDAI (21.8%) and cUSDC (11.7%). Among the top ten holders is another lending protocol (Notional Finance) that accepts cTokens (cETH, cWBTC, cDAI, and cUSDC) as collateral. These protocols increase the connectedness among participants in DeFi.

Further investigation of cumulative borrowing activities up to June 2021, reported in Table A4, shows that distressed names such as Alameda Research and Three Arrows Capital are among the top tens borrowers. The address marked as Three Arrows Capital claimed more than 27,000 COMP rewards during the sample period, suggesting that they participated in some degree of leveraged yield farming within Compound, while the Alameda Research address has cumulative net withdrawals of $6.7 billion, which could result from buying cTokens in secondary markets to redeem for deposits, which, depending on market prices, could provide arbitrage profits. The reported numbers are as of June 2021; by May 2022, their activities could have grown much more from another rise of the crypto asset market in late 2021.

Analyzing the degree of concentration and systemic risk is not within the scope of this paper, but loan liquidations during key episodes can provide some valuable insights. Fig. 8 shows the liquidations in 2022. Compared to the liquidations in the sample presented in Fig. 6, liquidations were more severe in 2022. For example, during 19–23 May 2021, when ETH price fell by almost 30%, Compound loans fell by $2.7 billion, and only $215 million (7.9%) were from liquidations. On the other hand, during 7–12 May 2022 (the TerraUSD collapse), ETH price fell by 24.4%, Compound loans fell by $483 million, and $54 million (11.2%) were from liquidations. Finally, during 11–18 June 2022 (Celsius Network halted withdrawals and transfers), ETH price fell by 39.2%, Compound loans fell by 287 million, and $161 million (56%) were from liquidations. The severity of liquidations appears to be higher when (1) Compound is more concentrated (2022 versus 2021) and (2) the shock involves the key user (Celsius Network).

In traditional finance, such concentration risk would be curtailed by risk management practices such as borrowing limits and identifying consolidated debt positions across related parties. However, with the pseudonymity of DeFi, such practices are challenging. While not all their transactions are entirely on-chain (hence, crypto businesses are often referred to as *CeDeFi*, a combination of centralized and decentralized finance), ex-post investigations such as bankruptcy filings reveal the credit relationships among them

[33] Source: https://dirtybubblemedia.substack.com/p/following-the-money, accessed November 28, 2022.

these entities, making their interconnection even tighter than on-chain data suggests.[34] Acemoglu et al. (2015) show that dense interconnections propagate shocks rather than enhance financial stability, and on-chain data shows that this is indeed the case for DeFi.

Prior to the collapse of FTX, The FSOC issued a Report on Digital Asset Financial Stability Risks and Regulation in early October 2022, citing "Financial Exposures via Interconnections within the Crypto Asset Ecosystem" as a potential source of risk.

Interconnections inside the crypto-asset ecosystem spread losses if a shock causes the default of an interconnected entity and its counterparties then incur knock-on losses. Losses can also spread from common holdings if an entity holds a crypto-asset that records a sharp price decline. The crypto-asset ecosystem currently features a number of significantly interconnected entities, including crypto-asset platforms, investors, and other counterparties. The failure of a significantly interconnected entity can cause substantial distress within the crypto-asset ecosystem.

Our investigations are conducted with hindsight. We do not claim that the collapses of the crypto businesses discussed earlier could have been predicted or prevented since many addresses identified in this paper were previously unrecognized to many until after the collapse. However, blockchain transparency can inform us about the nature of interactions that occur within DeFi. When many of the activities are leveraged investment strategies supported by risky collateral and concentrated among a few large participants, the credit chain can be very fragile.

5. Conclusion

In this paper, we outline how Compound works, who its users are, and how they interact with the protocol. Between May 2019 and June 2021, $61.4 billion of loans were made for an average duration of 31 days, with usage behavior consistent with leveraged investment strategy rather than financing. In addition, we document some novel facts about DeFi, such as users creating addresses and interacting in small amounts (the micro addresses) in anticipation of COMP airdrop (which did not eventually occur) and COMP rewards remaining unclaimed because of gas cost and real option value.

Depositors and borrowers in Compound are concentrated, with the top 100 depositor addresses accounting for 75% of all deposits and the top 100 borrower addresses 78% of all loans, while the top ten holders of selected cTokens accounting for 50 to 90% of outstanding tokens. We find that deposit demands are primarily idiosyncratic and do not respond to returns to deposits and market conditions. In contrast, loan demands are driven by leveraged yield farming and are responsive to COMP rewards. Further address-level and loan-level investigations reveal results consistent with this interpretation, with 11.4% of drawn loans redeposited to the protocol again within one day and addresses that are more likely to employ this strategy claiming more COMP rewards from Compound. We also find that the users interact with different tokens in different ways, even for stablecoins, suggesting that each token has different roles in the DeFi ecosystem.

As highlighted by The Financial Stability Oversight Council (FSOC), interconnections between on-chain protocols and off-chain crypto businesses make the crypto asset ecosystem prone to systemic risk. While DeFi protocols, such as Compound, have strict credit risk management mechanisms via overcollateralization, liquidation cascades can still occur when large shocks hit the system. Furthermore, Aramonte et al. (2021) show that automatic liquidation mechanisms can amplify shocks and instability of the financial system.

Lending protocols can contribute to systemic risk.[35] Events from May to November 2022 have shown that significant vulnerabilities can build up in the off-chain crypto businesses intertwined with on-chain DeFi protocols. Currently, the regulatory guardrails against excessive leverage for participants in the crypto asset ecosystem are not uniform. However, DeFi regulations can be challenging to implement, given how permissionless blockchains are designed to operate. In addition, with the currently ambiguous status of crypto assets and the global nature of crypto businesses, uncertainty regarding who ultimately has jurisdiction remains. This challenge will determine the success of DeFi and the permissionless ecosystem it strives to maintain.

Appendix: Smart contract and DeFi protocol classification

In this Appendix, we briefly explain the nature of DeFi protocols and how their incentives are distributed so readers can understand the distinctions and the reason behind the classification scheme.

5.1. Yield aggregator

Yield aggregator protocols are similar to mutual funds and hedge funds. In programmable blockchains, users must pay gas to compute and record new information onto the blockchain regardless of the monetary value behind that information because decentralized computing power and block space are limited resources in such blockchains. Claiming reward tokens (such as COMP) is a blockchain transaction that costs gas, so users with small transactions will not find it economical to claim rewards often, missing out on the compounding effect. With a larger pool of tokens, yield aggregators can claim rewards more frequently and thus accumulate more yield over time. In addition, yield aggregators can utilize complex strategies such as recursive leverage or staking wrapped tokens across multiple protocols to earn rewards distributed by those protocols. In return, the protocol will charge management fees on assets

[34] For example, the Chapter 11 petition filed by Celsius Network on July 14, 2022, shows that Alameda Research is one of its top 50 creditors. Source: https://pacer-documents.s3.amazonaws.com/115/312902/126122257414.pdf, accessed November 28, 2022.

[35] In previous versions circulated since September 2021, we stated that "yield farming warrants further investigation into whether DeFi composability lends itself to systemic risk." However, ex-post investigations by various sources, such as the FSOC, have now confirmed that many crypto businesses that collapsed were taking part in some form of leveraged yield farming.

under management and may also withhold a proportion of the yield (like hedge fund carry). Some strategies are illiquid, so mechanisms such as load fees are often included in protocol design to encourage users to lock their funds for longer. Examples of such protocols are Akropolis, Alpha Homora, Harvest, Idle, and Yearn.

Users deposit their tokens into the protocol's vault, creating wrapped tokens as depository receipts. These tokens are often referred to as interest-bearing tokens, and the small alphabet(s) in front of the original token's names depict this relationship. For example, cDAI and aDAI can be considered Compound's and Aave's interest-bearing tokens, while Yearn will create yvDAI when DAI is deposited into the DAI yVault. The deposited tokens would then be deployed according to the strategies set forth by the protocol. Users will receive a pro-rata share of the pool when the depository receipts are redeemed. Because the depository receipts are also tokens, they are tradeable and can be further deposited into protocols that accept them.

Yield aggregators may also form partnerships with other protocols. For example, Yearn created its governance token YFI in July 2020. However, it would only be distributed to users who staked their yTokens (Yearn's interest-bearing tokens received from depositing stablecoins) in Curve's liquidity pool. This type of interoperability is possible if smart contracts grant permission to interact with one another.

Yield aggregator protocols identified via manual inspection of the addresses in this paper are 88mph, DeFi Saver, Furucombo, Harvest, Idle, Inverse, Mushroom, PoolTogether, Rain Capital, Robo, Shell, Volatility, and Yearn.

5.2. On-ramp service providers

On-ramp service providers are addresses that identify themselves as belonging to centralized exchanges such as Binance and Coinbase and semi-centralized services such as InstaDapp. They aggregate orders and transact on behalf of clients, providing access points to the DeFi ecosystem.

On-ramp service providers identified via manual inspection of the addresses in this paper are Binance, Dharma Finance, Eth2Dai, and InstaDapp.

5.3. Decentralized exchange (DEX)

Decentralized exchange protocols are sometimes called automated market maker (AMM) protocols. They facilitate token exchanges without needing a centralized, off-chain institution that typically uses an order book matching system. However, order book matching in DeFi is not popular because order flows generate data trails that are incredibly costly to record on the blockchain. As such, unmatched orders submitted on-chain would still cost gas, necessitating an alternative design.

Just as the name AMM suggests, participants are, in fact, market makers who must then face inventory risk. Users who provide liquidity in a pool by depositing tokens become willing counterparties for users who wish to exchange their tokens. In the order book matching system, users send in the desired orders, which are then matched to counterparties with the same terms of trade, providing price certainty at the expense of execution uncertainty. In AMM, users send one type of token she wishes to exchange, and the pool will send the other in return. A bonding curve (essentially a pricing function) will determine how many tokens of the other type she will receive. In other words, the user will have execution certainty (provided that she pays enough gas and the pool has sufficient liquidity to exchange) but faces price uncertainty since the price is a mathematical output of the bonding function. The act of exchanging is often referred to as a swap.

The bonding curve is a function of the quantities of tokens available in the pool. For this reason, large transactions *will* result in price slippage. A self-stabilizing bonding curve should generate relative token prices that make the token type in low supply prohibitively expensive to acquire (and vice versa). When the relative price in a pool is different from other trading venues, arbitrageurs can act to restore price parity. One popular example of a bonding curve is the constant product function ($xy = k$) where x and y are quantities of two tokens in a pool and k is a constant. For given quantities x and y, the exchange rate is the ratio of the two tokens. This function was first suggested by Vitalik Buterin (co-founder of the Ethereum blockchain) in a blog post in 2016 and further developed by Hayden Adams into Uniswap protocol in 2018.[36]

Lehar and Parlour (2021) show how a small pool can have wild swings in prices that are out-of-sync with other trading venues. However, the price difference diminishes as pool size grows, but Park (2021) argues that it gives rise to sandwich attacks similar to front-running that increase the cost of trading and threaten the long-term viability of the DeFi ecosystem.

Despite these shortcomings, with its simplicity, the constant product function is the most popular and adopted by many protocols such as Uniswap and SushiSwap. However, it permits only a pair of tokens. More generalized versions of bonding curves can allow for more tokens, such as the more complex constant functions of Balancer or Curve, the latter of which is designed for and is the most favored protocol for stablecoin swaps. Furthermore, for some specifications of bonding curves, as market prices change, the ratios of tokens in liquidity pools will change to keep up with market prices. Consequently, some DEX protocols can also be viewed as asset management protocols providing automatic portfolio rebalancing for users without paying gas.

As protocol performance directly depends on liquidity, protocol developers often provide generous rewards for users willing to

[36] Source: https://www.reddit.com/r/ethereum/comments/55m04x/lets_run_onchain_decentralized_exchanges_the_way/, accessed on November 11, 2022.

Table A1

Determinants of net deposits by address type. This table reports the result from the regressions of daily net deposits (deposits minus withdrawals) in $ million between May 2019 and June 2021 for the five primary tokens: ETH, WBTC, DAI, USDC, and USDT. Similar to Table 3, the explanatory variables include lagged supply rate, its interaction with an indicator for periods post COMP distribution, lagged supply COMP reward rate, the log dollar value of deposits in $ million, 1-day ETH return, 7-day ETH return, and 30-day ETH volatility (measured in percentage point). The flows to and from are aggregated by address type. Panel A reports the results for large addresses, Panel B for small addresses, Panel C for yield aggregator and asset management protocols, Panel D for unidentified contracts, and Panel E for addresses that also borrow. Standard errors are computed using the Newey-West procedure with a one-day lag and reported in parenthesis. Stars correspond to the statistical significance level, with *, **, and *** representing 10%, 5%, and 1%, respectively.

Panel A: Large address

	(1)	(2)	(3)	(4)	(5)
	cETH	cWBTC	cDAI	cUSDC	cUSDT
Lagged supply rate	−9.46	0.151	−5.81	−1.97	0.588
	(16.79)	(0.24)	(3.56)	(2.11)	(0.51)
Post COMP distribution	−1.71	2.90	−13.74	−12.21	0.719
	(4.82)	(2.26)	(16.33)	(12.57)	(1.39)
Post * lagged supply rate	27.22	3.14	6.45	2.17	−0.236
	(53.96)	(4.18)	(4.17)	(3.19)	(0.55)
Lagged supply reward	5.17	−2.65	0.192	7.49	0.016
	(12.38)	(3.09)	(1.82)	(5.48)	(0.23)
Log(pool size)	−0.002	−0.001	−0.004	−0.004	−0.008*
	(0.000)	(0.000)	(0.000)	(0.010)	(0.000)
ETH return (1d)	6.57	−21.54	−63.84	−68.13	−30.28*
	(54.21)	(28.62)	(83.09)	(120.52)	(16.18)
ETH return (7d)	−3.03	14.79	29.92	−4.04	7.45
	(22.79)	(13.92)	(29.22)	(59.90)	(6.44)
ETH SD (30d)	−37.08	1.955	110.59	−237.08	75.38*
	(230.14)	(117.53)	(220.28)	(415.71)	(44.93)
Constant	2.76	−1.29	14.14	12.71	−4.49**
	(9.24)	(4.23)	(12.54)	(15.91)	(1.94)
Observations	426	351	426	426	425
Adj R-squared	−0.014	−0.017	0.003	−0.006	0.037

Panel B: Small address

	(1)	(2)	(3)	(4)	(5)
	cETH	cWBTC	cDAI	cUSDC	cUSDT
Lagged supply rate	−12.83	1.64***	0.213	−0.202	1.29**
	(8.83)	(0.100)	(1.31)	(0.390)	(0.550)
Post COMP distribution	−4.47	2.64***	−2.16	−3.29*	3.24**
	(2.72)	(0.880)	(4.41)	(1.73)	(1.48)
Post * lagged supply rate	22.571	0.362	0.164	1.27***	−0.842
	(23.23)	(2.02)	(1.37)	(0.45)	(0.56)
Lagged supply reward	1.61	−0.957	0.108	0.047	−0.149
	(4.63)	(1.24)	(0.420)	(0.480)	(0.140)
Log(pool size)	0.000	0.000	−0.001	0.000	0.001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ETH return (1d)	−7.63	−24.49**	13.98	−0.204	8.56
	(18.70)	(12.18)	(13.12)	(12.40)	(5.69)
ETH return (7d)	11.052	8.25	8.52	−0.330	1.69
	(9.71)	(5.27)	(7.03)	(6.28)	(2.90)
ETH SD (30d)	−62.77	−75.59**	16.16	59.59	−6.85
	(67.00)	(38.24)	(35.11)	(39.09)	(29.26)
Constant	4.16	1.16	1.29	−1.35	−4.10**
	(3.06)	(1.27)	(2.80)	(1.76)	(1.68)
Observations	426	351	426	426	425
Adj R-squared	0.001	0.023	0.003	0.080	0.126

Panel C: Protocols

	(1)	(2)	(3)	(4)	(5)
	cETH	cWBTC	cDAI	cUSDC	cUSDT
Lagged supply rate	3.26	−0.006	−0.034	−0.551	0.007
	(3.12)	(0.010)	(0.140)	(0.430)	(0.010)
Post COMP distribution	−0.806	0.200	−0.910	−1.07	−0.058
	(0.92)	(0.160)	(1.48)	(1.92)	(0.360)
Post * lagged supply rate	17.79*	−0.005	0.311	0.615	0.001
	(10.23)	(0.11)	(0.23)	(0.49)	(0.04)
Lagged supply reward	−3.21	0.085	−0.063	0.260	0.025
	(2.79)	(0.160)	(0.200)	(0.730)	(0.070)
Log(pool size)	−0.002***	0.000	0.000	−0.000	−0.000

(continued on next page)

Table A1 (*continued*)

Panel C: Protocols					
	(1)	(2)	(3)	(4)	(5)
	(0.00)	(0.000)	(0.000)	(0.000)	(0.000)
ETH return (1d)	5.27	2.03	18.34**	−10.04	−8.14**
	(7.39)	(1.67)	(7.37)	(13.27)	(3.48)
ETH return (7d)	12.18**	0.841	−2.53	2.94	0.511
	(5.97)	(0.620)	(3.33)	(5.70)	(1.21)
ETH SD (30d)	72.18**	−2.82	−3.27	26.13	−0.814
	(31.67)	(3.71)	(21.02)	(45.01)	(8.20)
Constant	−2.93**	−0.012	0.162	0.001	0.039
	(1.22)	(0.120)	(0.830)	(1.77)	(0.300)
Observations	426	351	426	426	425
Adj R-squared	0.150	−0.001	0.016	−0.011	0.001

Panel D: Unidentified contract					
	(1)	(2)	(3)	(4)	(5)
	cETH	cWBTC	cDAI	cUSDC	cUSDT
Lagged supply rate	2.28	−0.041	0.021	−1.62	−0.164
	(3.05)	(0.040)	(0.020)	(2.03)	(0.32)
Post COMP distribution	−0.436	−0.212	−0.002	−17.93	−0.910
	(0.570)	(0.480)	(0.050)	(19.37)	(3.08)
Post * lagged supply rate	−5.25	−0.520	−0.027	5.44**	0.599
	(5.06)	(1.13)	(0.020)	(2.50)	(0.52)
Lagged supply reward	0.572	0.368	0.009	1.31	−0.812
	(0.960)	(0.650)	(0.020)	(2.04)	(1.03)
Log(pool size)	0.001***	0.000	0.000	0.001	0.002
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
ETH return (1d)	6.34	−2.80	0.779	53.98	31.38
	(5.13)	(7.82)	(0.520)	(80.28)	(21.47)
ETH return (7d)	−3.11	2.96	−0.519	58.06	2.39
	(2.35)	(3.52)	(0.360)	(49.03)	(11.78)
ETH SD (30d)	−10.81	41.82	−0.313	−262.56	122.56
	(17.89)	(38.26)	(1.19)	(256.86)	(94.58)
Constant	0.036	−1.44	0.033	9.86	−4.60
	(0.800)	(1.14)	(0.060)	(10.06)	(3.48)
Observations	426	351	426	426	425
Adj R-squared	0.095	−0.014	0.030	0.016	0.022

Panel E: Borrowers only					
	(1)	(2)	(3)	(4)	(5)
	cETH	cWBTC	cDAI	cUSDC	cUSDT
Lagged supply rate	−19.57	1.71***	−7.15	−2.04	1.08*
	(19.69)	(0.240)	(5.35)	(2.26)	(0.600)
Post COMP distribution	−6.44	4.16*	−34.09	−14.63	3.22**
	(5.66)	(2.46)	(28.01)	(14.62)	(1.47)
Post * lagged supply rate	46.35	2.64	11.39*	3.03	−1.098*
	(59.10)	(5.24)	(6.22)	(3.48)	(0.640)
Lagged supply reward	7.92	−3.18	2.22	7.24	0.061
	(13.66)	(3.82)	(3.27)	(5.95)	(0.220)
Log(pool size)	−0.001	0.000	−0.005	−0.004	−0.009*
	(0.000)	(0.000)	(0.010)	(0.010)	(0.010)
ETH return (1d)	2.10	−30.94	16.85	−35.47	−8.48
	(54.91)	(33.48)	(134.92)	(141.49)	(9.38)
ETH return (7d)	3.93	12.57	93.54	−14.46	5.43
	(24.58)	(17.21)	(64.38)	(72.42)	(6.15)
ETH SD (30d)	−108.140	–23.34	−105.32	27.744	94.81*
	(239.86)	(144.52)	(411.14)	(495.63)	(50.14)
Constant	6.94	−0.824	25.32	3.91	−6.83***
	(9.73)	(5.08)	(19.89)	(18.99)	(2.28)
Observations	426	351	426	426	425
Adj R-squared	−0.013	−0.018	0.013	−0.011	0.034

provide liquidity, especially when the market is thin, leading to the term *liquidity mining* used to describe this activity. Some of the most generous rewards are often found in the nascent days of a DEX protocol as it tries to attract liquidity.[37] Rewards could be provided in

[37] Uniswap only provided liquidity mining rewards for two months in 2020. Source: https://www.theblockcrypto.com/linked/84762/dex-uniswap-liquidity-mining-over, accessed on July 26, 2021.

Table A2

Determinants of loans drawn by address type. This table reports the result from the regressions of daily net deposits (deposits minus withdrawals) in $ million between May 2019 and June 2021 for the five primary tokens: ETH, WBTC, DAI, USDC, and USDT. Similar to Table 4, the explanatory variables include lagged borrow rate, its interaction with an indicator for periods post COMP distribution, lagged borrow COMP reward rate, the log dollar value of deposits in $ million, 1-day ETH return, 7-day ETH return, and 30-day ETH volatility (measured in percentage point). The flows to and from are aggregated by address type. Panel A reports the results for large addresses, Panel B for small addresses, Panel C for yield aggregator and asset management protocols, and Panel D for unidentified contracts. Standard errors are computed using the Newey-West procedure with a one-day lag and reported in parenthesis. Stars correspond to the statistical significance level, with *, **, and *** representing 10%, 5%, and 1%, respectively.

Panel A: Large address

	(1)	(2)	(3)	(4)	(5)
	cETH	cWBTC	cDAI	cUSDC	cUSDT
Lagged borrow rate	5.52***	−0.079	0.265**	0.332	0.638***
	(1.29)	(0.090)	(0.120)	(0.310)	(0.110)
Post COMP distribution	−6.14	−3.37**	−2.48***	2.48	9.16***
	(5.45)	(1.70)	(0.790)	(1.80)	(1.54)
Post * lagged borrow rate	−0.118	0.327	−0.149	−0.423	−0.511***
	(2.06)	(0.330)	(0.120)	(0.310)	(0.120)
Lagged borrow reward	0.574***	0.213*	0.257***	0.280***	−0.301**
	(0.120)	(0.120)	(0.050)	(0.080)	(0.150)
Log(pool size)	1.15***	0.844***	1.31***	2.32***	1.41***
	(0.420)	(0.250)	(0.150)	(0.250)	(0.150)
ETH return (1d)	1.90	0.413	2.81	−1.42	1.58
	(5.88)	(6.68)	(2.46)	(2.31)	(2.96)
ETH return (7d)	0.243	2.97	−0.193	1.35	−0.134
	(3.04)	(3.58)	(1.03)	(1.23)	(1.49)
ETH SD (30d)	−30.94	43.18	−34.12***	−65.49***	−24.35***
	(23.11)	(31.35)	(9.46)	(9.68)	(8.42)
Constant	−10.00***	−1.48	8.33***	0.392	−1.20
	(3.11)	(1.44)	(1.07)	(1.99)	(1.14)
Observations	426	351	426	426	425
Adj R-squared	0.175	0.095	0.364	0.596	0.585

Panel B: Small address

	(1)	(2)	(3)	(4)	(5)
	cETH	cWBTC	cDAI	cUSDC	cUSDT
Lagged borrow rate	2.49***	0.198***	0.087	−0.025	0.247***
	(0.560)	(0.070)	(0.060)	(0.080)	(0.090)
Post COMP distribution	3.84**	0.676	−1.22***	0.150	3.30***
	(1.68)	(0.91)	(0.41)	(0.52)	(1.02)
Post * lagged borrow rate	−1.15*	−0.477**	−0.052	−0.008	−0.226***
	(0.660)	(0.220)	(0.060)	(0.090)	(0.090)
Lagged borrow reward	0.015	0.102**	0.143***	0.103***	0.095*
	(0.040)	(0.050)	(0.030)	(0.030)	(0.050)
Log(pool size)	0.620***	0.267**	0.905***	0.973***	0.974***
	(0.090)	(0.130)	(0.080)	(0.070)	(0.120)
ETH return (1d)	2.36*	−3.96	1.37	0.461	−1.99
	(1.29)	(2.86)	(1.21)	(0.930)	(1.25)
ETH return (7d)	−0.541	0.203	0.788	0.525	1.67***
	(0.660)	(1.27)	(0.600)	(0.470)	(0.64)
ETH SD (30d)	−4.37	23.02	−14.83***	−17.57***	−14.18**
	(5.64)	(14.79)	(4.44)	(3.88)	(5.73)
Constant	2.02	8.40***	9.88***	9.49***	6.86***
	(1.39)	(0.790)	(0.490)	(0.530)	(0.940)
Observations	426	351	426	426	425
Adj R-squared	0.505	0.048	0.549	0.669	0.645

Panel C: Protocols

	(1)	(2)
VARIABLES	cWBTC	cUSDC
Lagged borrow rate	0.036	−0.125
	(0.030)	(0.270)
Post COMP distribution	−3.02***	−1.37
	(0.67)	(1.59)
Post * lagged borrow rate	0.487***	−0.140
	(0.160)	(0.280)
Lagged borrow reward	0.084*	−0.277**
	(0.050)	(0.120)
Log(pool size)	0.619***	3.16***

(continued on next page)

Table A2 (*continued*)

Panel C: Protocols

	(1)	(2)
	(0.140)	(0.290)
ETH return (1d)	−1.71	−0.623
	(4.71)	(3.80)
ETH return (7d)	2.70	−1.41
	(2.05)	(2.51)
ETH SD (30d)	0.701	60.81***
	(19.02)	(15.73)
Constant	−2.23***	−15.59***
	(0.500)	(1.62)
Observations	351	426
Adj R-squared	0.108	0.568

Panel D: Unidentified contract

	(1)	(2)	(3)	(4)	(5)
VARIABLES	cETH	cWBTC	cDAI	cUSDC	cUSDT
Lagged borrow rate	1.726*	0.086	−0.118	0.374	0.566***
	(1.00)	(0.24)	(0.24)	(0.45)	(0.20)
Post COMP distribution	3.21	−2.97	−5.26***	−2.90	5.07**
	(2.55)	(2.01)	(2.00)	(2.53)	(2.55)
Post * lagged borrow rate	−2.481**	−0.009	0.396	−0.260	−0.543**
	(1.10)	(0.35)	(0.25)	(0.47)	(0.21)
Lagged borrow reward	0.052	0.021	−0.065	0.031	0.288*
	(0.060)	(0.080)	(0.120)	(0.160)	(0.150)
Log(pool size)	0.490***	0.740***	1.94***	2.89***	0.317
	(0.170)	(0.190)	(0.340)	(0.300)	(0.200)
ETH return (1d)	0.978	−4.48	4.14	1.78	−2.19
	(3.59)	(5.80)	(4.34)	(5.12)	(6.24)
ETH return (7d)	−2.09	1.32	−0.231	1.47	−0.437
	(1.48)	(2.84)	(2.15)	(2.57)	(3.63)
ETH SD (30d)	34.62**	−3.63	21.75	36.46**	−68.85***
	(16.69)	(27.56)	(15.63)	(16.76)	(18.08)
Constant	−6.09***	1.76	0.935	−9.80***	0.735
	(2.35)	(1.82)	(1.52)	(2.67)	(1.91)
Observations	426	351	426	426	425
Adj R-squared	0.109	0.024	0.188	0.318	0.061

the protocol's native tokens or other protocol's native tokens if a partnership between protocols can be formed. For example, the Aave liquidity pool on Curve, which accepts aDAI, aUSDC, and aUSDT, distributes CRV (Curve's governance token) and stkAAVE (staked version of AAVE) as rewards.

Like yield aggregators, when tokens are deposited, users receive depository receipts, which in this context are LP tokens, representing a pro-rata share of the pool. Most DEX pools accrue transaction fees, so users will also get their share of fees upon redemption. For liquidity pools containing tokens with low price correlation, the value of the redeemed pro-rata tokens can be different from the value of the deposited tokens. This slight discrepancy arises from the curvature of the bonding curve. The severity depends on how the prices of the tokens diverge, leading to this counterfactual loss being called *divergent loss* or *impermanent loss*. For pools where tokens prices are highly correlated such as stablecoins or wrapped tokens, this problem is less pertinent; consequently, such pools also tend to receive little or no liquidity mining reward.

The reliance on the depth of liquidity is not limited to DEX but is a general feature of peer-to-pool transactions in DeFi. As discussed earlier, lending protocols also require liquidity (reflected in the utilization ratio); otherwise, interest rates will adjust. Thus, smart contracts can be viewed as another intermediary with explicit rules governing interactions between users and the intermediary. The rules are hardcoded into the blockchain and enforced autonomously without discretion or prejudice. Because the protocol's liquidity directly influences a protocol's efficiency, developers often employ strategies such as offering liquidity mining rewards to bootstrap liquidity from users.

Decentralized exchange protocols identified via manual inspection of the addresses in this paper are 1 in., BlackHoleSwap, Curve, ParaSwap, SushiSwap, and Uniswap.

5.4. Asset management

While the services provided by yield aggregators can also be considered asset management, in this paper, we define asset management protocols as protocols that behave like indexed funds, allowing users to maintain a balanced exposure to a basket of tokens or a specific strategy. The protocol involves a pool of tokens where the proportion of each token mirrors an index, where depositors, in turn, are given depository tokens like fund units. Because the units are tradeable assets, this makes them more similar to exchange-traded funds (ETFs) than mutual funds. However, the creation and redemption process is open to all, not limited to authorized

Table A3
cToken holder leaderboard. This table reports the cToken holders at different points in time. Historical holders are computed based on the entire history of the cToken transfers, while the holders as of February 2022 are obtained from Etherscan.io. Addresses of the top 10 holders are manually examined and classified using the scheme described in the Appendix.

Panel A: cETH holders	
cETH as of June 30, 2021	Share (%)
[Celsius Network] 0x8aceab8167c80cb8b3de7fa6228b889bb1130ee8	13.77
[Address] 0x716034c25d9fb4b38c837afe417b7f2b9af3e9ae	12.41
[Yield Agg / Vesper] 0xffc4c270244f9c0890c744f042f5f25f9ff8d4b5	4.99
[Address] 0xc33d98e88682c883fe32b8f6620660692092d39f	3.94
[Address] 0x388b93c535b5c3ccdb14770516d7caf5590ed009	3.52
[Address] 0x4740fa6b32c5b41ebbf631fe1af41e6fff6e2388	3.14
[Gnosis Safe] 0xbc79855178842fdba0c353494895deef509e26bb	3.00
[AssetMgmt / Index Coop] 0xaa6e8127831c9de45ae56bb1b0d4d4da6e5665bd	2.97
[Address] 0x2baba0cba8241fda56871589835e0b05ec64ca41	2.05
[Address] 0xc26b5977c42c4fa2dd41750f8658f6bd2b67869c	1.80
The sum of the top ten addresses	51.60
cETH as of Feb 11, 2022	Share (%)
[Celsius Network] 0x8aceab8167c80cb8b3de7fa6228b889bb1130ee8	21.02
[Address] 0x716034c25d9fb4b38c837afe417b7f2b9af3e9ae	11.37
[AssetMgmt / Index Coop] 0xaa6e8127831c9de45ae56bb1b0d4d4da6e5665bd	4.66
[InstaDApp] 0xfa5dcf356a2d80cf0c89d64a18a742edaf8d30e8	4.23
[InstaDApp] 0x3a0dc3fc4b84e2427ced214c9ce858ea218e97d9	3.60
[Address] 0xc26b5977c42c4fa2dd41750f8658f6bd2b67869c	2.54
[Holdnuat] 0x99fd1378ca799ed6772fe7bcdc9b30b389518962	2.41
[Address] 0xbebcf4b70935f029697f39f66f4e5cea315128c3	2.37
[Address] 0x1f244e040713b4139b4d98890db0d2d7d6468de4	1.89
[Gnosis Safe] 0xe84a061897afc2e7ff5fb7e3686717c528617487	1.79
The sum of the top ten addresses	55.88
Panel B: cDAI holders	
cDAI as of June 30, 2021	Share
[Address] 0x9b4772e59385ec732bccb06018e318b7b3477459	23.11
[InstaDApp] 0x4c81ac8a069122d2a7146b08818fbaddcb2ff1f0	10.01
[InstaDApp] 0xe4bed3988b25eb625466102f2d0bea1c9fafcd86	9.05
[InstaDApp] 0x742fb193517619eecd6595ff106fce2f45488ebf	5.79
[InstaDApp] 0x9fe9dc57bf733bdafd0d6d4610d2d671f8dc974f	4.38
[YieldAgg / Idle] 0x78751b12da02728f467a44eac40f5cbc16bd7934	4.16
[InstaDApp] 0x2cc308d515a73690ba58ed637d1b20b4b7324fcd	3.71
[Contract] 0x2cc308d515a73690ba58ed637d1b20b4b7324fcd	3.71
[InstaDApp] 0x10d88638be3c26f3a47d861b8b5641508501035d	3.61
[Address] 0x10bf1dcb5ab7860bab1c3320163c6dddf8dcc0e4	3.25
The sum of the top ten addresses	70.80
cDAI as of Feb 11, 2022	Share (%)
[Contract / Yearn] 0x1676055fe954ee6fc388f9096210e5ebe0a9070c	21.81
[InstaDApp] 0x1d1e63975486dfa6e7f28448ae224c9f41588642	16.87
[InstaDApp] 0x10d88638be3c26f3a47d861b8b5641508501035d	15.86
[InstaDApp] 0x638e9ad05dbd35b1c19df3a4eaa0642a3b90a2ad	14.86
[InstaDApp] 0x41d207bc7e5d1f44aaf572d4a06cd0ef1ea2b01b	6.45
[Lending / Notional] 0x1344a36a1b56144c3bc62e7757377d288fde0369	6.25
[DEX / Curve.fi] 0xa2b47e3d5c44877cca798226b7b8118f9bfb7a56	2.47
[Contract / Bridge] 0x4aa42145aa6ebf72e164c9bbc74fbd3788045016	2.12
[Address] 0x10bf1dcb5ab7860bab1c3320163c6dddf8dcc0e4	1.69
[Fei Protocol: PCV] 0xe0f73b8d76d2ad33492f995af218b03564b8ce20	1.04
The sum of the top ten addresses	89.42
Panel C: cUSDC holders	
cUSDC as of June 30, 2021	Share (%)
[Address] 0xb3bd459e0598dde1fe84b1d0a1430be175b5d5be	6.16
[YieldAgg / PoolTogether] 0xde9ec95d7708b8319ccca4b8bc92c0a3b70bf416	4.44
[DEX / Curve.fi] 0xa2b47e3d5c44877cca798226b7b8118f9bfb7a56	4.42
[Contract] 0x25a033316752ac9e443a10be07fa56c125b93c29	4.36
[YieldAgg / Vesper] 0xbf84b97beabc953a7a2ad630940065b69d24c912	4.30
[Contract] 0xdaa037f99d168b552c0c61b7fb64cf7819d78310	4.22
[YieldAgg / Idle] 0x5274891bec421b39d23760c04a6755ecb444797c	3.40
[Address] 0xd31ab5ab8cd0f482f5728888519b5c39b5a4a6a0	3.07

(continued on next page)

Table A3 (*continued*)

Panel C: cUSDC holders	
cUSDC as of June 30, 2021	**Share (%)**
[Address] 0x22fa8cc33a42320385cbd3690ed60a021891cb32	2.92
[Address] 0x1e17f8876b175d37ebe08849434973c051261461	2.78
The sum of the top ten addresses	40.07
cUSDC as of Feb 11, 2022	**Share (%)**
[YieldAgg / Yearn] 0x342491c093a640c7c2347c4ffa7d8b9cbc84d1eb	7.25
[InstaDApp] 0x3a0dc3fc4b84e2427ced214c9ce858ea218e97d9	6.62
[Address] 0xabde2f02fe84e083e1920471b54c3612456365ef	6.50
[YieldAgg / Angle] 0x6d7ccd6d3e4948579891f90e98c1bb09a8c677ea	6.33
[Lending / Notional] 0x1344a36a1b56144c3bc62e7757377d288fde0369	5.91
[Address] 0xdb7030beb1c07668aa49ea32fbe0282fe8e9d12f	4.47
[YieldAgg / Yearn] 0x7900c70a377f89df29d1d1939469ae3b74c5b740	4.45
[Address] 0xb3bd459e0598dde1fe84b1d0a1430be175b5d5be	4.07
[Justin Sun] 0x3ddfa8ec3052539b6c9549f12cea2c295cff5296	3.70
[Proxy Contract] 0x2d15fcd5d6849a72f0bda676a1f2f1aede7467f5	3.64
The sum of the top ten addresses	52.94
Panel D: cUSDT holders	
cUSDT as of June 30, 2021	**Share (%)**
[Address] 0xf23913349c935dacc7c51ee692961ebc0d69fc35	7.25
[Address] 0x7d6149ad9a573a6e2ca6ebf7d4897c1b766841b4	4.69
[Address] 0xb99cc7e10fe0acc68c50c7829f473d81e23249cc	4.59
[Address] 0x102fa4db3bc6a70d85513a4f424e739ef922bf1e	3.15
[Address] 0x0c731fb0d03211dd32a456370ad2ec3ffad46520	2.84
[Address] 0x01d2e7cea783b0458ba6b58e93906b19b9741889	2.65
[Address] 0x133b590c0d9d9051c78f959ac1eb435c7676dcdc	2.63
[Address] 0xfb849f0b58ee2421b788005c15c1485f384de73f	2.07
[Address] 0xd5433168ed0b1f7714819646606db509d9d8ec1f	1.86
[Address] 0x251b32806b4cd6bc50470ea94a07462609ef798d	1.67
The sum of the top ten addresses	33.41
cUSDT as of Feb 11, 2022	**Share (%)**
[Justin Sun] 0x3ddfa8ec3052539b6c9549f12cea2c295cff5296	9.81
[Address] 0x1a8c53147e7b61c015159723408762fc60a34d17	8.34
[Address] 0xb99cc7e10fe0acc68c50c7829f473d81e23249cc	6.40
[Alameda Research] 0x712d0f306956a6a4b4f9319ad9b9de48c5345996	6.14
[Address] 0xe9bf81b432e5bf34995afae08747c530c8406c4d	4.32
[Address] 0x01d2e7cea783b0458ba6b58e93906b19b9741889	2.03
[Address] 0x638edf6438ec145454b3ea483fea7339377fe80f	1.91
[FTX Exchange] 0x2faf487a4414fe77e2327f0bf4ae2a264a776ad2	1.62
[Address] 0xfb849f0b58ee2421b788005c15c1485f384de73f	1.60
[Address] 0xf07766108cdb54082f7b06cad20d6adab1342d46	1.42
The sum of the top ten addresses	43.58

market participants. Examples of such protocols are Set Protocol and Balancer.

There are few protocols under this category because some liquidity pools in decentralized exchanges can also be considered asset management protocols, maintaining a balanced exposure to the tokens they hold. However, the permissible baskets are much more limited (e.g., two tokens or stablecoins only), and the exposure rule is defined by the bonding curve rather than an index. Under this definition, stablecoin protocols that create stablecoins from other stablecoins (e.g., mStable) can also be considered an asset management protocol, as it is indexed to the US dollar value.

Asset management protocols identified via manual inspection of the addresses in this paper are BasketDAO, DeFiner, Index Coop, Origin Dollar, PieDAO, Set Protocol, and mStable.

5.5. Unidentified contracts

Ethereum addresses that contain codes are classified as smart contracts rather than wallets. This information is visible on blockchain explorer websites such as Etherscan.io. However, not all smart contracts disclose source codes and affiliations, and we can only see their binary data. One example is '0x0000006daea1723962647b7e189d311d757Fb793' which, as of July 26, 2021, holds records of over 546,400 transactions and 124 types of tokens worth over $104 million. However, nothing else about the address is known. Nevertheless, not all contracts are as active and valuable as this example.

Complicated instructions such as recursive borrowing (also employed by yield aggregator protocols) can be automated via smart contracts. These addresses may belong to individuals or institutions but suggest a higher level of sophistication than simple addresses that need to submit each step of the instructions manually, so we separate them into a distinct classifications. They may also be part of a

Table A4
Borrower leaderboard. This table reports the cumulative loans drawn from cToken contracts until June 2021. Net deposits are the net dollar amount deposited or withdrawn from cToken contracts. If net deposits are negative, the address owner likely acquired cTokens via other means and used them to redeem for deposits from cToken contracts. Buying them to redeem could provide arbitrage profit depending on the secondary market price of the cTokens. COMP governance tokens claimed are reported in units.

Address	Total Loans ($ m)	Net Deposits ($ m)	COMP Claimed (units)
[Address] 0x4740fa6b32c5b41ebbf631fe1af41e6fff6e2388	4,331.17	81.5	196.4
[Address] 0x2bdded18e2ca464355091266b7616956944ee7ee	3,781.70	−407.4	50,349.2
[yDai exploiter] 0x62494b3ed9663334e57f23532155ea0575c487c5	2,940.41	0.0	0.0
[InstaDApp] 0x691d4172331a11912c6d0e6d1a002e3d7ced6a66	1,997.00	0.0	0.0
[Contract / Yearn] 0x77b7cd137dd9d94e7056f78308d7f65d2ce68910	1,788.63	−3.1	6,659.8
[Alameda Research] 0x4deb3edd991cfd2fcdaa6dcfe5f1743f6e7d16a6	1,440.20	−6,693.5	6,225.3
[Contract / Yearn] 0x4031afd3b0f71bace9181e554a9e680ee4abe7df	1,389.26	−6.8	15,331.9
[Three Arrows Capital] 0x3ba21b6477f48273f41d241aa3722ffb9e07e247	1,357.27	−130.2	27,088.7
[Address] 0x3aa39dff4964043a61d94029fcedaac2f02f3187	1,162.90	−22.0	4,741.5
[Contract / Yearn] 0xe68a8565b4f837bda10e2e917bfaaa562e1cd143	1,075.70	−3.4	7,215.2
[Proxy Contract] 0xccb06b8026cb33ee501476af87d5ccaf56883112	1,055.34	−162.5	61,569.4
[Contract / Yearn] 0x339dc96a37dba86008126b3391db77af93cc0bd9	956.85	−0.3	1,893.3
[Address] 0x9b4772e59385ec732bccb06018e318b7b3477459	955.91	1,126.8	4,188.3
[Address] 0x1f99aaa8b4fb631d25b38b8a9099ef8f2611e46b	908.00	23.4	4,708.1
[InstaDApp] 0x2a1739d7f07d40e76852ca8f0d82275aa087992f	813.70	0.0	0.0
[Contract / Yearn] 0x55ec3771376b6e1e4ca88d0eea5e42a448f51c7f	793.60	−0.4	2,151.3
[Contract / Yearn] 0x4d7d4485fd600c61d840ccbec328bfd76a050f87	792.51	−3.7	10,108.7
[Address] 0x767ecb395def19ab8d1b2fcc89b3ddfbed28fd6b	767.72	−3,585.8	8,687.9
[Address] 0xb1adceddb2941033a090dd166a462fe1c2029484	761.99	−3,085.0	6,119.4
[InstaDApp] 0x06cb7c24990cbe6b9f99982f975f9147c000fec6	711.26	−1,813.1	47.0

yield aggregator protocol but are not labeled explicitly in Etherscan.io, making them harder to identify.

CRediT authorship contribution statement

Kanis Saengchote: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix. Determinants of net deposits and loan demand by address type

See Tables A1-A2.
Appendix: Compound Leaderboards.
See Tables A3-A4.

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