DAO Governance[*]

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Abstract

Decentralized autonomous organizations (DAOs) are entities without central leadership that operate based on a set of decision-making rules encoded into smart contracts using blockchain technology. In this study, we develop a theoretical model of DAO governance featuring strategic token trading under token-based voting to investigate potential conflicts of interest between a large participant (a "whale") and many small participants. Our results show that ownership concentration can have a negative effect on platform growth, but platform size, token illiquidity, and long-term incentives can mitigate the negative effects. We confirm these predictions using novel voting data on over 200 DAOs between 2020 and 2022.

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1 Introduction

Blockchain technology has popularized decentralized autonomous organizations (DAOs) as a new kind of organizational structure that runs as “smart contracts” on the blockchain. Unlike traditional companies, DAOs are entities without central leadership and are instead collectively owned and managed by their members through decision-making and economic rights provided by tokens. DAOs have experienced rapid growth in recent years, with the number of DAOs increasing by 300% in 2022 alone (Pixelplex, 2023). Despite the increasing popularity of DAOs, there continues to be a general lack of understanding about them. Specifically, DAO governance is a subject that has recently drawn great attention.

On the one hand, DAOs can offer benefits through increased transparency and democratic decision-making. For example, Uniswap, a decentralized exchange (DEX), employs a two-step governance structure that involves off-chain discussions (“temperature checks”) before voting on proposals via the Ethereum blockchain to decide on new liquidity pools and fee structures. This bottom-up governance structure harnesses collective wisdom to allow the platform to evolve and grow. On the other hand, despite their potential benefits, there has also been evidence against the effectiveness of DAOs in practice. For example, there have been instances of governance failure on DEXs, notably “rug pulls,” where large holders (often developers) make unfavorable changes to take advantage of private benefits and subsequently dump tokens, harming minority token holders (Li et al., 2022). Notorious cases of such rug pulls include the YAM Finance and SushiSwap incidents. In the YAM Finance incident, the developers behind the project created a bug in the smart contract that caused the entire project to collapse, resulting in significant losses for investors. The SushiSwap incident involved the original developer of the project, known as “Chef Nomi,” abruptly leaving and selling all of their SUSHI tokens, causing the price to plummet and leading to investor losses.

These rug pull incidents highlight an important but understudied issue in DAO governance: the potential conflict of interest between large token holders, commonly known as "whales," and small token holders in DAOs. The autonomous nature of DAOs means that there is no need for monitoring agents to control the organization. But this also means that there is a danger that whales can capture control and impose their preferences on the system (Makarov and Schoar, 2022). A whale can swing the vote outcome using their large holdings whereas dispersed small token holders cannot individually. Therefore, open-market trading of governance tokens that carry voting rights may enable whales to accumulate enough voting power to manipulate votes, leading to short-term gains at the expense of minority token holders. This governance risk can impede platform growth. Using the setup of token-based voting systems, our paper sheds light on understanding the triangular relationship between the value (or the growth) of a DAO platform, its ownership concentration, and token trading. Our paper is the first to investigate both theoretically and empirically the conflicts of interest between whales and small token holders of DAOs, their negative effects, and possible ways to mitigate these consequences.

To formally study the aforementioned problem, we develop an equilibrium model of a DAO platform featuring token-based voting and dynamic token trading. Initially, one unit of tokens is issued upon the establishment of the platform, and voting rights are equally distributed across all token units (i.e., "one token, one vote"). The platform uses a token-based voting system to decide whether to implement a proposal based on voting outcomes according to token ownership.

The model includes a continuum of small participants, referred to as "users," and a large participant referred to as the "whale." The platform generates utility flows for participants based on their token ownership. However, if the incentives between the users and the whale are misaligned, the whale may benefit privately from implementing a value-destroying proposal for users. The whale must acquire enough tokens to win the vote (e.g., half of the tokens in the case of the majority rule), even with their own voting power, despite the users' opposition to the proposal. However, acquiring tokens may be costly due to the significant price impact that the whale has to internalize in open-market trading. The fundamental value of the platform could be destroyed if the whale's self-serving proposal is more likely to be implemented in equilibrium. Therefore, the platform with a greater governance problem will face lower growth in its value.

The whale faces a trade-off between their private benefit and the cost of implementing a rug-pull strategy. This cost arises from two sources: the loss in platform service value caused by the whale's own stake in the platform and the transaction costs incurred by acquiring tokens to win the proposal. Considering the convexity of the price impact cost, it becomes more advantageous for the whale if the target token acquisition for influencing voting outcomes is smaller. Therefore, ownership concentration can greatly mitigate the cost of acquiring voting rights, implying that the value of a platform should be negatively associated with ownership concentration (Prediction 1). In other words, the more concentrated voting power the whale has, the more likely they are to destroy the platform's value.

We further investigate the impact of other key characteristics of a DAO that affect the negative relationship between ownership concentration by the whale and the growth of the platform's value. Our second finding is that the impact of the whale's ownership concentration on value-destroying voting outcomes is reduced if the platform already has a higher service value (Prediction 2). Since the whale already has a stake in the platform, they do not want to incur a loss by passing a value-destroying proposal.

Our third finding is that the impact of ownership concentration on the platform's value is reduced by token illiquidity (Prediction 3). When tokens are illiquid, it is more expensive for the whale to acquire extra tokens to implement self-serving proposals. Therefore, illiquidity can shield users against the effects of bad governance. This insight aligns with that of quadratic voting schemes, which discourage a single participant from achieving dominant voting power. Therefore, token illiquidity serves as a natural quadratic voting scheme that does not have disadvantages such as a Sybil attack in the case of token-based voting schemes.[1]

This seemingly paradoxical result, where illiquidity can benefit the governance of a DAO, hinges on the fact that active monitoring is unnecessary due to its autonomous nature. As noted in our literature review, liquidity is known to have a beneficial effect on the governance of traditional firms by facilitating active monitoring in the presence of a principal-agent problem between management and shareholders.

Finally, our model suggests that if a whale also pursues the platform's long-term growth, a platform may expand more swiftly and increase in value. Therefore, a different governance mechanism that rewards the whale for making long-term commitments could resolve any potential governance concerns in decentralized digital organizations (Prediction 4).

We bring these predictions to the data, uncovering consistent evidence that largely supports our theory. We begin with the 460 largest DAOs that sponsored proposals through Snapshot, a dominant off-chain voting platform, during the period running from July 20, 2020 through July 31, 2022. Our final sample includes 207 DAOs that have non-missing price and volume information for their governance tokens as well as non-missing data on total value locked (TVL), a proxy for platform size. Importantly, we manually collect data on the various governance mechanisms used by these decentralized platforms, such as governance tokens, staking, and vote escrow/locking strategies, the latter of which reward investors greater voting power and yields for locking their governance tokens. Our sample includes most major DAO platforms and is more comprehensive than those used in the literature. For example, Fritsch, Müller, and Wattenhofer (2022) features only three platforms.

We perform weekly panel regressions to examine the relationship between platform growth

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[1] A Sybil attack is a situation where an attacker exploits a network system by creating a large number of pseudonymous identities and uses them to gain a disproportionately large influence.

and two proxies for voting power concentration. Since proposals typically are not made every day, we convert the voting data to weekly series. If multiple proposals are sponsored in a given week, we use weekly averages of voting power concentration. Our dependent variable is the weekly growth rate of TVL and our independent variables of interest are the Herfindahl-Hirschman Index (HHI) of voting power and the total voting shares controlled by the top three voters in each DAO. These independent variables are lagged by one week. We control for DAO and week-fixed effects, with standard errors being clustered at the DAO level.

We find a significant and negative correlation between TVL growth and the HHI of voting power. A one standard deviation increase in HHI is associated with a 1.1 percentage-point decrease in weekly TVL growth. The magnitude is economically significant given that the average weekly TVL growth is only -0.9%. Similarly, we show that the top three voters' ownership negatively influences platform growth, with the marginal effect being significantly greater than the average weekly TVL growth. These results are consistent with our first theoretical prediction, which states that platform growth accelerates when voting power is more decentralized.

We further test our second prediction that the negative effect of the HHI of voting power on TVL growth would be reduced if a platform has a wider user group hence a higher network value. We expect a similar dampening effect of token illiquidity (Prediction 3), which leads whales to suffer a significant price impact when they attempt to amass a large stake. To potentially manipulate the price of a token, a whale can accumulate significant voting power to pass a proposal that generates private benefits to the whale (e.g., a proposal that drains the funds of a liquidity pool) while hurting other investors. Such actions are ex-ante more costly when tokens are illiquid, prompting whales to align their incentives with minority token holders. We use the Amihud (2002) illiquidity measure as our empirical proxy for token illiquidity.

We test these predictions by adding an interaction term between the HHI of voting power and platform size (proxied by lagged TVL) to our baseline regression specification. We find a positive and statistically significant coefficient on the interaction term, suggesting that higher valuation indeed reduces the negative relationship between platform growth and ownership concentration. We find a similar result when using an interaction term of HHI and token illiquidity instead.

Finally, we test our last prediction by examining events where platforms shifted from the one-token-one-vote model, which is used by most DAOs such as Lido and Uniswap, to a staking model. Pioneered by Curve Finance, a DEX launched in 2020, a growing number of protocols have adopted a staking model, which assigns vote weights and yields that are generally proportional to a "locking period." That is, investors can lock their governance tokens to gain more voting power and enhance their investment yields. Using an event-study framework, we compare the TVL growth of a set of DAOs that switched to a staking model during our sample period with that of a control group of DAOs that did not adopt staking models. To sharpen identification, we use a relatively short event window of Day -6 to Day 1 around the adoption date of the new governance model. Treated platforms exhibit an 8.3 percentage-point higher growth rate during the event window compared to control platforms. This is an economically significant effect given that our sample DAOs on average generate a slightly negative weekly growth rate.

Our study contributes to the literature on the governance of DAOs. To the best of our knowledge, we are the first to theoretically examine DAOs' governance issues and derive equilibrium implications, whereas the few studies in this literature primarily provide empirical descriptions of the distribution of votes (Fritsch, Müller, and Wattenhofer, 2022; Appel and Grennan, 2023a,b). A contemporaneous theory paper by Aoyagi and Ito (2022) is a notable exception. They, however, focus on competition among DAOs rather than conflicts of interest among DAO investors, which we analyze in this paper.

We are also the first to provide empirical evidence linking decentralization to platform growth and token valuation, expanding the theoretical intuitions proposed by Cong, Li, and Wang (2021) and Sockin and Xiong (2023). We theoretically demonstrate how minority token investors in a DAO can endogenize their participation decision to prevent being harmed by whales. We also show how costly token acquisition by whales can improve DAO governance. We provide empirical evidence that supports both intuitions using our novel voting data on DAOs. Furthermore, our event-study setup reveals that alternative governance mechanisms, such as staking and vote escrow systems, as opposed to the typical one-token-one-vote model, can increase long-term incentives of whales and hence platform growth. Overall, our study provides a comprehensive analysis of DAO governance issues and their potential solutions, both theoretically and empirically, thus filling an important gap in the literature.

Related Literature Our work is broadly related to the literature on the wisdom of crowds, information cascade, and decentralization in cryptocurrency markets. Notable theoretical contributions to token-based platforms include Cong and Xiao (2019), Li and Mann (2020), Chod and Lyandres (2021), Lee and Parlour (2021), Gan, Tsoukalas, and Netessine (2021), and Cong, Li, and Wang (2022). A string of empirical studies in this area also contributes to our understanding of the issues at play during and after platforms' fundraising (Howell, Niessner, and Yermack, 2020; Lee, Li, and Shin, 2021; Bourveau et al., 2022; Lyandres, Palazzo, and Rabetti, 2022; Davydiuk, Gupta, and Rosen, 2023). Our work is also related to the emerging literature on DeFi (e.g., Harvey, Ramachandran, and Santoro, 2021; Makarov and Schoar, 2021; Cong et al., 2022; Augustin, Chen-Zhang, and Shin, 2022; Park, 2022; Capponi and Jia, 2021; Lehar and Parlour, 2021; Barbon and Ranaldo, 2021).

Our paper contributes to the burgeoning literature on blockchain economics and its governance implications in the new digital era (Harvey, 2016; Yermack, 2017; Malinova and

Park, 2017; Cong and He, 2019; Makarov and Schoar, 2022; Saleh, 2021; Roşu and Saleh, 2021; Tsoukalas and Falk, 2020). Bena and Zhang (2022) analyze the trade-off between user adoption and technology advancement in the optimal design of a governance token. Ferreira, Li, and Nikolowa (2022) show that the proof-of-work system in a blockchain ecosystem allows large firms that produce equipment and manage mining pools to capture blockchain governance by leveraging their advantage in operating these pools to influence votes. Benhaim, Falk, and Tsoukalas (2022) show that committee-based consensus using approval voting converges to optimality quickly, and has the potential to address issues raised by commonly employed mechanisms. Sockin and Xiong (2023) show that tokenization through utility tokens can be a commitment device that prevents the owner of a platform from exploiting its users. Our paper complements this strand of literature by studying DAO governance, which operates without a central authority to govern the organization. Specifically, we investigate the role of strategic trading by a whale for accumulating voting power under a token-based voting scheme.

Our theory also draws on key insights from the extensive literature on organizational economics, corporate governance, shareholder voting, and blockholder governance (e.g., Shleifer and Vishny, 1986; Holmstrom and Tirole, 1989; Harris and Raviv, 1989, 2006; Burkart and Lee, 2008). Specifically, our paper is related to the literature that examines the interplay between corporate control and trading of ownership shares, as seen in works such as Maug (1998), Bolton and Von Thadden (1998), and Pagano and Röell (1998). Previous studies in this line of literature emphasize the monitoring role of large shareholders in correcting managerial failures.[2] Our paper is closely related to recent contributions to the literature

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[2] In models featuring monitoring by blockholders, Maug (1998) demonstrates that a more liquid stock market increases monitoring activities by allowing investors to cover monitoring costs through informed trades. Bolton and Von Thadden (1998) demonstrate that a firm is more likely to adopt a dispersed ownership structure if there is greater active trading in its secondary market and if regulations enable takeovers as a means of gaining control.

which study the impact of pivotality in voting in connection with trading of voting rights (e.g., Posner and Weyl (2014) and Lalley and Weyl (2018)). In Levit, Malenko, and Maug (2019), multiplicity of voting outcomes can arise because of the reinforcement between voting and trading. Levit, Malenko, and Maug (2021) show that a voting premium can emerge due to the price impact of blockholders who want to accumulate more shares to control the voting. DAO governance differs from those in the previous governance literature along several important dimensions. First, the autonomous nature of DAOs means that there is no need for active management monitoring. Second, in DAO governance, the traditional distinction between users and shareholders is blurred, which, combined with the network externality of user participation, has significant implications for the value of DAOs. These stark differences necessitate a new approach to governance of DAOs. Our paper complements this strand of literature by examining the role of token trading in this unique form of governance.

2 Institutional Background

A corporation is a legal structure that separates its owners (shareholders) from its managers (agents). It operates on a top-down governance model where agents are given authority to manage the company on behalf of shareholders, who expect to receive earnings based on their ownership in the business. However, under this centralized governance structure, agents may prioritize their own interests over those of shareholders if proper monitoring mechanisms and incentives are not in place. This is known as the managerial agency problem. Several approaches have been proposed to address it, such as blockholder ownership, managerial stock options, board independence, and markets for control and competition (Bebchuk and Weisbach, 2010; Adams, Hermalin, and Weisbach, 2010). Additionally, when shareholders' interests diverge from those of other stakeholders, such as employees, customers, and suppliers, the company may not be able to withstand extreme market risks (e.g., climate risk, reputational damage, pandemic events) or achieve sustainable growth (Edmans, 2011, 2021; Lins, Servaes, and Tamayo, 2017; Albuquerque et al., 2020; Ding et al., 2021).

An alternative to this structure is a DAO. Unlike a corporation, a DAO is not managed by a single person or team but rather governed by all its members through a token-based voting system. Members discuss and make decisions online and implement changes using smart contracts on a decentralized ledger. This allows for immediate implementation of new policies once consensus is reached among members who hold tokens issued by the platform.

DAOs are fundamentally different from corporations in terms of control and decision-making. Below we delve deeper into the key distinctions between these two organizational structures.

Automation and Decentralization-based Economies of Scale

DAOs can leverage automation and decentralization to achieve economies of scale. By eliminating traditional overhead expenses such as staff salaries and office rent, DAOs can operate with a leaner and more efficient structure. Additionally, the decentralized governance structure allows for participation from anyone holding tokens and an interest in the organization, giving DAOs the potential to reach a global audience more efficiently and respond to global needs more quickly than centralized organizations. Decisions are made through online voting and recorded on a public blockchain, allowing for collective management of resources. Network congestion and the resulting excessive gas fees, especially on the Ethereum blockchain, have popularized voting through off-chain platforms that connect to participants' digital wallets or layer-2 blockchains.[3] Smart contracts are used to implement the agreements made through voting and blockchain technology ensures transparency and immutability of a platform's policies, which contribute to the efficiency and scalability of DAOs.

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[3] For more information on specialized off-chain voting platforms, see Snapshot (https://docs.snapshot.org/).

Direct Token-Holder Democracy

In a DAO, decisions are made through direct token-holder democracy, where token holders have a vote proportionate to their token ownership. This allows small token holders to have a say in the organization's management. In a corporation, the board, on behalf of shareholders, selects managers, who are the agents, to run the company. In a DAO, however, there are no agents. This lack of intermediaries raises questions about how to define agency problems and what governance mechanisms are required to address them.

An important issue is the potential conflict of interest between a DAO's minority token holders and large token holders, the latter of whom are known as "whales." These conflicts may arise if whales prioritize short-term capital gains over long-term development of the platform's services, potentially harming the interests of the minority holders. This concern is reinforced by the prevalence of fraud and manipulation by platform insiders and whales in the cryptocurrency industry (Li, Shin, and Wang, 2021; Xia et al., 2021; Li et al., 2022; Phua et al., 2022). Therefore, to achieve efficiency, DAOs need governance measures that align whales' interests with those of minority token holders.

The Absence of Regulations

Initial coin offerings (ICOs) and initial DEX offerings (IDOs) are commonly used by DAOs to raise capital but they lack sufficient regulatory oversight and intermediaries to safeguard the interests of minority token investors. In the absence of these safeguards, it is crucial for DAO members to share information and collaborate to improve the organization's operations. The literature suggests that the crowd's wisdom can help overcome information asymmetry and associated governance issues in ICOs (Lee, Li, and Shin, 2021; Bourveau et al., 2022). As DAOs operate under a bottom-up control structure, the larger the token-holder base is the more wisdom the crowd can generate, potentially leading to sustainable long-term value.

The following sections theoretically explore the potential conflicts of interest between whales and minority token holders in a DAO and offer potential solutions to align the incentives of these two groups. In Section 7, we empirically test the resulting predictions using novel data.

3 Model

3.1 Setup

Consider an infinite-horizon, discrete-time model with a platform that provides services, such as bilateral or multilateral transactions among users. To use the platform's services, one must obtain tokens (or coins). The platform operates as a DAO, which does not have any central authority but is instead collectively managed by its community of token holders. Through the use of smart contracts, these token holders can participate in voting on proposals and changes to the platform.

Consider a situation where a proposal is brought up for the platform to make changes to its services. However, due to potential conflicts of interest arising from the varying benefits and costs of the proposed changes, participants are not in unanimous agreement. The platform's final decision will be determined by the outcome of a vote, according to a pre-specified rule.

The timeline is as follows: In $t = 0$, the platform is established and issues one unit of tokens. The token is distributed among the whale and users. In $t = 1$, participants vote for or against the proposal based on their token ownership. The proposal is implemented according to the voting result. From $t = 1$ onward, the platform provides utility flows to participants based on their token ownership.

3.1.1 Participants

In this model, there are two types of participants: small participants, whom we will refer to as "users," and a larger participant, whom we will refer to as the "whale." All participants are assumed to be risk-neutral, and their discount factor is denoted by δ. The risk-free rate is given by $r_f = 1/\delta - 1$.

We assume that there is a continuum of users uniformly distributed on the interval $[0, 1]$ who derive utility from using the service on the platform. To participate, a user indexed by i must pay a one-time participation cost of $\phi_i > 0$ in $t = 0$, and purchase tokens at an exogenously given initial offering price of $\bar{P}$ without incurring any transaction costs. The cost ϕ_i is individual-specific and has a cumulative density function $G(\cdot)$ defined on the interval $[0, \infty)$. For technical tractability, we assume that $G(\cdot)$ is sufficiently concave. More specifically we assume that $-\phi G''(\phi)/G'(\phi) \geq 1$ for all $\phi \in [0, \infty)$.[4] We denote the set of participating users as $\mathcal{U}$, and the unit of tokens held by user i in period t as $x_{i,t}$.

Upon the establishment of the platform, the whale receives y_0 units of the tokens. The whale can be considered as an individual or an institution with special interests in the platform (e.g., founders, developers, and financiers such as venture capitalists). We denote by y_t the unit of tokens held by the whale in period t.

We assume that the whale needs to liquidate its position before a finite horizon of $T \geq 2$. This assumption reflects short-termism of the whale which may result from agency or financial frictions. For example, the whale can be an institutional investor with financial interests whose compensation is determined by their short-term performance, either implicitly by fund flows or explicitly by their incentive contracts (see, for example, Dow, Han, and Sangiorgi, 2021, 2022, and van Binsbergen et al., forthcoming).

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[4] This assumption ensures that we have a unique fixed point for the equilibrium number of participating users, denoted by N (see the proof of Proposition **??**).

3.1.2 Technology

A participant, whether a user or a whale, holding X_t tokens in period $t \geq 1$ derives utility from the platform during that period according to the following:[5]

$$U(X_t) = A(a)NX_t, \tag{1}$$

where N represents the total number of participating users. The utility flows can be monetary payoffs or utility of service, and the value of service per unit of tokens is given by $A(a)N$, where $A(a)$ captures the technology (or efficiency) component, and N captures the network effect of user participation (see, for example, Cong, Li, and Wang, 2021 and Sockin and Xiong, 2023).

The technology component $A(a)$ is determined by the action $a \in \{R, I\}$ where $a = I$ means that the proposal is implemented, and $a = R$ means it is rejected. In $t = 1$, the platform implements the proposal $(a = I)$ if the total mass of votes in favor of its implementation exceeds the minimum threshold of $\bar{x}$:

$$\mathbb{1}\left(a_w = I\right) y_1 + \int_{\mathcal{U}} x_{i,1} \mathbb{1}\left(a_i = I\right) di \geq \bar{x}, \tag{2}$$

where $a_i \in \{I, R\}$ and $a_w \in \{I, R\}$ are the vote of each participating user $i \in \mathcal{U}$ and that of the whale, respectively, which are equal to I if they prefer the implementation of the proposal and R otherwise. The indicator functions $\mathbb{1}\left(a_w = I\right)$ and $\mathbb{1}\left(a_i = I\right)$ are one if $a_w = I$ and $a_i = I$, respectively, and zero otherwise. The threshold $\bar{x}$ is pre-specified upon the establishment of the platform. For example, we can set $\bar{x} = 1/2$ in the case of the majority rule.

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[5] The tokens provide access to services for the current period immediately after trading. For instance, if a participant begins period t with a holding of X_{t-1} and purchases an additional ΔX_t units of tokens during the period, their holdings in period t generating utility flows will be $X_t = X_{t-1} + \Delta X_t$.

To explore potential conflicts between users and the whale, we assume that implementing the proposal would destroy value for users if $A(R) > A(I) = (1-\theta)A(R)$, where θ is a parameter that captures the loss in efficiency due to the implementation of the proposal. Also, we assume that the platform is sufficiently valuable regardless of implementing the proposal, i.e., we focus on parameter values where $A(R)$ is sufficiently large. [***See proof] The whale obtains private benefits if the proposal is implemented. The expected private benefit increases with the whale's initial endowment of tokens. Specifically, we assume that the whale's benefit from implementing the proposal is given by a random variable B, which has a cumulative distribution function $F(\cdot)$ defined on the interval $[0, \infty)$. The value of B is initially unknown, but becomes public in $t = 1$.

Once the realization of the whale's private benefit B becomes public in $t = 1$, users correctly infer whether the proposal will be accepted or not. That is, users have rational expectations about the outcome of the vote event and the corresponding price path. Users take the implementation of the proposal $a \in \{I, R\}$ and the path of token prices $\{P_t^a\}_{t=1}^{\infty}$ under the action a as given.

We denote by $P(a)$ the intrinsic value of the tokens to users given the status of the proposal implementation a and the mass of participating users N. It is given by the present value of utility flows per unit of tokens:

$$P(a) = \sum_{s=0}^{\infty} \delta^s A(a) N = \frac{A(a)N}{1-\delta}. \tag{3}$$

In the absence of the whale, the price would converge to this intrinsic value.

3.1.3 Trading

The platform's tokens are traded in exchanges. We assume that trading costs are increasing convexly in the amount of trading volumes. Although convex trading costs may arise from various sources, one major source can be the illiquidity of tokens (e.g., Kyle, 1985). For tractability, we assume a quadratic function for the trading costs as a function of the amount of traded tokens, ΔX:

$$C(\Delta X) = \frac{\lambda}{2}(\Delta X)^2, \tag{4}$$

where $\lambda > 0$ is a parameter that captures the magnitude of illiquidity (see, for example, van Binsbergen et al., forthcoming for further discussion). Additionally, we assume that short sales are not allowed.

3.2 Optimal Choices

3.2.1 User's Problem

In periods $t = 1, 2, \ldots$, each participating user maximizes their expected utility of enjoying the platform's service as well as trading gains. Since users are symmetric once they participate in the market, we suppress the index i for notational convenience from now on.

Given the platform's action a in $t = 1$, a user's value in period $t \geq 1$ can be represented in a recursive form as:

$$V_t^a(x_{t-1}) = \max_{\Delta x_t} A(a)N(x_{t-1} + \Delta x_t) - P_t^a \Delta x_t - \frac{\lambda}{2}\Delta x_t^2 + \delta V_{t+1}^a(x_{t-1} + \Delta x_t), \tag{5}$$

subject to the constraints:

$$x_t = x_{t-1} + \Delta x_t; \tag{6}$$

$$x_t \geq 0. \tag{7}$$

The first term in Eq. (5) is the utility flows given the token holdings at the end of the period, the second term is the cost of acquisition (or the proceeds from selling), the third term is trading costs (Eq. (4)), and the fourth term is the continuation value given the choice. Eq. (7) represents the short sale constraint for token trading, which is always satisfied in equilibrium.

By solving the optimization problem in Eq. (5), we can represent the value function of a user as an affine function of their token holdings at the beginning of the period:

Lemma 1 *The value function of a user in period $t \geq 1$ with the token holdings x_{t-1} at the beginning of period t is given by*

$$V_t^a(x_{t-1}) = \alpha_t + \beta x_{t-1}, \tag{8}$$

where α_t is the present value of future trading gains:

$$\alpha_t = \frac{1}{2\lambda} \sum_{s=t}^{\infty} \delta^{s-t} \left(P(a) - P_s^a\right)^2, \tag{9}$$

and β is the marginal value of tokens:

$$\beta = P(a). \tag{10}$$

The optimal trading strategy of tokens in period t given price P_t^a is

$$\Delta x_t = \frac{P(a) - P_t^a}{\lambda}. \tag{11}$$

Proof. See Appendix. ■

3.2.2 Token Prices

The market clearing condition states that the sum of all the trading volumes should be net zero:

$$N\Delta x_t + \Delta y_t = 0. \tag{12}$$

Then, Eq. (12) together with Eq. (11) implies that the inverse demand function of users is given by

$$P_t^a = P(a) - \lambda \Delta x_t. \tag{13}$$

Therefore, when the whale trades Δy_t units of tokens, Eq. (12) implies that the equilibrium price of tokens is a function of Δy_t given a:

$$P(\Delta y_t; a) = P(a) + \frac{\lambda}{N}\Delta y_t. \tag{14}$$

Eq. (14) shows that the price has to increase above the intrinsic value whenever the whale buys more tokens and decrease below the intrinsic value whenever the whale sells the tokens. In the absence of the whale's trading, the price becomes the intrinsic value.

3.2.3 Whale's Problem

In $t = 0$, the whale receives y_0 units of tokens from the platform. In $t = 1$, the whale decides whether to accumulate more tokens strategically to influence the voting outcome. After the outcome $a \in \{I, R\}$ is determined, the whale begins to unwind their position, completely liquidating it by period T. The whale trades tokens similar to users in Eq. (5) but incorporates their own price impact into their optimization problem. We can represent the whale's value, given y_{t-1}, in a recursive form as:

$$V_{w,t}^{a}(y_{t-1}) = \max_{\Delta y_t} A(a)N(y_{t-1} + \Delta y_t) - P(\Delta y_t; a)\Delta y_t - \frac{\lambda}{2}\Delta y_t^2 + \delta V_{w,t+1}^{a}(y_{t-1} + \Delta y_t), \quad (15)$$

subject to the constraints:

$$y_t = y_{t-1} + \Delta y_t; \quad (16)$$

$$y_t \geq 0, \quad (17)$$

and the boundary condition:

$$y_T = 0. \quad (18)$$

The interpretation of Eq. (15) is identical to that of a user in Eq. (5) except that the price of tokens $P(\Delta y_t; a)$ is a function of own trading volumes Δy_t (see Eq. (14)). The boundary condition in Eq. (18) ensures that the holdings are completely liquidated by period T. By optimally reducing their position over the investment horizon, the whale can maximize their expected utility, considering the trade-offs between token payoffs and trading costs. Eq. (17) represents the short sale constraint for token trading, which is always satisfied in equilibrium.

Substituting the price function Eq. (14) into Eq. (15), we can represent the objective function as follows:

$$V_{w,t}^{a}(y_{t-1}) = \max_{\Delta y_t} A(a)N(y_{t-1} + \Delta y_t) - P(a)\Delta y_t - \frac{\lambda_w}{2}\Delta y_t^2 + \delta V_{w,t+1}^{a}(y_{t-1} + \Delta y_t), \quad (19)$$

where λ_w is the effective cost of trading per unit of tokens for the whale:

$$\lambda_w = \lambda \left(\frac{N+2}{N} \right). \tag{20}$$

The interpretation of Eq. (19) is that the whale trades tokens at their fundamental value, denoted as $P(a)$, and incurs the effective trading cost λ_w, which reflects both the quadratic transaction cost in Eq. (4) and the extra price impact in Eq. (14).

We get the following result by solving the whale's problem:

Lemma 2 *Given the initial holdings of tokens y_{t-1} in the beginning of period t, the optimal trading strategy of the whale in period $s \geq t$ is given by*

$$\Delta y_s = -\delta^{-(s-t)} \frac{y_{t-1}}{\Gamma(t,T)}, \tag{21}$$

where $\Gamma(t,T)$ is a function which is strictly greater than one for all values of t, T:

$$\Gamma(t,T) = \sum_{k=t}^{T} \delta^{-(k-t)} = \frac{\delta^{-(T-t)} - \delta}{1-\delta}. \tag{22}$$

Furthermore, the value function in $t \geq 2$ under $a \in \{I, R\}$ is given by

$$V^a_{w,t}(y_{t-1}) = P(a) y_{t-1} - \frac{\lambda_w}{2} \frac{y^2_{t-1}}{\Gamma(t,T)}. \tag{23}$$

Proof. See Appendix. ■

The optimal trading strategy in Eq. (21) reflects dividing the initial holdings among the remaining periods in proportion to the discount factor.[6] The value in Eq. (23) reflects the intrinsic value of the whale's current token holdings less the cost of liquidating them under the optimal trading strategy.

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[6] In the case where the discount factor is one, this term simplifies to the total trading volume divided by

3.3 Equilibrium

3.3.1 Voting and Strategic Trading

In $t = 1$, the value of private benefit B realizes. Given B, the whale decides whether to implement the proposal jointly with trading of tokens. To solve the whale's optimization problem in $t = 1$, we first analyze the value given the implementation of the proposal a and trading volume Δy_1 under a realized value of B.

Lemma 3 *Given the realized value of B and the implementation of the proposal a, we can derive the whale's value with the choice of Δy_1 in $t = 1$ is given by*

$$V^a_{w,1}(y_0) = B\mathbb{1}(a = I) + P(a)y_0 - \frac{\lambda_w}{2}\Delta y_1^2 - \delta\frac{\lambda_w}{2}\frac{(y_0 + \Delta y_1)^2}{\Gamma(2, T)}. \tag{25}$$

Proof. See Appendix. ■

From Eq. (25), we can see that the whale's value in $t = 1$ is equal to their private benefit of implementing the proposal and the fundamental value of their initial token holdings, less the cost of trading in $t = 1$ and the cost of liquidating the remaining tokens over the given horizon.

The proposed changes do not benefit users; therefore, they do not support the implementation of the proposal. Since trading is costly, the whale purchases only the minimum amount necessary to gain just enough voting power, which is $\bar{x} - y_0$, to ensure the success of their desired outcome in the vote. This is evident from the observation that the value is decreasing in Δy_1, as shown in Eq. (25). Therefore, the following is a direct consequence of Lemma 3:

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the remaining number of days before the liquidation:

$$\Delta y_s = -\frac{y_{t-1}}{T - t + 1}, \qquad \text{for all } t \leq s \leq T. \tag{24}$$

Corollary 1 *If the whale intends to implement the proposal, it is optimal to purchase* $\bar{x} - y_0$ *units of tokens.*

From Eq. (25), we can represent the whale's value in $t = 1$ in case of implementing the proposal and buying an additional $\bar{x} - y_0$ units of tokens as follows:

$$V^I_{w,1}(y_0) = \underbrace{B}_{\text{Private benefit}} + \underbrace{P(I)y_0}_{\text{Intrinsic value}} \underbrace{-\frac{\lambda_w}{2}(\bar{x} - y_0)^2 - \delta\frac{\lambda_w}{2}\frac{\bar{x}^2}{\Gamma(2,T)}}_{\text{Trading costs}}. \tag{26}$$

The whale's value reflects the private benefit plus intrinsic value under the implementation of the proposal, less the trading costs. Note that the intrinsic value is lowered to $P(I)y_0$ due to the implementation of the proposal. The trading costs involve the cost of acquiring additional tokens to influence the vote and the cost of liquidating the increased amount of tokens from the subsequent period. The whale's behavior can be viewed as a form of rug-pulling scheme in this context.

In contrast, the whale's value of choosing not to implement the proposal is given by the intrinsic value under the status quo, less the trading costs of liquidating the initial holdings:

$$V^R_{w,1}(y_0) = \underbrace{P(R)y_0}_{\text{Intrinsic value}} \underbrace{-\frac{\lambda_w}{2}\frac{y_0^2}{\Gamma(1,T)}}_{\text{Trading costs}}. \tag{27}$$

The whale does not enjoy the private benefit but benefits from the higher valuation of tokens, $P(R)y_0$, due to the rejection of the value-destroying proposal. Furthermore, the cost of trading is lower because the whale does not need to accumulate more tokens to manipulate the voting outcomes.

Therefore, the whale will implement the proposal if and only if $V^I_{w,1}(y_0)$ is greater than $V^R_{w,1}(y_0)$. Equivalently, the value-destroying proposal is implemented if and only if the incentive misalignment between the whale and users is sufficiently strong:

$$B > \bar{B}, \tag{28}$$

where $\bar{B}$ is the threshold of private benefits over which implementing the proposal is more beneficial:

$$\bar{B} = \underbrace{[P(R) - P(I)]y_0}_{\text{Loss in intrinsic value}} + \underbrace{\frac{\lambda_w}{2}\left[(\bar{x} - y_0)^2 + \delta\frac{\bar{x}^2}{\Gamma(2,T)} - \frac{y_0^2}{\Gamma(1,T)}\right]}_{\text{Increment in trading costs}}. \tag{29}$$

The whale prefer implementing the proposal whenever the private benefit exceeds the cost of implementing the proposal, which includes the loss in intrinsic value and the incremental trading costs incurred by strategically acquiring more tokens for voting.

3.4 Equilibrium Token Price Process

The equilibrium price process can be obtained from the inverse demand function Eq. (14) and the optimal trading schedule of the whale. If the whale chooses to implement the proposal, the whale purchases $\bar{x} - y_0$ unit of tokens (Corollary 1). Therefore, the price in $t = 1$ is given by

$$P_1^I = P(I) + \frac{\lambda}{N}(\bar{x} - y_0). \tag{30}$$

Then the whale's holdings in the beginning of period $t = 2$ becomes $\bar{x}$, which together with the optimal trading schedule in Eq. (21) for $t \geq 2$ implies that the price in $t \geq 2$ is given by

$$P_t^I = \begin{cases} P(I) - \delta^{-(t-2)}\frac{\lambda}{N}\frac{\bar{x}}{\Gamma(2,T)} & \text{if } 2 \leq t \leq T; \\ P(I) & \text{if } t \geq T+1. \end{cases} \tag{31}$$

This price process reflects the whale's optimal trading strategy of liquidating its increased holdings of $\bar{x}$ over the horizon between $t = 2$ and T. The price also reverts back to the intrinsic value from $T + 1$ once the whale fully liquidates

Initially, in $t = 1$, the price is driven above the intrinsic value ($P_1^I > P(I)$), but once the whale exploits the private benefit, the price rapidly drops ($P_2^I < P(I)$). The price pattern observed when a value-destroying proposal is implemented is similar to that of pump-and-dump schemes, where the price is artificially inflated and subsequently experiences large drops.

If the whale chooses not to implement the proposal, the whale starts liquidating the tokens from $t = 1$. Then, Eq. (14) together with the optimal trading schedule in Eq. (21) implies that the price in $t \geq 1$ is given by

$$P_t^R = \begin{cases} P(R) - \delta^{-(t-1)} \frac{\lambda}{N} \frac{y_0}{\Gamma(1,T)} & \text{if } 1 \leq t \leq T; \\ P(R) & \text{if } t \geq T + 1. \end{cases} \tag{32}$$

This price process reflects the whale's optimal trading strategy of liquidating its initial holdings of y_0 over the horizon between $t = 1$ and T. The price impact of the whale's selling in Eq. (32) is smaller than that in Eq. (31) due to smaller volumes of trading. It should be noted that unlike the situation where the proposal is implemented, the price pattern does not exhibit any movement similar to that of a pump-and-dump.

3.5 Equilibrium User Participation in the Platform

We now close the model by solving for the equilibrium participation. This will determine the ex-ante value of the DAO platform. Using the equilibrium price process in each of the two possible scenarios derived in Section 3.4, we can derive the value of a user participating in the platform in $t = 0$:

Lemma 4 *Given N, the value for each inidividual user in $t = 0$ when $a = I$ is given by*

$$V_0^I(N) = (\delta P(I) - \bar{P})\frac{1 - y_0}{N} + \delta\frac{\lambda}{2N^2}\left[(\bar{x} - y_0)^2 + \frac{\delta\bar{x}^2}{\Gamma(2, T)}\right], \tag{33}$$

and, when $a = R$, it is given by

$$V_0^R(N) = (\delta P(R) - \bar{P})\frac{1 - y_0}{N} + \delta\frac{\lambda}{2N^2}\frac{\bar{y_0}^2}{\Gamma(1, T)}. \tag{34}$$

Recall from Eq. (28) that the whale implements the proposal if and only if there is a strong enough incentive misalignment between the whale and the users ($B > \bar{B}$). It is then clear that the probability of implementing a value-destroying proposal is equal to $F(\bar{B})$. Therefore, the expected intrinsic value of the DAO platform is equal to:

$$\begin{aligned} V_0(N) &= F(\bar{B})V_0^I(N) + (1 - F(\bar{B}))V_0^R(N) \\ &= F(\bar{B})\frac{A(R)N}{1 - \delta} + (1 - F(\bar{B}))\frac{(1 - \theta)A(R)N}{1 - \delta} \\ &= \frac{A(R)N}{1 - \delta}\left[1 - \theta(1 - F(\bar{B}))\right] + \delta\frac{\lambda}{2N^2}\left[F(\bar{B})\frac{\delta\bar{x}^2}{\Gamma(2, T)} + (1 - F(\bar{B}))\frac{\bar{y_0}^2}{\Gamma(1, T)}\right]. \end{aligned} \tag{35}$$

Eq. (28) shows that the whale implements the proposal if and only if the private benefit dominates the cost ($\Delta V_w > 0$) in case their incentives are misaligned with those users ($B = \bar{B}$). In this case, the ex-ante value of users is equal to

$$V_0(N) = Pr(\Delta V_w \geq 0)V_0^I(N) + (1 - Pr(\Delta V_w \geq 0))V_0^R(N). \tag{36}$$

Finally, the equilibrium mass of participating users is determined by solving for N that satisfies the following equation:

$$N^* = F\left(V_0(N^*)\right), \tag{37}$$

where N^* is the equilibrium mass of participating users.

3.5.1 Equilibrium Value of the DAO Platform

Recall from Eq. (28) that the whale implements the proposal if and only if there is a strong enough incentive misalignment between the whale and the users ($B > \bar{B}$). It is then clear that the probability of implementing a value-destroying proposal is equal to $F(\bar{B})$. Therefore, the expected intrinsic value of the DAO platform is equal to:

$$\begin{aligned} V_0 &= F(\bar{B})\frac{A(R)N}{1-\delta} + (1-F(\bar{B}))\frac{(1-\theta)A(R)N}{1-\delta} \\ &= \frac{A(R)N}{1-\delta}\left[1-\theta(1-F(\bar{B}))\right]. \end{aligned} \tag{38}$$

The expected value of the platform is determined by subtracting the expected loss caused by the whale's incentive misalignment from the present value of the highest potential future utility flows. The magnitude of expected loss is captured by $\theta(1-F(\bar{B}))$.

Because $F(\cdot)$ is monotone increasing, the expected value of the platform increases in the threshold $\bar{B}$:

$$\frac{\partial V_0}{\partial \bar{B}} = \frac{A(R)N}{1-\delta}\theta f(\bar{B}) > 0, \tag{39}$$

where $f(\cdot)$ is the probability density function of $\bar{B}$ (i.e., $F' = f$). Based on Eqs. (28) and Eq. (39), it is clear that the probability of value-destroying voting outcomes rises as the threshold $\bar{B}$ decreases, thereby destroying the value of the platform.

With larger token holdings, two opposing effects come into play simultaneously. On the one hand, implementing the proposal may become more expensive due to the whale's increased stake in the platform. On the other hand, it can become less expensive because the cost of acquiring additional voting rights decreases. Due to this trade-off, the threshold of private benefit initially rises with concentration but ultimately starts falling with high concentration. Because $\Gamma(1,T) > 1$ (Lemma 2), the derivative of $\bar{B}$ decreases in y_0:

$$\frac{\partial \bar{B}}{\partial y_0} = \frac{\theta A(R) N}{1-\delta} - \lambda_w \bar{x} + \lambda_w \left[1 - \frac{1}{\Gamma(1,T)}\right] y_0 < 0, \qquad \text{for all } y_0 < \bar{x}. \tag{40}$$

There is a positive relationship between ownership concentration and the likelihood of value-destroying voting outcomes. However, there is also ultimately a hump-shaped relationship once the concentration goes up further.

The derivative of $\bar{B}$ with respect to $A(R)$ reveals that the threshold of the private benefit to implement the proposal increases in the service value:

$$\frac{\partial \bar{B}}{\partial A(R)} = \frac{\theta N}{1-\delta} y_0 > 0. \tag{41}$$

Since the whale holds a stake in the platform, they have no incentive to incur a loss resulting from a value-destroying change. This motivates the whale to avoid any activity that would result in a loss especially when the platform is well-established.

The derivative of $\bar{B}$ with respect to λ reveals that the threshold of the private benefit to implement the proposal in creases in illiquidity:

$$\frac{\partial \bar{B}}{\partial \lambda} = \frac{N+2}{2N} \left[(\bar{x} - y_0)^2 + \delta \frac{\bar{x}^2}{\Gamma(2,T)} - \frac{y_0^2}{\Gamma(1,T)}\right] > 0. \tag{42}$$

As the illiquidity parameter λ increases, it becomes more expensive for the whale to acquire extra tokens needed to implement the proposal. Hence, the whale may find it too expensive to implement the value-destroying proposal in case the private benefit is not big enough or already owns enough voting power. This is in line with the insight of quadratic voting schemes, which aim to prevent one participant from gaining a dominating share of voting rights. This seemingly-puzzling result that illiquidity can improve the governance of a DAO is explained by the fact that the DAO's self-governing nature obviates the need for active monitoring. In contrast, the governance of traditional firms may benefit from liquidity, for example, by enabling the emergence of blockholders who can actively monitor management.

We summarize our main findings in the following proposition:

Proposition 1 *There is a hump-shaped relationship between ownership concentration and the likelihood of value-destroying voting outcomes, initially increasing with concentration but decreasing at very high levels. Furthermore, the likelihood decreases in the service value of the platform and the illiquidity of tokens.*

4 An Extension with Delayed Liquidation

Some DAOs consider governance mechanisms that lock in token positions for voting participants (e.g., vote escrowed tokens). In this subsection, we implement such a mechanism by delaying the liquidation of the whale by a certain additional amount of time $1 \leq T_L < T - 1$ only in case of implementing the proposal. That is, the whale can only start liquidating only from period $t = 1 + T_L$ following their voting in period $t = 1$ if $a = I$ whereas they can start liquidating the tokens immediately from $t = 1$ otherwise.

Under the delayed liquidation scheme, the whale's value of implementing the proposal in

$t = 1$ is changed as follows:

$$V^I_{w,1}(y_0) = \underbrace{B}_{\text{Private benefit}} + \underbrace{P(I)y_0}_{\text{Intrinsic value}} \underbrace{-\frac{\lambda_w}{2}(\bar{x} - y_0)^2 - \delta^{T_L+1}\frac{\lambda_w}{2}\frac{\bar{x}^2}{\Gamma(2+T_L, T)}}_{\text{Trading costs}}. \tag{43}$$

This scheme makes the whale suffer from larger trading costs because of the short horizon before their target liquidation period. Therefore, the whale's threshold of private benefits over which implementing the proposal is more beneficial is given as follows:

$$\bar{B} = \underbrace{(P(R) - P(I))y_0}_{\text{Loss in intrinsic value}} + \underbrace{\frac{\lambda_w}{2}\left[(\bar{x} - y_0)^2 + \delta^{T_L+1}\frac{\lambda_w}{2}\frac{\bar{x}^2}{\Gamma(2+T_L, T)} - \frac{y_0^2}{\Gamma(1, T)}\right]}_{\text{Increment in trading costs}}. \tag{44}$$

The right-hand side is clearly greater than that in Eq. (28), which means that delayed liquidation makes it more difficult for the whale to implement the proposal compared to the case without delayed liquidation.[7]

We summarize our results in the following proposition:

Proposition 2 *Delaying the liquidation of the whale's tokens mitigates the impact of ownership concentration on the likelihood of value-destroying outcomes.*

5 Theoretical Predictions

We now summarize the main predictions relevant to our empirical analyses. The first three predictions are direct consequences of Proposition 1. The fourth prediction is due to Proposition 2:

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[7] To see this, note that the RHS in Eq. (28) is greater than that in Eq. (44) if and only if

$$\delta\frac{\bar{x}^2}{\Gamma(2, T)} < \delta^{T_L+1}\frac{\bar{x}^2}{\Gamma(2+T_L, T)},$$

which is always true for $\delta \in (0, 1)$ due to the definition of $\Gamma(t, T)$ in Eq. (22).

Prediction 1 *The growth rate of platforms is negatively correlated with their ownership concentrations.*

Prediction 2 *The higher service value of platforms reduces the negative correlations between the growth rate of platforms and their ownership concentrations.*

Prediction 3 *The illiquidity of tokens reduces the negative correlations between the total value of platforms and their ownership concentrations.*

Prediction 4 *Long-term incentives of the whale reduce the negative correlations between the growth rate of platforms and their ownership concentrations.*

6 Data Description

Our empirical analyses draw data from several sources. Individual DAO investors' voting records are obtained from Snapshot, a popular voting platform that allows DAOs and other blockchain protocols (e.g. DeFi protocols) to create proposals and manage votes.[8] Unlike traditional on-chain voting systems, which charge voters gas fees for processing the movement of cryptocurrencies from one wallet to another, this *off-chain* platform enables gas-free voting.

We download all votes cast on proposals that were active during the period running from July 20, 2020 through July 31, 2022. The dataset includes a DAO's name, symbol and contract address of its voting token, proposal name and text, start date and deadline of voting, voter address, vote date, and number of votes cast.[9] Because anyone can create a

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[8] To use the voting platform, a DAO needs to claim a domain on the Ethereum Name Service (ENS), a blockchain equivalent of the internet naming convention known as the Domain Name System (DNS). This voting platform automates key aspects of investor voting, including the selection of the voting mechanism, proposal and vote validation, and real-time vote tally.

[9] Information on voting strategies has been manually collected as the original data from the popular voting platform is incomplete.

DAO and feature it on the voting platform, most of the DAOs on the platform are small and do not appear to have any underlying business. Therefore, we start with a subsample of DAOs that are most likely to have underlying businesses: 460 DAOs which had received at least 650 individual votes as of the end of our sample period.

For most DAOs, participants use the underlying governance tokens to cast votes. However, a growing string of DAOs have shifted to a staking model, including the vote escrow/locking model that reward investors greater voting power and yields for locking their governance tokens. For each DAO, we locate the contract detail of its voting token by manually searching its contract address on the corresponding blockchain explorer (e.g. etherscan.io, bscscan.com, or polygonscan.com). The contract detail is used to determine a DAO's voting strategy. That is, whether investors of the DAO cast votes using its governance token or a staked token including a vote escrowed/locked token.

We then manually search these DAO names on CoinMarketCap, a website that is a top source of cryptocurrency market data and that covers most major cryptocurrencies. This step yields 381 cryptocurrencies that are associated with the DAOs. These 381 DAOs received more than 2.3 million individual votes, accounting for 41.3% of all votes in our initial sample. We then download their daily price and volume data. Of the 381 DAOs, 375 have associated price and volume data during our sample period.

Because a number of DAOs adopt staking and vote escrow/locking strategies, ownership of the underlying native governance token is unlikely to capture a voter's economic ownership represented by her votes cast. Therefore, we use the number of voters and the number of votes cast to proxy for the number of DAO members and ownership in the DAO, respectively. Because many DAOs do not feature proposals on a daily basis, we convert the voting data into weekly series. Specifically, for each proposal we first calculate the Herfindahl–Hirschman Index (HHI) of voting power, which is calculated by squaring the share of each individual's votes then summing the resulting numbers, the fraction of votes cast by the top three voters, and the number of voters.[10] We then average each of the three variables for each DAO-week pair using proposals' deadlines.

To capture the size and growth of DAOs, we obtain daily total value locked (TVL) for each DAO from DefiLlama, which is a TVL aggregator and analytics dashboard for DeFi protocols. DefiLlama tracks protocols from over 80 blockchains, including major ones such as Ethereum, BNB Chain (formerly known as Binance Smart Chain), Polygon, Avalanche, and Fantom. We manually search names of the 381 DAOs on DefiLlama and obtain a list of 248 that are featured by DefiLlama. We then download aggregate daily TVL for each of these DAOs if it is available. We merge week-end price, volume, TVL data into our weekly voting dataset using name and symbol. Our final dataset includes 207 DAOs that have non-missing price, volume, TVL data during our sample period.

6.1 Descriptive Statistics

Before reporting the summary statistics for the key variables in our study, we plot the aggregate TVL for our sample platforms. As shown in Figure 1, during the week of July 20, 2020, our platforms' combined TVL was around \$1.3 billion, a relative low starting point. However, TVL grew quickly as the DeFi and cryptocurrency spaces boomed as the COVID-19 pandemic dragged on, likely attributed to easy monetary policy and interest from retail investors. Total valuation surpassed \$145 billion in November and December 2021, before declining in January 2022. By July 31, 2022, aggregate TVL was only \$45.8 billion, a drop of more than 68% from its peak. We note that this boom-and-bust pattern is consistent with the valuation cycle for the whole DeFi industry—the peak TVL of \$181 billion was

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[10] Some DAOs allow token holders to delegate their votes to a third-party delegate, who will be responsible for voting on proposals. In our data, an individual or voter refers to a delegate, implying that the HHI of voting power captures the concentration of delegates' voting power.

reached in December 2021 before dropping precipitously. This comparison also shows that our dataset captures most major DeFi platforms.

[Insert Figure 1 here.]

As shown in Table 1, during our sample period the average platform has a TVL of $1.2 billion while the median is only $103 million, suggesting the distribution of DeFi valuations is highly skewed. The average and median weekly TVL growth are both -0.9%, with an interquartile range of -8.8% to 7.5%. The weekly returns of the associated (governance) tokens are more negative, with the average and median being -4.3% and -3.5%, respectively. The average weekly HHI of voting power is 0.29 (equivalent to 2,900 points based on a maximum of 10,000 points), suggesting that the market is highly concentrated.[11] The largest three whales on average command almost two thirds of the voting power, supporting the notion that the DeFi market is highly concentrated. Remarkably, even at the 25th percentile, the top three whales still dictate 49% of the votes.

[Insert Table 1 here.]

The average (median) number of platform participants is 212 (46) while the average (median) age of platforms is six (five) months. The distribution of the illiquidity measure is skewed, with the average and median figures being 0.112 and 0.017.

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[11] Regulators generally consider markets in which the HHI is in excess of 2,500 points to be highly concentrated. See the Horizontal Merger Guidelines (2010) issued by the U.S. Department of Justice and the Federal Trade Commission.

7 Empirical Analyses

7.1 Ownership Concentration and Platform Growth

To test whether platform growth is negatively related to ownership concentration, as outlined in Prediction 1, we begin by regressing weekly TVL growth on past week's HHI of voting power, controlling for platform and week fixed effects. As shown in column (1) of Table 2, a one standard-deviation increase in HHI is associated with a 1.1 percentage-point decrease in weekly TVL growth. Given that the average weekly TVL growth is -0.9%, the marginal effect is substantial. To test whether a platform's valuation reduces the negative relationship between platform growth and ownership concentration (Prediction 2), we add to the specification used in column (1) an interaction term of HHI and lagged TVL and re-estimate it. A positive coefficient suggests that for larger platforms ownership concentration affects TVL growth less negatively. Indeed, the estimated coefficient on *HHI* × *Lagged TVL* is positive and statistically significant at the 5%, lending support to Prediction 2. Interestingly, platform size itself has a large negative effect on TVL growth, with a one standard-deviation increase in TVL being associated with a 5.1 percentage-point decrease in TVL growth. This is intuitive as larger and more mature platforms tend to grow more slowly (Cong, Li, and Wang, 2021).

Similarly, to test whether token illiquidity mitigates the negative correlation between platform growth and ownership concentration (Prediction 3), we replace the interaction term used in column (2) with an interaction term of HHI and Amihud illiquidity. The estimated coefficient on the interaction term is again positive and significant, consistent with the notion that the more difficult it is for whales to acquire large blocks of tokens the higher the platform growth is. Not surprisingly, token illiquidity negatively affects platform growth, with the marginal effects being 0.9 percentage points when the illiquidity measure increases by one standard deviation.

One concern is that illiquidity may be related to platform size, which is similar to illiquidity being generally negatively associated with a stock's market capitalization (see Amihud, 2002, among many others), causing potential omitted-variable bias. To mitigate such a concern, we further control for lagged platform size in the regression. As shown in column (5), the estimated coefficient on the interaction term becomes slightly larger and more significant. In column (6), we instead control for the number of participants as an alternative measure of platform size, which leads to consistent results.

[Insert Table 2 here.]

7.2 Whales' Ownership and Platform Growth

In addition to the negative correlation between platform growth and ownership concentration, proxied by the HHI of voting power, we explicitly study how ownership by the largest whales may affect platform growth. Whales' ownership is proxied by the fraction of votes cast by the top three voters in a given week. As reported in column (1) of Table 3, whales' ownership negatively influences platform growth, with the effect being significant at the 1% level. A one standard-deviation increase in whales' ownership is associated with a 2.6 percentage-point decrease in weekly TVL growth. This marginal effect is substantially larger than the average weekly TVL growth of -0.9%. Consistent with the results reported in Section 7.1, both platform size and token illiquidity reduce the negative correlation between whales' ownership and TVL growth, as the positive coefficients on the interaction terms in columns (3)-(6) suggest.

[Insert Table 3 here.]

Overall, our results reported in Sections 7.1 and 7.2 lend support to the theoretical prediction that ownership concentration, especially ownership by whales, is negatively related to platform growth. Such a negative effect is mitigated by platform size and token illiquidity.

7.3 Platforms' Long-Term Incentives and Growth

On most DeFi platforms, such as Lido DAO (LDO) and Uniswap (UNI), voters use the native governance tokens to vote on proposals. They use the one-token-one-vote model. However, in recent years a growing string of DeFi protocols have shifted to a staking model, the vote escrow model in particular, which is pioneered by Curve Finance (CRV), a DEX launched in 2020. Investors would lock their governance tokens for up to four years. Vote weights and share of rewards are generally proportional to the preset time periods, which means that those that lock the governance token for a longer period will accrue greater voting power and enhanced yields. This mechanism potentially provides more long-term incentives to whales, making them more patient. Such a mechanism would boost platform growth, as predicted in Prediction 4.

In this subsection, we adopt an event-study framework to study whether adopting the staking model boosts platform growth. We identify 45 platforms which switched to a staking model during our sample period. For each of these platforms, we calculate TVL growth from Day -6 to Day 1, where Day 0 is the date when the staking model was adopted. The six-day period before adoption captures possible run-up in valuation in anticipation of the adoption. This is our treatment sample. Our control sample includes TVL growth from Day -6 to Day 1 for all the platforms that never adopted staking models. We then regress *TVL growth* on *Staking adoption*, which equals one for platforms that adopted a staking model and zero otherwise, controlling for certain platform characteristics.

As shown in column (1) of Table 4, a platform's TVL growth increased 8.3 percentage points after it adopted the staking model, controlling for lagged TVL, HHI of voting power, and platform and week fixed effects. This is highly significant given the average weekly TVL growth is slightly negative. As reported in columns (2)-(4), we obtain similar results when replacing HHI of voting power with whales' ownership, the number of participants, and platform age, respectively.

[Insert Table 4 here.]

8 Conclusion

In this paper, we explore conflicts of interest among token holders in DAOs, which are powered by open-source smart contracts. We develop a new theory that can explain why whales (large token holders in a DAO) may disrupt the long-term growth of the platform through "rug pulls," in which they inflate token prices before they start unwinding their positions. Our theoretical model features a whale who may enjoy private benefits through controlling the platform. The whale trades off between private benefit and the cost of manipulating voting outcomes; the cost includes a loss in public value as well as trading costs due to token illiquidity.

Our model predicts four major results: 1) a negative correlation between whales' voting power concentration and DAO growth; 2) mitigation of such a negative correlation as platforms become larger and more widely adopted; 3) similar dampening effects for platforms with illiquid tokens; and 4) alleviation of these DAO governance issues by shifting toward staking and vote escrow models that encourage long-term commitment incentives among whales.

Our empirical evidence strongly supports these theoretical predictions. Using the proposal-level voting outcomes and trading information of tokens from more than 200 DAOs running from July 2020 to July 2022, we confirm a negative correlation between voting power concentration and platform growth, which is significantly alleviated by large platform sizes and alternative voting mechanisms, including staking and vote escrow models.

Overall, our research fills a significant gap in the literature on DAO governance by incorporating micro-foundations of the conflicts of interest among different token holders and providing insights into alternative voting mechanisms to improve the effectiveness of this new type of digital organization. The effectiveness of DAOs is a crucial economic issue in the digital age, and thus, our research contributes to innovation in organizational economics and its practical implications for corporate finance and governance policies. Further questions remain to be explored in this important research area. We hope to return to these questions in subsequent research.

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Figure 1. Total Value Locked Over Time

This figure plots the weekly combined total value locked (TVL) for our sample DAOs. The sample period runs from July 20, 2020 (the week of July 20, 2022) to July 31, 2022 (the week of July 25, 2022).

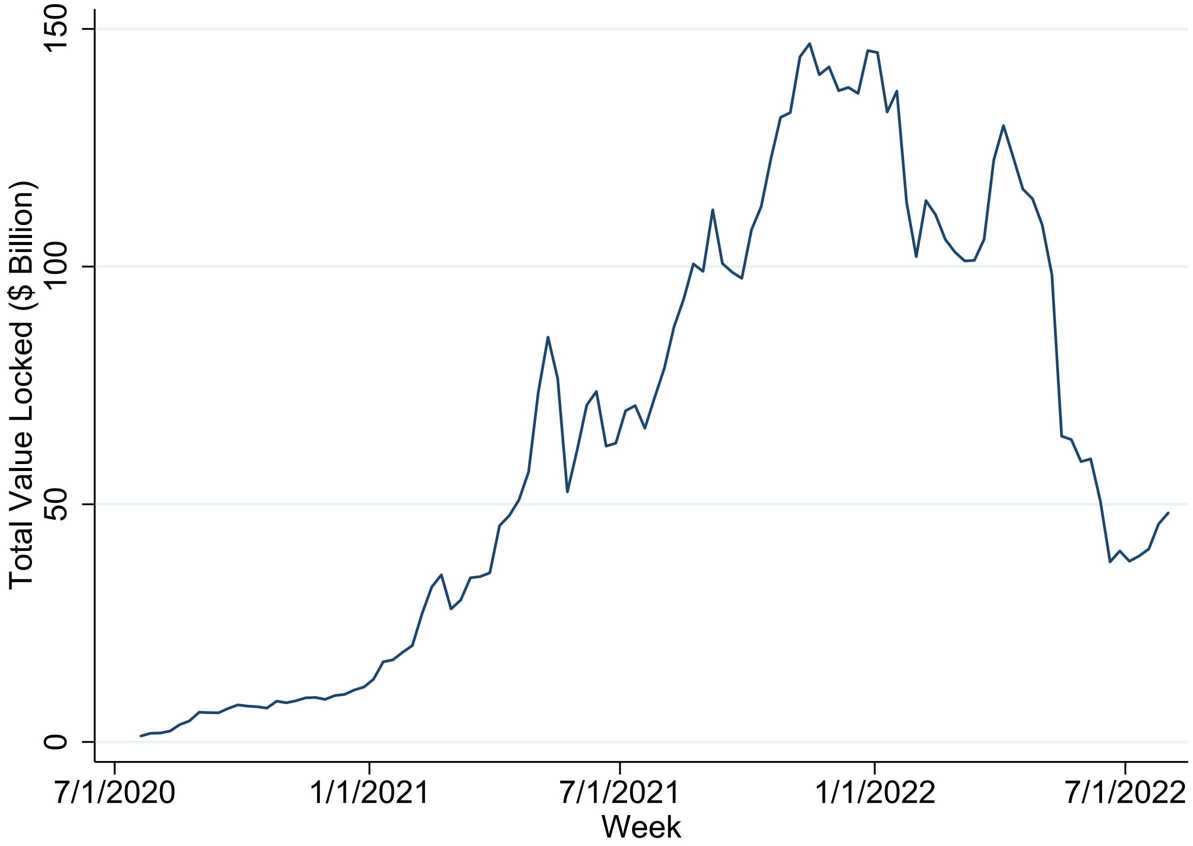

Table 1. Descriptive Statistics

In this table, we report descriptive statistics on the 207 DAOs in our sample. The sample period runs from July 20, 2020 to July 31, 2022. *TVL* is total value locked in billions of dollars, reported by DefiLlama. *TVL growth* is the weekly growth rate of TVL. *Crypto return* is the weekly return of the crypto associated with each DAO. For each DAO, *HHI* is the average Herfindahl–Hirschman Index of the number of votes cast for proposals that end in a given week; *Top 3 ownership* is the average fraction of votes cast by the top three voters for proposals that end in a given week; and *No. of participants* is the average number of voters voting on proposals that end in a given week. Age is the number of years since a DAO's inception. *Amihud illiquidity* is the Amihud (2002) illiquidity measure, defined as the weekly average of $100\sqrt{|Return|/Dollar\ Trading\ Volume}$ using daily data.

	Average (1)	25th percentile (2)	Median (3)	75th percentile (4)	Std. Dev. (5)	Obs. (6)
TVL ($ billion)	1.209	0.013	0.103	0.601	3.163	2860
TVL growth	-0.009	-0.088	-0.009	0.075	0.233	2860
Crypto return	-0.043	-0.159	-0.035	0.079	0.265	2701
HHI	0.286	0.119	0.215	0.375	0.239	2860
Top 3 ownership	0.665	0.492	0.680	0.866	0.237	2809
No. of participants	212.1	15.4	46	150.5	556.4	2860
Age	0.508	0.159	0.425	0.781	0.411	2860
Amihud illiquidity	0.112	0.004	0.017	0.054	0.725	2650

Table 2. Ownership Concentration and Platform Growth

In this table, we report results on the relationship between ownership concentration and platform growth. The sample period runs from July 20, 2020 to July 31, 2022. All regressions are performed at the weekly frequency. *Lagged TVL* is total value locked in billions of dollars as of the end of the past week. *Amihud illiquidity* is the Amihud (2002) illiquidity measure as of the end of the past week. All other variables are as defined in Table 1. Standard errors are clustered at the platform level. In each column we report estimated coefficients and their associated *t*-statistics. *, ** and *** indicate statistical significance at the 10%, 5% and 1% levels, respectively. Singleton observations are dropped from each fixed-effects model.

	Dependent variable: TVL growth					
	(1)	(2)	(3)	(4)	(5)	(6)
HHI	-0.048**	-0.341***	-0.057**	-0.036	-0.038	0.004
	(-2.14)	(-4.48)	(-2.35)	(-1.44)	(-1.49)	(0.13)
HHI^2		0.311***				
		(4.27)				
HHI × Lagged VL			0.007**			
			(2.28)			
Lagged TVL			-0.016***		-0.013***	
			(-4.72)		(-4.41)	
HHI × Amihud illiquidity				0.029***	0.030***	0.029***
				(2.88)	(3.03)	(3.14)
Amihud illiquidity				-0.013***	-0.013***	-0.013***
				(-2.79)	(-2.86)	(-2.95)
log(No. of participants)						-0.015**
						(-2.31)
Observations	2,860	2,860	2,860	2,650	2,650	2,650
R-squared	0.12	0.13	0.13	0.13	0.13	0.13
DAO FEs	Y	Y	Y	Y	Y	Y
Week FEs	Y	Y	Y	Y	Y	Y

Table 3. Whales' Ownership and Platform Growth

In this table, we report results on the relationship between whales' ownership and platform growth. The sample period runs from July 20, 2020 to July 31, 2022. All regressions are performed at the weekly frequency. *Lagged TVL* is total value locked in billions of dollars as of the end of the past week. *Amihud illiquidity* is the Amihud (2002) illiquidity measure as of the end of the past week. All other variables are as defined in Table 1. Standard errors are clustered at the platform level. In each column we report estimated coefficients and their associated *t*-statistics. *, ** and *** indicate statistical significance at the 10%, 5% and 1% levels, respectively. Singleton observations are dropped from each fixed-effects model.

	Dependent variable: TVL growth					
	(1)	(2)	(3)	(4)	(5)	(6)
Top 3 ownership	-0.109***	-0.273**	-0.124***	-0.087***	-0.090***	-0.067*
	(-3.93)	(-2.19)	(-4.11)	(-2.87)	(-2.94)	(-1.79)
Top 3 ownership^2		0.201**				
		(2.10)				
Top 3 ownership × Lagged TVL			0.013**			
			(2.42)			
Lagged TVL			-0.023***		-0.013***	
			(-4.28)		(-4.47)	
Top 3 ownership × Amihud illiquidity				0.015**	0.015**	0.015**
				(2.47)	(2.57)	(2.57)
Amihud illiquidity				-0.012***	-0.012***	-0.012***
				(-2.76)	(-2.78)	(-2.84)
log(No. of participants)						-0.008
						(-1.43)
Observations	2,809	2,809	2,809	2,612	2,612	2,612
R-squared	0.13	0.13	0.14	0.14	0.14	0.14
DAO FEs	Y	Y	Y	Y	Y	Y
Week FEs	Y	Y	Y	Y	Y	Y

Table 4. Platforms' Long-Term Incentives and Growth

In this table, we report results on whether long-term incentives of a platform affects platform growth. The sample period runs from July 20, 2020 to July 31, 2022. *Implementing staking* is an indicator equal to 1 if a platform adopts staking or vote escrow as part of its voting strategy and zero otherwise. *TVL growth* is growth in TVL from Day -6 to Day 1, where Day 0 is the date when staking or vote escrow is adopted. All other variables are as defined in Table 1 and are measured as of the week immediately before the adoption date. Standard errors are clustered at the platform level. In each column we report estimated coefficients and their associated *t*-statistics. *, ** and *** indicate statistical significance at the 10%, 5% and 1% levels, respectively. Singleton observations are dropped from each fixed-effects model.

	Dependent variable: TVL growth			
	(1)	(2)	(3)	(4)
Implementing staking	0.083**	0.069**	0.080**	0.077**
	(2.44)	(1.98)	(2.35)	(2.39)
Lagged TVL	-0.002	-0.003	-0.002	-0.002
	(-1.05)	(-1.12)	(-0.77)	(-0.89)
HHI	0.009			
	(0.15)			
Top 3 ownership		0.036		
		(0.57)		
log(No. of participants)			-0.005	
			(-0.73)	
Age				-0.025
				(-0.49)
Observations	884	881	884	910
R-squared	0.15	0.16	0.15	0.16
DAO FEs	Y	Y	Y	Y
Week FEs	Y	Y	Y	Y

Appendix

Proof of Lemma 1:

We conjecture that the value function of the user in $t \geq 1$ is an affine function of x_{t-1} as follows:

$$V_t^a(x_{t-1}) = \alpha_t + \beta x_{t-1}, \tag{A.1}$$

where α_t and β are constants. Note that α_t is time-dependent whereas β is not. We can ignore the short sale constraint ($x_t \geq 0$) because it is always satisfied in equilibrium. Then, Eqs. (5) and (A.1) imply

$$\begin{aligned} V_t^a(x_{t-1}) &= \max_{\Delta x_t} A(a)N(x_{t-1} + \Delta x_t) - P_t^a \Delta x_t - \frac{\lambda}{2}\Delta x_t^2 + \delta\left[\alpha_{t+1} + \beta(x_{t-1} + \Delta x_t)\right] \\ &= \max_{\Delta x_t} A(a)N x_{t-1} + \delta\left[\alpha_{t+1} + \beta x_{t-1}\right] + (A(a)N + \delta\beta - P_t^a)\Delta x_t - \frac{\lambda}{2}\Delta x_t^2. \end{aligned} \tag{A.2}$$

Then, the first order condition is[12]

$$A(a)N + \delta\beta - P_t^a - \lambda \Delta x_t = 0, \tag{A.3}$$

which implies the optimal trading amount:

$$\Delta x_t = \frac{A(a)N + \delta\beta - P_t^a}{\lambda}. \tag{A.4}$$

Therefore, substituting the solution in Eq. (A.4) into the objective function in Eq. (A.2)

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[12] The second order condition is always satisfied because λ is positive.

yields the indirect value function as follows:

$$V_t^a(x_{t-1}) = \delta\alpha_{t+1} + \frac{\left(A(a)N + \delta\beta - P_t^a\right)^2}{2\lambda} + \left(A(a)N + \delta\beta\right) x_{t-1}, \tag{A.5}$$

Eq. (A.5) together with the initial conjecture in Eq. (A.1) implies that

$$\alpha_t = \delta\alpha_{t+1} + \frac{1}{2\lambda}\left(A(a)N + \delta\beta - P_t^a\right)^2, \tag{A.6}$$

and

$$\beta = A(a)N + \delta\beta. \tag{A.7}$$

Solving for α_t and β yields

$$\beta = \frac{1}{1-\delta}A(a)N = P(a), \tag{A.8}$$

where the second equality is due to Eq. (3). This together with Eq. (A.6) in turn implies

$$\alpha_t = \delta\alpha_{t+1} + \frac{1}{2\lambda}\left(P(a) - P_t^a\right)^2. \tag{A.9}$$

By recursive substitution, we obtain the following from Eq. (A.9):

$$\alpha_t = \frac{1}{2\lambda}\sum_{s=t}^{\infty}\delta^{s-t}\left(P(a) - P_s^a\right)^2. \tag{A.10}$$

Therefore, this verifies our initial conjecture in Eq. (A.1) is indeed true. Furthermore, substituting Eq. (A.8) into Eq. (A.4) yields Eq. (11), which finishes the proof.

Proof of Lemma 2:

Using the objective function Eq. (19) and the constraints (16)-(18), the whale's optimization problem in Eq. (15) can be rewritten as follows:

$$V^a_{w,t}(y_{t-1}) = \max_{\{\Delta y_s\}_{s=t}^T} \sum_{s=t}^{T} \delta^{s-t} \left[A(a)N \left(y_{t-1} + \sum_{k=t}^{s} \Delta y_k \right) - P(a)\Delta y_s - \frac{\lambda_w}{2} \Delta y_s^2 \right], \quad \text{(A.11)}$$

subject to

$$y_{t-1} = -\sum_{s=t}^{T} \Delta y_s. \quad \text{(A.12)}$$

Then, we can maximize the objective function Eq. (A.11) subject to the constraints Eqs. (16)-(18).[13] As the short sale constraint is always satisfied, we can use the lagrangian of the problem, defined as:

$$\mathcal{L} = \sum_{s=t}^{T} \delta^{s-t} \left[A(a)N \left(y_{t-1} + \sum_{k=t}^{s} \Delta y_k \right) - P(a)\Delta y_s - \frac{\lambda_w}{2} \Delta y_s^2 \right] + \eta \left(y_{t-1} + \sum_{s=t}^{T} \Delta y_s \right), \quad \text{(A.13)}$$

where $\eta \geq 0$ is the lagrangian multiplier. The first order condition with respect to Δy_s is

$$A(a)N \left[\frac{\delta^{s-t} \left(1 - \delta^{T-s+1}\right)}{1-\delta} \right] - \delta^{s-t} \left(P(a) + \lambda_w \Delta y_s \right) = -\eta, \quad \text{(A.14)}$$

or equivalently,

$$A(a)N \left(\frac{1 - \delta^{T-s+1}}{1-\delta} \right) - P(a) - \lambda_w \Delta y_s = -\delta^{-(s-t)}\eta. \quad \text{(A.15)}$$

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[13] Our model generalizes the approach used in van Binsbergen et al. (forthcoming) by further including strategic trading under price impact (i.e., endogenous prices) and utility flows of the investment opportunity.

The second order condition is always satisfied. Then, the optimal solution for Δy_s given η is given by

$$\Delta y_s = \frac{1}{\lambda_w}\left[A(a)N\left(\frac{1-\delta^{T-s+1}}{1-\delta}\right) - P(a) + \delta^{-(s-t)}\eta\right]. \tag{A.16}$$

Using the constraint Eq. (16), summing across the first order conditions Eq. (A.15) for all Δy_s's yields

$$A(a)N\left(\frac{1}{1-\delta}\right)\left(T-t+1-\delta^{T-t+1}\Gamma(t,T)\right) - (T-t+1)P(a) + \lambda_w y_{t-1} = -\Gamma(t,T)\eta. \tag{A.17}$$

where $\Gamma(t,T)$ is a constant strictly greater than one:

$$\Gamma(t,T) = \sum_{k=t}^{T}\delta^{-(k-t)} = \frac{\delta^{-(T-t+1)}-1}{\delta^{-1}-1} = \frac{\delta^{-(T-t)}-\delta}{1-\delta}. \tag{A.18}$$

Then, the lagrangian multiplier η is given by

$$\eta = -\frac{1}{\Gamma(t,T)}\left[A(a)N\left(\frac{1}{1-\delta}\right)\left(T-t+1-\delta^{T-t+1}\Gamma(t,T)\right) - (T-t+1)P(a) + \lambda_w y_{t-1}\right]. \tag{A.19}$$

Using Eqs. (A.16) and (A.19), we derive the closed-form solution for Δy:

$$\Delta y_s = -\delta^{-(s-t)}\frac{y_{t-1}}{\Gamma(t,T)} + \frac{1}{\lambda_w}\left[\frac{A(a)N}{1-\delta} - P(a)\right]\left(1 - \frac{\delta^{-(s-t)}}{\Gamma(t,T)}(T-t+1)\right). \tag{A.20}$$

Due to Eq. (3), we have

$$\Delta y_s = -\delta^{-(s-t)}\frac{y_{t-1}}{\Gamma(t,T)}. \tag{A.21}$$

Finally, substituting Eq. (A.21) into Eq. (A.11) yields the indirect value in Eq. (23).

Proof of Lemma 3:

Using Eq. (19), we can represent the whale's value with the choice of Δy_1 in $t = 1$, given a and B ,as follows:

$$V^a_{w,1}(y_0) = By_0\mathbb{1}(a = I) + A(a)N(y_0 + \Delta y_1) - P(a)\Delta y_1 - \frac{\lambda_w}{2}\Delta y_1^2 + \delta V^a_{w,2}(y_0 + \Delta y_1). \tag{A.22}$$

From Eq. (23) in Lemma 2, the value in $t = 2$ is given by

$$V^a_{w,2}(y_0 + \Delta y_1) = P(a)(y_0 + \Delta y_1) - \frac{\lambda_w}{2}\frac{(y_0 + \Delta y_1)^2}{\Gamma(2,T)^2}. \tag{A.23}$$

Therefore, substituting Eq. (A.23) into Eq. (A.22) yields

$$\begin{aligned} V^a_{w,1}(y_0) =& By_0\mathbb{1}(a = I) + A(a)N(y_0 + \Delta y_1) - P(a)\Delta y_1 - \delta P(a)(y_0 + \Delta y_1) \\ &- \frac{\lambda_w}{2}\Delta y_1^2 - \delta\frac{\lambda_w}{2}\frac{(y_0 + \Delta y_1)^2}{\Gamma(2,T)^2} \\ =& By_0\mathbb{1}(a = I) + P(a)y_0 - \frac{\lambda_w}{2}\Delta y_1^2 - \delta\frac{\lambda_w}{2}\frac{(y_0 + \Delta y_1)^2}{\Gamma(2,T)^2}. \end{aligned} \tag{A.24}$$

where the second equality is due to Eq. (3).

Proof of Lemma 4:

When the whale implements the proposal ($a = I$), the value function of users in Lemma 1 together with the equilibrium price process in Eq. (31) implies that the intercept in the value function in $t = 2$ is given by

$$\alpha_2 = \frac{\lambda}{2\Gamma(2,T)} \frac{\bar{x}^2}{N^2}, \tag{A.25}$$

which in turn implies the intercept in the value function in $t = 1$ is given by

$$\alpha_1 = \frac{1}{2\lambda}(P(I) - P_1^I)^2 + \delta\alpha_2 \tag{A.26}$$

$$= \frac{\lambda}{2N^2}\left[(\bar{x} - y_0)^2 + \frac{\delta\bar{x}^2}{\Gamma(2,T)}\right] \tag{A.27}$$

Therefore the value of users in $t = 1$ is

$$V_1(x_0) = \frac{\lambda}{2N^2}\left[(\bar{x} - y_0)^2 + \frac{\delta\bar{x}^2}{\Gamma(2,T)}\right] + P(I)x_0. \tag{A.28}$$

Finally, the value in $t = 0$ becomes

$$V_0(I) = -\bar{P}x_0 + \delta V_1(x_0, W_0) = -\bar{P}(1 - y_0) + \delta V_1(1 - y_0, 0) \tag{A.29}$$

$$= (\delta P(I) - \bar{P})(1 - y_0) + \delta\frac{\lambda}{2N^2}\left[(\bar{x} - y_0)^2 + \frac{\delta\bar{x}^2}{\Gamma(2,T)}\right]. \tag{A.30}$$

When the whale does not implement the proposal ($a = R$), the value function of users in Lemma 1 together with the equilibrium price process in Eq. (31) implies that the intercept in the value function in $t = 1$ is given by

$$\alpha_1 = \frac{\lambda}{2N^2}\frac{\bar{y_0}^2}{\Gamma(1,T)}. \tag{A.31}$$

Then, the value of users in $t = 1$ is

$$V_1(x_0, W_0) = \frac{\lambda}{2N^2} \frac{\bar{y_0}^2}{\Gamma(1, T)} + P(R)x_0. \tag{A.32}$$

Therefore we can obtain the value in $t = 0$ as follows:

$$\begin{aligned} V_0(R) &= -\bar{P}x_0 + \delta V_1(x_0, W_0) = -\bar{P}(1 - y_0) + \delta V_1(1 - y_0, 0) && \text{(A.33)} \\ &= (\delta P(I) - \bar{P})(1 - y_0) + \delta \frac{\lambda}{2N^2} \frac{\bar{y_0}^2}{\Gamma(1, T)}. && \text{(A.34)} \end{aligned}$$

Then the difference between $V_0(R)$ and $V_0(I)$ is positive due to Eq. (28).