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Three Essays on Blockchain and the Transformation of International Trade, Finance, and Money

PhD Student

Christopher Seta

Supervisor

Prof. Marco Cucculelli

Coordinator of the PhD Programme

Prof. Flavio Corradini

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Abstract (EN)

This dissertation consists of three essays on how blockchain-based infrastructures reshape cross-border economic activity by changing how trust is produced, how intermediation is organized, and how liquidity and money are provided. The unifying lens is that blockchain enables shared verification and programmable assets, which can reduce coordination frictions, but can also generate new forms of systemic risk and policy trade-offs. The first essay studies blockchain adoption in international trade through a PRISMA-based systematic literature review. It synthesizes evidence on where distributed ledgers can improve transparency, auditability, and process efficiency in trade documentation and supply-chain coordination, and identifies recurring constraints related to stakeholder incentives, scalability/interoperability, data governance at the on-/off-chain boundary, and regulatory fragmentation. The second essay analyzes the DeFi ecosystem as a laboratory for blockchain-enabled financial intermediation. Using monthly category-level Total Value Locked (TVL) data from the Cambridge DeFi Navigator, it estimates VAR and time-varying VAR models to map short-run spillovers and state-dependent connectedness. Results point to a hierarchical structure in which staking-related expansions precede broader increases in credit and trading activity, while credit-related shocks explain a large share of short-run uncertainty and connectedness intensifies during stress regimes. The third essay examines USD-pegged stablecoins as tokenized private money that can alter domestic liquidity portfolios in small open economies. It develops a portfolio model of monetary substitution and monetary-policy leakage, in which households allocate real liquidity between domestic money and tokenized dollars. The model is brought to the data using local projections on a monthly panel of 24 countries over 2018–2025. The results show a negative dynamic response of M1 growth in relatively high-exposure economies following expansions in global stablecoin capitalization, suggesting that tokenized dollar use is already detectable on the monetary margin, although the estimated effects remain modest at current scale.

Key words (EN)

Blockchain; Decentralized Finance (DeFi); Stablecoins; International Trade

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DECLARATION

I hereby declare that I have produced this dissertation under the supervision of Prof. Marco Cucculelli.

Christopher Seta
June 2026

* This dissertation is presented in partial fulfillment of the requirements for
Ph.D. degree in the School of Advanced Studies of University of Camerino.

Abstract

This dissertation consists of three essays on how blockchain-based infrastructures reshape cross-border economic activity by changing how trust is produced, how intermediation is organized, and how liquidity and money are provided. The unifying lens is that blockchain enables shared verification and programmable assets, which can reduce coordination frictions, but can also generate new forms of systemic risk and policy trade-offs. The first essay studies blockchain adoption in international trade through a PRISMA-based systematic literature review. It synthesizes evidence on where distributed ledgers can improve transparency, auditability, and process efficiency in trade documentation and supply-chain coordination, and identifies recurring constraints related to stakeholder incentives, scalability/interoperability, data governance at the on-/off-chain boundary, and regulatory fragmentation. The second essay analyzes the DeFi ecosystem as a laboratory for blockchain-enabled financial intermediation. Using monthly category-level Total Value Locked (TVL) data from the Cambridge DeFi Navigator, it estimates VAR and time-varying VAR models to map short-run spillovers and state-dependent connectedness. Results point to a hierarchical structure in which staking-related expansions precede broader increases in credit and trading activity, while credit-related shocks explain a large share of short-run uncertainty and connectedness intensifies during stress regimes. The third essay examines USD-pegged stablecoins as tokenized private money that can alter domestic liquidity portfolios in small open economies. It develops a portfolio model of monetary substitution and monetary-policy leakage, in which households allocate real liquidity between domestic money and tokenized dollars. The model is brought to the data using local projections on a monthly panel of 24 countries over 2018–2025. The results show a negative dynamic response of M1 growth in relatively high-exposure economies following expansions in global stablecoin capitalization, suggesting that tokenized dollar use is already detectable on the monetary margin, although the estimated effects remain modest at current scale.

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Chapter 1

Introduction

1.1 Motivation and research context

Over the past decade, blockchain and distributed ledger technologies (DLT) have evolved from a niche innovation associated with cryptocurrencies into a broader class of infrastructures for recording, validating, and transferring value and information across organizational boundaries [1, 2]. This evolution matters for economics because many high-value transactions, especially those that are cross-border, are constrained not only by the availability of digital tools, but also by the costs of coordination, verification, and settlement among parties operating under heterogeneous legal regimes, standards, and information systems. In such environments, trust is often produced through layers of intermediation and repeated reconciliation. These mechanisms can be effective, but they are also costly, slow, and prone to disputes.

This dissertation studies blockchain as an infrastructure that can reshape cross-border exchange along three connected layers: international trade, financial intermediation, and money. At the trade layer, cross-border shipments involve exporters and importers, logistics providers, customs authorities, insurers, banks, and inspection agencies, each maintaining internal records and compliance procedures. Even where logistics and payment infrastructures have improved, administrative workflows often remain fragmented and paper-heavy, generating delays, documentary discrepancies, and barriers to participation for smaller firms. These frictions are economically consequential because they shape access to trade finance, the allocation of risk along supply chains, and participation in global value chains. Blockchain-based systems have been proposed as coordination technologies that could support shared verification and improve traceability and auditability in multi-party workflows. At the same time, their real-world impact depends on governance, incentives for truthful data entry, interoperability with legacy systems, and legal recognition of digital records, as well as on whether on-chain records can credibly map to off-chain states.

At the financial intermediation layer, smart-contract platforms enabled programmable and composable applications, giving rise to decentralized finance (DeFi) as a parallel architecture for trading, lending, and liquidity provision [3, 4]. DeFi therefore offers a laboratory-like setting in which intermediation functions are implemented as code and activity is measured through platform and on-chain metrics, while also raising questions about risk propagation and effective decentralization [5]. At the monetary layer, USD-pegged stablecoins extend tokenization to money itself by creating globally accessible private dollar claims used in cross-border transfers and as settlement and collateral instruments in digital markets. As adoption scales, these instruments can interact with monetary conditions in non-issuing economies through mechanisms related to monetary substitution and exposure to dollar liquidity conditions [6, 7].

The dissertation takes these developments as part of a broader phenomenon. Blockchain-based systems can alter how cross-border exchange is organized by changing how information is verified and shared, how intermediation functions are replicated or reconfigured, and how settlement assets and liquidity are provided. These changes can generate benefits, such as improved auditability, faster coordination, or wider access, but they may also introduce new vulnerabilities, governance burdens, and macro-financial dependencies. Consequently, the relevant research question is not whether blockchain can transform trade and finance in principle, but under what institutional conditions, through which mechanisms, and with what measurable implications.

1.1.1 Research problem and guiding questions

The core research problem motivating this dissertation is the following. When blockchain-based infrastructures are introduced into cross-border processes, whether in real-economy trade workflows or in digital financial markets, under what conditions do they reduce coordination and settlement frictions, how do they reshape the organization of intermediation and liquidity, and what new risks or constraints emerge as a result?

This problem is addressed through a set of guiding questions that run across the three essays. First, how does DLT adoption affect verification and coordination in trade-related processes, including traceability and the credibility of shared records, and what adoption constraints recur in practice? Second, how do blockchain-native financial services evolve as an ecosystem, and what do their internal interdependencies imply for shock transmission and risk monitoring in a composable environment [3, 5]? Third, how does tokenized private money, in particular USD-pegged stablecoins, interact with cross-border settlement and monetary conditions in non-issuing economies, and when might macro effects become quantitatively relevant as scale increases [6, 7]? Fourth, which governance, regulatory, and measurement constraints shape the ability to draw credible conclusions about economic impact, given endogeneity of adoption and data limitations?

1.1.2 Dissertation overview

This dissertation follows a three-essay format. Each essay is self-contained, but together they address a unified theme: the transformation of cross-border exchange through infrastructures for shared verification, programmable intermediation, and tokenized settlement.

The first essay is a systematic literature review of blockchain applications in international trade. Using a PRISMA-guided selection process [8], it synthesizes research on proposed and implemented applications in trade documentation, logistics, and related processes. It organizes the evidence around recurring mechanisms and claimed effects, while also identifying persistent barriers to adoption, including stakeholder participation constraints, interoperability and scalability issues, and regulatory fragmentation.

The second essay examines the DeFi ecosystem using monthly Total Value Locked (TVL) data by functional category from the Cambridge Centre for Alternative Finance DeFi Navigator. It studies short-run interdependencies across major DeFi segments over a balanced sample from December 2020 to June 2025. After testing for unit roots and the absence of cointegration in levels, the analysis estimates a parsimonious vector autoregression (VAR) in log differences and complements it with a time-varying parameter approach to track connectedness over time. The empirical strategy draws on established time-series methods for multivariate dynamics and spillover measurement [9, 10, 11, 12]. The focus is on intra-DeFi dynamics and on how shock transmission changes across regimes, rather than on forecasting or on structurally identifying external drivers.

The third essay studies USD-pegged stablecoins as tokenized private money that can compete with domestic money in the liquid portfolios of residents in small open economies. It develops a portfolio framework focused on two monetary mechanisms: monetary substitution, through which tokenized dollars displace domestic liquid balances, and monetary-policy leakage, through which a foreign-currency liquidity substitute attenuates the response of domestic money demand to local policy conditions [6, 13]. The essay then uses local projections on a monthly panel of 24 countries over 2018–2025 to examine whether expansions in global stablecoin capitalization are followed by weaker M1 growth in relatively high-exposure economies.

1.1.3 Contributions and positioning

The dissertation contributes to the literature by integrating three strands that are often studied separately. It connects the trade-related literature on shared verification and coordination with empirical evidence on how programmable intermediation behaves within DeFi, and with a macroeconomic analysis of tokenized private money through stablecoins. Methodologically, it combines three modes of evidence that are common in economics and finance dissertations: systematic synthesis of a fragmented applied literature, time-series econometric mapping of ecosystem interdependencies using category-level activity measures, and macroeconomic modeling complemented by cross-country panel evidence on monetary substitution.

Throughout, the dissertation adopts a comparative and conditional stance. Blockchain adoption is not assumed to be inherently welfare-improving. Reductions in frictions along one dimension can be accompanied by costs in another, including governance complexity, new attack surfaces introduced by programmability, or increased dependence on foreign-currency liquidity. The relevant evaluation is therefore relative to existing institutional arrangements and conditional on design choices, governance, and scale.

1.2 Structure

The remainder of this dissertation is organized as follows. Chapter 2 sets the background by outlining how blockchain-based systems evolved from early cryptocurrencies to programmable smart contracts and, subsequently, to decentralized finance and tokenized forms of money. Chapters 3 to 5 present the three essays in turn, describing their respective data, methods, results, and implications. Chapter 6 concludes by synthesizing cross-essay insights for research and policy and by outlining open questions about the future integration of blockchain-based infrastructures into international trade, cross-border finance, and the global monetary system.

Chapter 2

Historical and Technical Foundations of Blockchain-Based Systems

2.1 Introduction

This chapter provides the historical, conceptual, and technological foundations that underpin the three essays of this dissertation. It traces the evolution of blockchain and distributed ledger technologies (DLT) from their origins in Bitcoin to their applications across decentralized finance (DeFi), tokenized assets, and digital forms of money. The objective is to establish a coherent understanding of how blockchain operates as an infrastructure for recording, verifying, and transferring value, and how its design principles and use cases have expanded over time.

Blockchain's relevance to economics lies in its ability to create shared records of truth without centralized control. Through distributed consensus, cryptographic validation, and transparent auditability, blockchain offers a new mechanism for organizing economic coordination in environments characterized by limited trust.

2.2 From Bitcoin to Programmable Ledgers

The first generation of blockchain emerged with Bitcoin, introduced by [1]. Its central innovation was the ability to achieve consensus in a decentralized network without trusted intermediaries, using proof-of-work to validate transactions and secure the ledger. Economically, Bitcoin can be interpreted both as a payment system and as a new type of monetary asset—one that is scarce, borderless, and resistant to censorship.

However, Bitcoin's architecture was intentionally narrow: it allowed for the secure transfer of value but not for programmable contracts or complex state transitions. The second generation, led by Ethereum [2], extended blockchain functionality through smart contracts—self-executing code that operates directly on the ledger. This innovation transformed blockchains from payment systems into general-purpose computational platforms capable of hosting decentralized applications (dApps) across sectors such as finance, logistics, and governance.

Smart contracts introduced the principle of composability: on-chain assets and protocols can interact programmatically to form complex financial ecosystems. This feature laid the groundwork for decentralized finance and the broader tokenization of value, enabling markets and coordination systems to emerge natively within blockchain environments.

2.3 The Rise of Decentralized Finance (DeFi)

DeFi refers to an ecosystem of financial services built on public blockchains and smart contracts that replicate and extend traditional financial functions such as trading, market making, lending, borrowing, leverage, and risk transfer without relying on conventional intermediaries [3, 5]. Historically, DeFi developed in waves that reflect both technological progress and market cycles. Early building blocks emerged after the diffusion of programmable smart contracts, when decentralized exchanges and automated market makers enabled on-chain trading and liquidity provision, while over-collateralized money markets and derivatives protocols introduced credit, leverage, and hedging in a permissionless setting. The rapid expansion of protocol composability and incentive design, most visibly during the 2020–2021 boom, led to an increasingly interconnected "stack" in which tokens, collateral positions, and liquidity claims circulate across protocols. This architecture delivered novel forms of capital efficiency and continuous settlement, but it also generated new sources of fragility: endogenous liquidity spirals, oracle dependence, governance capture, and complex chains of interdependence that can amplify shocks [5]. After the 2022 stress episodes, the ecosystem entered a phase of consolidation and reconfiguration, marked by re-pricing of risk, a reduction in leverage, and gradual institutional experimentation with permissioned interfaces and regulated on-ramps, while DeFi's core economic functions (exchange, credit, and liquidity provision) continued to operate as blockchain-native market infrastructure [3].

2.4 Stablecoins: Evolution of Use Cases and Economic Role

Stablecoins are blockchain-based tokens designed to maintain a stable value relative to a reference asset, most commonly the U.S. dollar. Their economic role evolved alongside the DeFi ecosystem and broader crypto-market adoption. In early stages, stablecoins were used primarily as a transactional bridge for trading and as a convenient unit of account in environments dominated by highly volatile crypto-assets. As DeFi expanded, stablecoins became central to on-chain credit creation and collateral management, functioning as base assets in lending markets and as key inputs into liquidity pools and automated market-making. Over time, their use extended beyond retail trading and DeFi into what can be described as market "plumbing": stablecoins increasingly serve as settlement assets, collateral for leveraged positions, and liquidity instruments connecting centralized exchanges, on-chain protocols, and cross-chain bridges. This functional expansion has direct macro-financial relevance because stablecoins provide globally accessible private dollar claims; at scale, this can reinforce dollar dependence, interact with capital flows, and create channels of monetary substitution in non-issuing economies [6, 7]. The fragility revealed by unstable designs and stress episodes contributed to a sharper regulatory focus, with frameworks such as the EU Markets in Crypto-Assets Regulation (MiCA) aiming to define issuance, reserve management, and consumer protection standards for the stablecoin segment [14].

2.5 Tokenized Money and the Emerging Monetary Stack

Tokenized money refers to monetary instruments represented as transferable digital tokens on distributed ledgers. While stablecoins are the most visible example in open, permissionless networks, tokenized money is broader and can be organized into three main categories that differ in issuer, legal nature, and policy implications. First, stablecoins are typically private liabilities (or claims structured through private arrangements) designed to track a fiat reference, widely used in public blockchain environments and increasingly relevant for cross-border settlement and liquidity provision [7]. Second, tokenized deposits are digital representations of commercial bank deposits, normally issued within permissioned infrastructures and aligned with existing banking regulation; conceptually, they aim to combine the legal certainty of deposit money with programmability and near-instant settlement. Third, central bank digital currencies (CBDCs) are direct liabilities of central banks that extend sovereign money into digital form, with design choices spanning retail versus wholesale architectures and varying degrees of programmability and privacy. From an economic perspective, these instruments represent distinct answers to the same underlying question: how to modernize the settlement layer of the economy while balancing efficiency, stability, and governance. Recent policy discussions emphasize that the growth of private tokenized money, especially dollar-pegged stablecoins, can reshape cross-border payments and monetary conditions, while public and bank-based tokenization initiatives (CBDCs and tokenized deposits) are increasingly framed as counter-designs that preserve monetary sovereignty and financial stability while adopting some of the operational advantages of DLT [15]. In practice, the near-term landscape is likely to be hybrid: stablecoins dominate open networks due to composability and global accessibility, whereas tokenized deposits and CBDCs are developing within regulated environments and may connect to broader digital-asset markets through controlled interoperability layers rather than direct, permissionless circulation.

Chapter 3

International Trade in the Age of Blockchain: A Systematic Literature Review on Transparency, Security, and Efficiency Perspectives

Abstract

As blockchain technology continues to mature, it allows a rethinking of international trade structures. This study provides a systematic literature review to evaluate blockchain's impact on key aspects of cross-border trade. An initial pool of 327 articles was identified through a keyword-based search on Scopus, and subsequently refined to 112 studies through a systematic selection process following PRISMA guidelines. These studies were organized into five thematic categories, enabling a structured exploration of blockchain applications and innovations in international trade. The review reveals that distributed ledger technologies offer a range of substantial benefits, particularly in terms of increasing efficiency, enhancing transparency, and strengthening data security. Nevertheless, the literature highlights key limitations, such as limited stakeholder participation, scalability challenges, and the absence of a global regulatory framework. These results open new avenues for exploring the challenges and opportunities associated with the future integration of blockchain technology into the global trade ecosystem.

Keywords

Blockchain, International Trade, Transparency, efficiency, security, DLT.

3.1 Introduction

We have had the fastest-reaching technological advancements ever since the 21st century, when digital innovations drove progress in nearly every sector. Blockchain is one of the several emerging technologies allegedly bringing about transformative changes, often described generically as "general-purpose technology" [16], with the potential to revolutionize sectors ranging from finance and health to international trade. Blockchain technology, as designed by pseudonymous Satoshi Nakamoto and implemented in the Bitcoin network as a white paper in 2008, has extended well beyond its original use case within digital currency. While Bitcoin has served as a platform for decentralized, incorruptible data storage and verification mechanisms with far-reaching applications beyond cryptocurrency [1], grasping the possibility of blockchain entails a deep dive into its principal ideas and building blocks, more so the Distributed Ledger Technology (DLT) that enables it.

Conventional centralized databases depend on a solitary authority holder to maintain records. At the same time, DLTs, the decentralized databases at the heart of blockchain, operated by a network of participants or nodes, run with no central focal point and are much more robust and open. All members in the DLT have a copy of the ledger and it is updated based on consensus over the network. Such a decentralized architecture guarantees that all records are consistent, secure, and resistant to data manipulation. Immutability is one of the distinct characteristics regarding DLTs. Once data has been recorded to the ledger, it cannot be changed. Due to the use of cryptography, this property guarantees that an entry in the ledger cannot be erased, thereby providing a uniquely high level of security and transparency to the system. In addition to this, DLTs can be divided into permissioned and permissionless networks. Permissionless DLTs (e.g., blockchain underlying Bitcoin) are open networks where anyone can join the network and participate in its consensus mechanisms. Conversely, permissioned DLTs are limited to certain indexes that must have passed an approval process and are typically utilized in private or enterprise environments where privacy of data as well as control over access is a priority [17].

The key distinguishing feature of a blockchain is that it stores data in "blocks" linked to each other via cryptographic hashes, thus forming a chronological "chain" of records. Blockchain technology enables linking blocks and creates a secure sequential record of all transactions, recasting the need for tampering with one block to change the entire trading history that has occurred, prior to it (with its unauthorized changes almost impossible) [18].

Consensus mechanisms are prominent features of Blockchain, two examples of them are Proof-of-Work (PoW) and Proof-of-Stake (PoS). For example, Bitcoin uses PoW, which is energy-hungry and has participants to solve complex cryptographic puzzles. PoS, on the other hand, and used by Ethereum, enables participants to confirm transactions according to their participation in the network tokens. It is more efficient regarding energy but increases security concerns and potential centralization [19].

From early trade routes, such as the Silk Road, to modern exchanges of goods and services across lakes and continents, international trade has developed considerably over its millennia-long history. Originally, trade consisted of direct exchange of goods and simple barter systems but evolved into a system of economic networks that extended worldwide. The globalization of the 20th century took trade a step further, and multinationals soon began developing complex supply chains that allow for goods, services, and capital to flow across national borders. Yet, this evolution has brought with it many challenges because of the complexity inherent in international trade, which is still grounded on slow and expensive paper-based processes, needing intermediaries and over-reliance on untrustworthy systems [20].

The innovative, decentralized, transparent and secure nature of blockchain technology offers solutions to some of these historic inefficiencies in international trade. Firstly, it reduces the need for all documentation and transaction verification by replacing traditional paper-based records with digital, validated (via cryptographic signatures), immutable records on a blockchain ledger. Since these actions involve many parties, processing times and costs usually increase with the increase in the number of intermediaries involved in such actions and so does the possibility of errors or missing data to the detriment of security. Security that with blockchain would significantly improve since the real-time proof of transactions by each party could provide greater guarantees on transactions than what is currently available [21]. Moreover, it also allows traceability back and forth in the whole supply chain as it can provide full transparency for tracking the goods from its source to delivery [22], especially beneficial for food, pharmaceutical, and luxury goods where provenance of the goods is essential. The application of blockchain in trade is further increased with its use of smart contracts, which are self-executing contracts whose terms are directly written into code. They automatically initiate certain processes when conditions have been met, reducing the need for third parties and bias. In the case of cross-border trade, for example, a smart contract could automatically pay the supplier once they receive confirmation about shipment via a form of financial smart contract [23], allowing payment to be made on time and contingent upon particular conditions with lower fraudulent risk.

In this sense, blockchain is becoming a general-purpose technology that can change the way things are done in commerce similarly to the Internet in previous decades. Blockchain's applications in international trade are far more than just simplifying transactions; it fundamentally changes the way in which trust is built between parties of global commerce. Blockchain improves the trustworthiness of data by eliminating the reliance on a third-party entity that can verify transactions in the network in exchange for money, with an open and unchanging model of blockchain data structure. Such a shift might have far-reaching consequences for trade in areas where the regulatory environment differs and trust in legal systems may be lower, facilitating fairer and safer cross-border trading relationships [24]. Additionally, the potential of blockchain for data standardization across jurisdictions is helping make it an attractive solution to harmonize international trade regulations and compliance requirements. At present, different countries and regulatory bodies have their own trade documentation and compliance requirements that lead to inefficient processes, delays in international trade process, and increased costs of doing business. Blockchain can provide a decentralized solution to the inconsistency among regulatory regimes by developing a standardized, permanent record-keeping system that facilitates global interoperability [25].

Although blockchain has shown extensive theoretical and practical potential for its applications in international trade, the existing studies are very few and largely scattered. Existing research tends to either cover applications within certain domains, or pinch out sectors, leading to missing an integral part on holistic effects of blockchain-based services on the three pillars of trade, efficiency, transparency, and security. The aim of the current study is to fill this gap by providing a systematic literature review that synthesizes existing studies on blockchain applications in trade and their transformative potential.

This review aims at three objectives: First, to provide a comprehensive description of blockchain characteristics such as transparency, security and immutability and their relevance in trade; second, to identify common themes in the literature and classify these into major themes where blockchain appears to impact trade; thirdly, to clarify substantive gaps in the literature while pointing out future opportunities for research highlighting where current inefficiencies in trade may be addressed with blockchain technology or how it evolves according regulatory needs across jurisdictions.

The remainder of this paper is organized as follows: The next section briefly describes the research methods, specifically selection criteria used to identify the relevant literature. Subsequently, we provide a structured summary of the chosen articles and discuss five dominant themes of research which identify how blockchain creates transparency, efficiency and security for trade. The final part discusses the gaps in current literature and possible ways forward for blockchain diffusion in global trade.

3.2 Materials and Methods

In order to get a comprehensive and methodologically rigorous literature review of the main usages of DLTs, specifically blockchain, in international trade, a reliance on bibliometric and content analysis techniques had to be made. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were followed in the process of reviewing because these reporting items are widely regarded for bringing transparency, rigor, and reproducibility together into systematic reviews. The PRISMA framework guided our identification process with strict inclusion and exclusion criteria to comprehensively and qualitatively assess the literature (Fig. 1).

This review therefore had the scope to identify, appraise, and synthesize the available evidence on the actual uses of blockchain and other DLTs in international trade, focusing on thematic areas of interest related to transparency, efficiency, and safety. We began the review by conducting a systematic search in the Scopus database using a carefully constructed set of keywords, designed to cover the literature related to the intersection of blockchain and international trade. As can be seen in the selection process in Figure 1, we combined these keywords using the Boolean operator AND to narrow down our search and eliminate any non-relevant results. The initial search yielded 327 articles.

Following the guidelines of PRISMA, several exclusion criteria were applied in order to increase the relevance and quality of this review. Articles written in a non-English language, conference papers, book chapters, and non-peer-reviewed publications were excluded in this review by including only journal articles and review papers for a higher level of evidence. Because blockchain is still a pretty new concept, no time constraints were set; nevertheless, most of the relevant works appeared after the beginning of 2016. The filtering step reduced the dataset to 137 articles that underwent careful quality control. Abstracts and full texts were reviewed to exclude articles that did not relate directly to the topic of blockchain and international trade. This step further refined our dataset, eventually providing us with 112 articles on which the subsequent analysis was based (full list in Appendix A).

A bibliometric analysis has been carried out in order to investigate the structure and characteristics of the selected literature. More specifically, we have analyzed general publication trends, citation patterns, and co-authorship networks. The tools used for visualization included VosViewer and AI

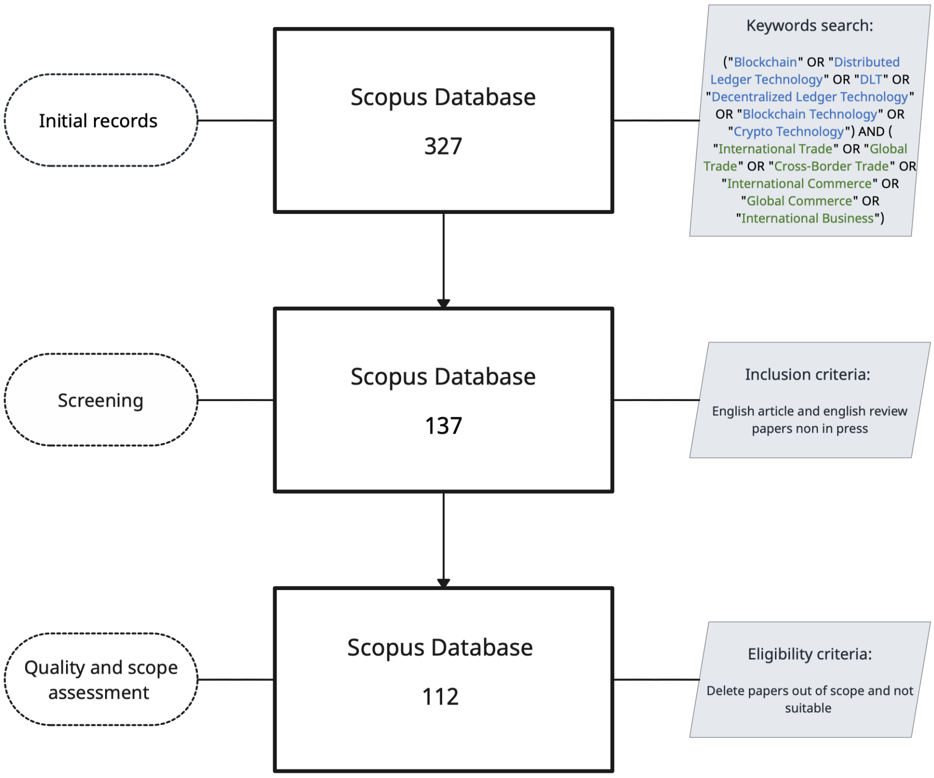

Figure 3.1: PRISMA framework

software applications, such as PowerDrill, for showing visualizations of critical metrics, including publication growth rate, average citations per article, and disciplinary distribution. Quantitatively, these metrics are summarized in Table 1 below, indicating sequential publication growth and discipline breadth.

Regarding disciplinary contributions, the majority of articles originate from the field of Business, Management, and Accounting, which is the leading category, followed by significant contributions from Computer Science and Social Sciences (Fig. 2). The publication trends from 2016 to the present demonstrate a progressive growth of interest in the topic up to 2022. However, a noticeable decline in publications during the most recent reporting period may indicate shifts in research focus or priorities (Fig. 3). To further understand the landscape, a detailed analysis of the journals publishing these articles was conducted, highlighting the diversity of publication sources and providing insights into the breadth of scholarly engagement in this area. The most frequent journals are listed in Table 2; it follows the confirmation of a heterogeneous literature base, since only a few sources have published more than two articles on the topic. Remarkably, "Mobile Information Systems" is identified as a key publication outlet with four articles, while other journals publish one or two on average.

Table 3, which lists the most cited articles within our dataset, further supports this: only three studies have received more than 200 citations, and five have an average citation rate above 30 per year. Research on blockchain in international trade is at its emerging stage now, and interest in the area has not been well-distributed but instead concentrated on some particular points.

Following this bibliometric analysis, a content analysis was done to dig deeper into the thematic content of the selected articles. Co-occurrence examined keywords by VosViewer's means with the ability to visualize and identify dominant or recurring themes or topics in the literature. Figure 4 depicts such co-occurrence network, emphasizing the most salient themes that blockchain applications are being used for in international trade, such as themes like supply chain management, trade finance, and cross-border payments.

Table 3.1: General information about records extracted.

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2016:2024
Sources (Journals, Books, etc)	Journals
Documents	112
Average citations per doc	25.4
DOCUMENT CONTENTS	
Keywords	917
Author's Keywords (DE)	389
AUTHORS	
Authors	338
Authors of single-authored docs	27
AUTHORS COLLABORATION	
Single-authored docs	27
Co-Authors per Doc	3
DOCUMENT TYPES	
Article	106
Review	6

Table 3.2: Most frequent sources

Sources	Articles Published
"Mobile Information System"	4
"International Journal Of Production Research"	3
"Review Of International Business And Strategy"	3
"Sustainability Switzerland"	3
"Computers and Industrial Engineering"	3
"Transportation Research Part E Logistics And Transportation Review"	3

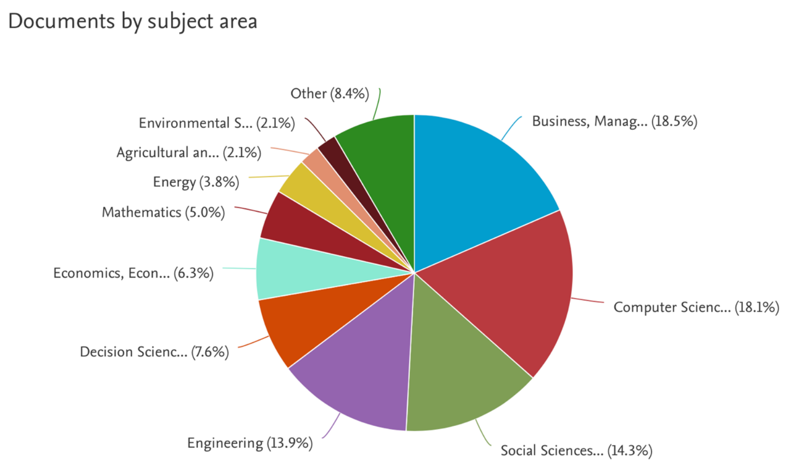

Figure 3.2: The distribution of research on the subject base

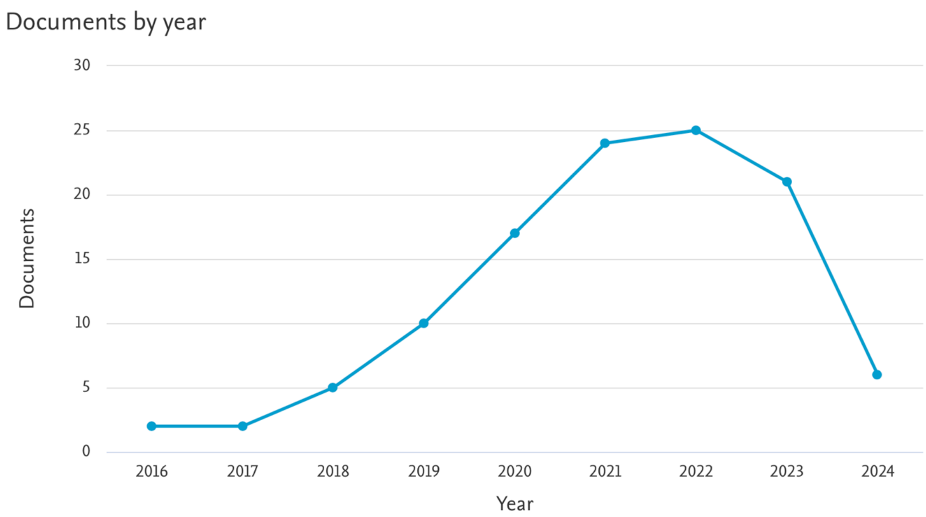

Figure 3.3: Allocation of the published literature.

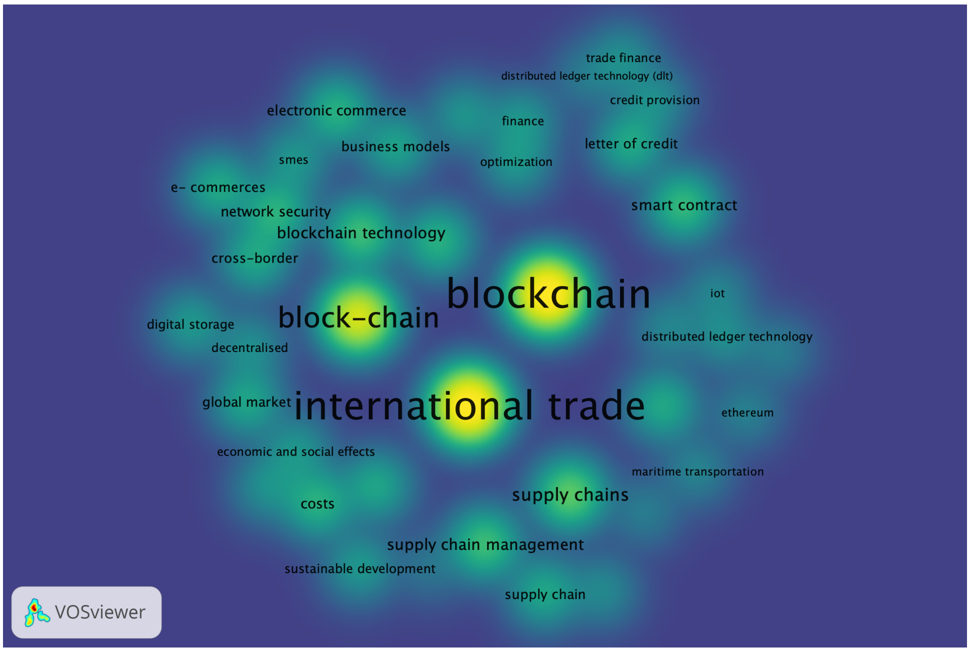

Figure 3.4: Co-occurrence of keywords using VOS viewer

Table 3.3: Most-cited articles

Authors	Title	Cited by	Avg. citations/year
Berdik, Otoum, Schmidt, Porter & Jararweh (2021) [26]	"A Survey on Blockchain for Information Systems Management and Security"	323	107.7
Chang, Iakovou & Shi (2020) [27]	"Blockchain in global supply chains and cross border trade: a critical synthesis of the state-of-the-art, challenges and opportunities"	312	78
Mackey & Nayyar (2017) [28]	"A review of existing and emerging digital technologies to combat the global trade in fake medicines"	220	31.4
Alonso, Sittón-Candanedo, García, Prieto & Rodríguez-González (2020) [29]	"An intelligent Edge-IoT platform for monitoring livestock and crops in a dairy farming scenario"	169	42.2
Hasan, AlHadhrami, AlDhaheri, Salah & Jayaraman (2019) [30]	"Smart contract-based approach for efficient shipment management"	148	29.6
Qian, Ruiz-Garcia, Fan, Robla Villalba, McCarthy, Zhang, Yu & Wu (2020) [31]	"Food traceability system from governmental, corporate, and consumer perspectives in the European Union and China: A comparative review"	107	26.7
Kimani, Adams, Attah-Boakye, Frecknall-Hughes & Kim (2020) [32]	"Blockchain, business and the fourth industrial revolution: Whence, whither, wherefore and how?"	87	21.7
Ahmad, Hasan, Jayaraman, Salah & Omar (2021) [33]	"Blockchain applications and architectures for port operations and logistics management"	82	27.3
Yoon, Talluri, Yildiz & Sheu (2020) [34]	"The value of Blockchain technology implementation in international trades under demand volatility risk"	76	19
Chang, Chen & Wu (2019) [35]	"Exploring blockchain technology in international trade: Business process re-engineering for letter of credit"	71	14.2
Gao, Xu, Chen, Lu & Shi (2018) [36]	"CoC: A Unified Distributed Ledger Based Supply Chain Management System"	71	11.8
Cao, Powell, Foth, Natanelov, Miller & Dulleck (2021) [37]	"Strengthening consumer trust in beef supply chain traceability with a blockchain-based human-machine reconcile mechanism"	70	23.3
Juma, Shaalan & Kamel (2019) [38]	"A Survey on Using Blockchain in Trade Supply Chain Solutions"	65	16.2
Biswas, Jalali, Ansaripoor & De Giovanni (2023) [39]	"Traceability vs. sustainability in supply chains: The implications of blockchain"	56	56
Chang, Luo & Chen (2020) [40]	"Blockchain-enabled trade finance innovation: A potential paradigm shift on using letter of credit"	54	13.5

3.3 Results

Following title/abstract screening and full-text assessment, we identified five thematic research streams: (i) financial technology and cross-border payments, (ii) supply chain and logistics, (iii) regulation and standards, (iv) sustainability, and (v) security, trust, and privacy.

Each of the streams was reviewed in depth, what were some of the key findings, limitations, and knowledge gaps in this research. This structured approach allowed us to piece together a comprehensive view about the current state of research into the role of blockchain in international trade and indicate areas where further research might be required. In short, this section describes the systematic and transparent approach of literature review that merges both bibliometric and content analyses. We have done an in-depth, complex study of the literature related to blockchain issues in international trade, by established methodologies using the most advanced analytical tools that set the stage for an in-depth discussion of our findings in the next parts.

Once the five research categories were outlined, an in-depth analysis of each strand was performed in detail to understand the key topics of discussion, main findings, limitations, and research gaps within each category. This analysis forms the basis for formulating a comprehensive understanding of blockchain technology's current and potential capabilities in different aspects of international trade. It was further facilitated by artificial intelligence tools that could group these studies more efficiently and match the text with the respective category.

These clusters are meaningful for giving an overview of the wide-ranging themes in the literature. In the following sections, we will analyze each specific cluster in more detail, underlining some of the most relevant works in each category.

3.3.1 Stream 1: Financial Technology & Cross-Border Payments

This cluster encompasses research into the usage of blockchain technology in trade finance, cross-border payments, financial trading, and generally in any finance-related innovation or technology that uses blockchain as its base. The research contributions here bring to light the probable transformational force of blockchain in reimagining and optimizing financial operations in light of cross-border transactions. Key works include [35], [40], [41], [42], and [43], which discuss how blockchain technology may help to improve the efficiency and security of the letter of credit, a basic document in international trade.

Despite its wide usage, there are a number of disadvantages with the traditional letter of credit. These range from expensive transaction costs that partly stem from bank charges to entrance conditions, trading opportunities for those firms assessed with poor creditworthiness, to eventual risks of the evasion of payment by importers when the deliveries of goods are affected. For this process, it remains highly document-based; that is, using much paper that is usually liable to tampering or frauds. These conditions potentially drive cases of commercial disputes in the case of the presentation of the Bill of Lading (B/L) upon demands of the payments. The procedure involves the exchange of such documents between banks from both sides, which is very expensive and time-consuming when the trading involves two far-away countries.

In the system designed by Chang et al. [35], consortium blockchain infrastructure is utilized together with smart contracts for letter of credit management to handle the exchange between exporter and importer in the whole process. This approach practically removes all the risks of alteration and manipulation of contracts since the contract is on the blockchain, and any alteration is transparently logged in the chain. No paper documents or printed bills of lading are needed anymore since the only proof for payments will be identification by the consortium. Payments on the blockchain execute in near real time, while importers verified by the consortium can receive goods without any physical bills of lading. In addition, this application will incorporate a feature for real-time logistics tracking with contractual notifications, reducing costs of transactions to a minimum. An international trade participant database can be developed that can be used to conduct real-time credit rating evaluations based on platform interactions, enhancing the efficiency and user experience.

The traditional letter of credit from contract signing to execution involves 15 steps. It engages both buyer and seller, including the banks acting as intermediaries. Using a blockchain-based letter of credit mechanism, Toorajipour et al. [41] hypothesize that this will be streamlined into eight distinct phases divided into three transaction bundles forming a data packet. These packets are then collected to form a data block, added to the blockchain, and stored in a secure manner.

Most of the studies reviewed in this cluster underline how blockchain technology can contribute to the reduction of transaction costs while at the same time enhancing safety and efficiency. For instance, Dynamic Trade Finance (DTF) is an innovative, flexible approach that embeds digital technologies, including blockchain, in managing international trade financial needs, therefore raising efficiency and security of transactions considerably [44]. This is made possible through smart contracts that compel banks, exporters, and importers to act in compliance with their contractual obligations when conditions are met. Besides, blockchain solutions can cut down the time needed to verify the information from several days to mere hours.

3.3.2 Stream 2: Supply Chain and Logistics

The most recurring themes in the literature on Blockchain and International Trade relate to the logistics sector, broadly understood to include all supply chain processes. This is an explicit consequence of the need for the supply chain to have intrinsic qualities of transparency, efficiency, and security—qualities that blockchain technology embodies.

Traditional instruments of mutual interest for buyers and sellers include delivery receipts, insurance policies, and invoices, which are not that secure against fraud. It is quite easy to forge documents in order not to allow the system to check their falsity. Still, blockchain technology may seriously enhance traceability, digitization, and security throughout the entire global supply chains and port logistics operation. For instance, Gao et al. [36], designed an effective architecture of the public-ledger-based supply chain management system that will handle issues such as unified platform management, low-latency block generation, efficient storage, and security. The authors support a hybridized model, whereby a blockchain fully dependent on the PoW consensus protocol is inefficient in regard to transactional time, while fully based on PoS, it might face severe problems, like insufficient stake for many participants or too many stakeholders. In order to avoid such problems, the proposed platform differentiates the roles and permissions of participating actors.

The platform categorizes participants into three main groups: ordinary users, third-party users, and users in charge of block creation. Ordinary users can initiate new requests of raw materials, track transportation information, and process bills of lading; they are the biggest contributor to the amount of data for the entire platform. The third-party users, who include the government agencies in the form of customs authorities and insurance companies, merely monitor information on the platform and only interact with the platform, when need be, such as making a payment. These will submit all records regarding the supply chain to the platform. The final category involves the users who are tasked with creating data blocks within the platform using a two-phase block-building mechanism.

First-stage booking blocks are created, which would include general information on the user for whom this block is being booked, the fee paid by them, details of the helper who has actually created the block, and any other data that may be required. Helpers then attempt to mine a block, and once the block is added, other helpers work to reach a consensus that the block contains correct information and is part of the longest existing chain. The number of helpers driven is solely driven by demand. Phase two is activated when recording actual supply chain data in the distributed ledger is required by the user. The user checks for available booking blocks, and if available, a data block for the supply chain registration gets created and added to the blockchain after being verified by other helpers. It is an effective two-phase mechanism that saves considerable time in situations when there are sufficient booking blocks available, overcoming the limitations of PoW.

Private blockchains, like Hyperledger Fabric and Besu, respectively, were used for demonstrations where container turnaround times were reduced, thus improving efficient management in the context of port logistics [33]. These platforms are not only fast and secure but also ensure privacy.

The relationship between Internet of Things (IoT) and blockchain is surely one of the most critical themes in Supply Chain Management. IoT systems continuously produce enormous quantities of data, which can be stored on distributed ledgers. This will also become apparent in Smart Farming environments, where resource monitoring and traceability along the value chains are possible thanks to IoT and DLT systems. This capability enables producers to optimize processes, trace the origin of their products, and ensure the quality of their products for consumers [29].

Chen et al. [45] have presented the interaction of IoT with blockchain. The authors discuss the problem of switched goods in logistics transactions that has not been satisfactorily covered in the literature of security mechanisms. They introduce a new logistics security architecture that allows clients to track information on the status of purchased goods using sensors attached to the package. It provides data integrity, resistance to replay attacks, and non-repudiation, with mutual authentication of the parties in the logistical process. Its architecture basically relies on interaction among six basic actors, opposed in five clearly distinguished steps.

Herewith, all the parties must register themselves on the blockchain platform and get a private-public key. For any purchase, the customer has to negotiate with the inserted subliminal message in the package, which is only recognizable by them. This message needs to be placed on the label of the package, and the store needs to update the data in the blockchain through smart contracts. It sends a package into the logistics center, which authenticates the packet, putting this on a label. Then, it fills in the subliminal message. Change the status update into blockchain data, and forward the packet to the courier, with his identity stored by a sensor attachment. While in transit, a customer will be able to verify various parameters such as GPS location, temperature, and humidity of the package. At delivery, the customer verifies the package information and subliminal message for authenticity, then updates the blockchain as a confirmation of correct delivery.

Blockchain technologies quantitatively reduce costs as high as 15% to enhance the profit margins of an organization in supply chain and logistics operations [46]. The cost savings mainly emanate from how blockchain infrastructure prevents different types of fraud scenarios besides resolving other issues in the supply chain and logistics industry, which includes coordination between various logistics entities, a lot of documentation, centralization of decision-making, inadequate data, and inefficient privacy and security.

3.3.3 Stream 3: Regulations and Standards

As stated in the two previous clusters, it has often been emphasized that for blockchain technology to develop further for use in international trade, robust regulations and similar standards must be set at a global level. Thus, it is no surprise that this theme also plays an important role in the literature examined.

Probably the most significant barriers to the general diffusion of blockchain for international trade are a lack of critical tipping point stakeholder support, partial understanding of the technology, and the general absence of wide-ranging government regulations [47]. The authors address the tokenization of property rights on blockchain in light of these challenges. Tokenization means putting a right into a digital format, a so-called token, which may take many faces. The main types include currency tokens, otherwise known as cryptocurrencies, such as Bitcoin; security tokens, which represent ownership in companies or specific projects; utility tokens, which provide access to particular services; and asset-backed tokens, representing rights to physical assets. The main token protocols are ERC-20 for fungible tokens, ERC-721 for non-fungible tokens, and ERC-1238 for non-transferable tokens.

The paper discusses tokenization from the perspective of general private law and provides a comparative analysis of the legal feasibility of tokens representing usufruct rights over movable and immovable property and their potential limitations in six European jurisdictions.

In the case of movable property, the creation of usufruct does not normally require any specific formalities and can thus be established in smart contracts, including at least the required metadata such as duration of the right and description of the assets. However, there are exceptions, like under German law, where the validity of the contract depends on the physical delivery of the asset. This could, in the case of the asset being a security, be achieved by embedding a code within the token that unlocks for the usufructuary. German legislation also presents unique challenges regarding transferability of usufruct rights due to its prohibition on actual transfer of the usufruct, allowing only for the transfer of usage and enjoyment rights. Therefore, ERC-1238 tokens are preferred in such cases by nature of being non-transferable.

The tokenization of usufruct is more cumbersome in real estate since the formality-heavy process, in countries such as Germany and the Netherlands, requires notarial deeds and land registries to constitute the usufruct. In Italy, while the constitutive act must be either in writing or executed as a public deed, such may be considered fulfilled in the case of smart contracts inasmuch as Italian Law considers smart contracts to be written form, providing a declaration of the creation of the usufruct within the metadata of an ERC-721 token. France and Spain impose fewer limitations and, therefore, are as legally open to the tokenization of usufruct rights over real estate as Italy.

This has been possible due to rapid growth in the collaborative economy and related technologies, which has made the tokenization of most assets a reality that perhaps requires some regulation and depends on smart contracts for token creation and transfer in consensual systems. As long as international trade and finance operate within an appropriate technological, commercial, regulatory, and legal standards regime, there are issues that concern understanding how these will coexist with the standard set by the implementation of a new technology such as blockchain. Farrell [48] also focused on the gap between blockchain standards and international finance, analyzing such key divergences as immutability, a common feature in blockchains but foreign in international finance, where the contract can be void or cancelled under certain conditions. The integration of blockchain standards into international finance requires the cross-disciplinary collaboration of technology, business, regulation, and law in order to manage conflicts between these differing standards.

With blockchain, smart contracts would be self-executing, less complex, with better transparency and decreased operational and financial risk. Though that may be true, several countries have begun to develop private law frameworks with regard to blockchain transfers and crypto assets, which means developing a sound environment for the use of the distributed ledger technology and improving investor protection, but results in fragmentation at the national market level. This type of fragmentation causes inefficiency through higher transaction costs, the inability of systems to be interoperable, and possible legal disputes [49].

This cluster also focuses on the implementation of blockchain technology in creating digital standards to replace obsolete, paper-based processes. The example would range from assessing the impact of DLT on the administration of Value Added Tax, together with its advantages and challenges. The improvement of VAT administration requires creating a legal framework for the functioning of e-invoicing and blockchain, a mechanism of secure data exchange between taxpayers and tax authorities on national and international levels, and further cooperation of tax authorities in combating tax fraud. Effective implementation of digital technologies in taxation will take about 5-10 years in developed countries and even more time in countries that are less developed [50].

Regarding documentary standards in the logistics sector, traditional paper Bill of Lading, or pBL, has usually been problematic upon the arrival of the ship at the port of discharge over the pBLs. It is here that blockchain technology provides a secured ledger that ensures the uniqueness and integrity of the document, thus overcoming the shortcomings of traditional pBL, as stated by Todd (2019).

3.3.4 Stream 4: Sustainability

Sustainability is a strong and recurring topic in the literature on Blockchain and DLT. This focus naturally follows from the core characteristics of blockchain technology, such as traceability, security, and decentralization, which make this technology particularly suited for applications in the sustainability sector. Indeed, the energy sector has been one of the most active in working on blockchain-enabled decentralized energy markets. Therefore, business model guidelines regarding blockchain technology in electricity utility systems are under active consideration.

Leelasantitham [51] presents a case study on a blockchain-based business model of electric distribution systems in Thailand. This study investigates how such a system can be realized to aptly benefit from the shift away from a centralized energy distribution model-managed in most cases by state enterprises-to a decentralized one where consumers, prosumers, and SMEs can easily interact with each other in a horizontally integrated manner. An important part of the transition is the determination for each stakeholder group, an appropriate technical form of blockchain, where differences need to be finally connected through blockchain bridges effectively.

Such results obtained from this study show how much this model can drastically reduce the cost of consumption in addition to the consumer and SMEs. Undoubtedly, there will be upfront investments to adopt tools with blockchain and IoT technology, including batteries and smart meters; it saves a lot on operating costs. In particular, fuel costs are zero due to the renewable sources of energy exploited, such as solar panels, while distribution costs are zero because the system is based on a P2P exchange model with no intermediaries.

Another indicator of the growing interest in energy blockchain technology is the increasing number of patent applications, which reached a peak in 2018. The United States leads in the number of patent filings in this domain, accounting for 59% of total applications, followed by Germany with 9%, China with 6%, and the United Kingdom with 5%. The remaining 21% of applications are distributed among other countries or regions [52].

It also includes an in-depth analysis of the top ten patent filers in energy blockchain technologies, including Walmart Apollo. This entity reportedly has the highest number of patents filed in energy blockchain-related applications, closely followed by IBM and General Electric.

The variety of industries involved- from electrical producers and software companies to e-commerce and blockchain-focused enterprises- from these top companies underlines the innovative capability of blockchain technology in energy.

The feasibility of energy management and exchange systems based on free trade principles has been shown using blockchain technology, which optimizes resource exchange while reducing waste. D'Orazio et al. [53], however, maintain a delicate balance between energy availability, technological advancement, market dynamics, security, freedom, and individual user needs.

Outside of energy, blockchain for sustainability initiatives could focus on diverse topics, such as how DFAs can make the development of the hydrogen industry very promising with the so-called "Hydro Token" concept [54]. The Hydro Token, which is faster, cheaper to issue, and cross-border capable, would be an internal crowdfunding mechanism within corporate ecosystems for working toward hydrogen production. This token could provide investors with both capital and product participation without the need to rely on government, coordinating groups, or state-owned enterprise interventions.

Another important aspect of sustainability is how blockchain technology has been utilized to enhance traceability in timber products. Tracking the origin of timber by applying blockchain can significantly raise trust in purchasers of sustainable timber suppliers [55]. The study further explores what drives purchaser trust and how this critical trust can be reinforced through blockchain technology along the timber supply chain.

3.3.5 Stream 5: Security, Trust and Privacy

The last cluster of analysis focuses on security, trust, and privacy. The use of Blockchain in managing and securing information systems within an international business has been studied widely. These studies focus on the importance of information systems in international enterprises and explore possible ways to enhance them using distributed ledger technologies. Such technologies aim to minimize the role of third parties, therefore increasing the security of information communicated through a specialized Blockchain application. Additionally, Blockchain is highlighted as a tool that can be used for public scrutiny, providing transparency and enabling stakeholders to observe the actual nature of a company or entity for the benefit of all parties involved accordingly [26].

These studies, in this sense, focus more on how to reduce third-party dependency for an enterprise. The twin benefits of such approaches would also guarantee that the companies can protect their sensitive information and have higher efficiency and interoperability. In a healthcare sector, for example, a common Blockchain platform would mean safe communication channels and authenticity of information exchanged among the parties concerned. Also, for small firms or startups that may apply Blockchain systems, it could provide them with error elimination because instead of a company depending on one node, business operations are decentralized. For entities in that position, utilizing open-source Blockchain libraries and tools as well as offerings might prove to be advantageous by achieving immediate data control for the customer and lower incompatibility among shareholders.

Also, the security of data derived from supply chains: Blockchain networks make it very easy to trace a product's origin and its lifecycle to the consumer. Such levels of traceability are even verifiable independently by any party to reduce disputes or possible litigations. Thus, this level of transparency afforded by distributed ledger technologies massively boosts security and trust across a supply chain. A certain successful deployment of Practical Byzantine Fault Tolerance (PBFT) consensus algorithm, for example, has been observed in a steel company, where improvement of security, fault tolerance, efficiency, and reduction of delays in logistics processes have been ensured [56].

The international pharmaceutical industry has also demonstrated significant interest in Blockchain technology since it may significantly alter how stakeholders share information within the supply chain of drugs, thereby making the process safer and more transparent [28].

On one hand, consumers are asking for more authenticity and transparency in the food supply chain, especially after incidents like food fraud relating to labeling non-Australian beef as Australian in China [37]. Blockchain technology, with features of authentication and improvement in traceability, promises increased supply chain visibility and trust. Probably the most iconic use case is a Blockchain prototype that has been developed to provide assurances around the authenticity and origin of Australian meat, which realized substantial increases in trust on the part of Chinese consumers as to what they were consuming. The prototype allowed consumers to access information about the product by scanning a digital fingerprint or sticker on the packaging through a smartphone camera via a mini-app in WeChat, a popular messaging app in China. Scanning this digital fingerprint provided information to consumers about the product, such as text, images, and a video that showed supply chain stages from live cattle to farming and how the product would get from the producer to the consumer. The prototype also made available an export certificate and a button to view the metadata of the product. All the respective paperwork was uploaded to the Blockchain network of the entity BeefLedger; then second-tiered through multisignature validation protocol, A unique Ethereum multisig format wallet address was used for logging all the files on the BeefLedger Blockchain. Moving on, a hashing function was developed for each file, where uniquely valued output was derived, together with storage on the Blockchain. This allowed consumers to self-validate that the product, which they were buying, was authentic because they could run the same hash function and check whether the value of the resulting digest matched on the Blockchain.

The study also discusses balancing human-machine intelligence in the supply chain, where the shared responsibility of several actors leads to greater faith in products. In this cluster, active stakeholder involvement is indispensable for maximizing the beneficial impacts of Blockchain technology on trust and security.

3.4 Open Issues and Research Priorities

From the review of the main findings in blockchain-related research, significant improvements in practical uses are indeed happening within most aspects of international trade. Yet, not all identified or critical challenges in blockchain implementation have vanished and continue to show up with similar relevance next to current positive developments. Overcoming the identified challenges becomes necessary to go further with the use of blockchain in global trade contexts. The final part reflects on the key challenges related to each area and goes on to point out a perspective for further studies. Concretely, this might involve a set of recommendations covering the limitation related to technical, regulatory, and organizational aspects. The findings will thus set out a roadmap on how such obstacles could be overcome in order to achieve wider diffusion and fuller integration of blockchain solutions into international trade contexts.

3.4.1 Financial Technology & Cross-Border Payments

Most of blockchain's implications for cross-border payments are related to several important research gaps. First, most studies have been confined to pilots and early-stage implementations, which again limits the generalization of their results to a broader trade context. In addition, too little stakeholder involvement from financial institutions, regulators, and end-users hinders the development of holistic approaches to adoption. Another big barrier involves regulatory challenges; unequal legal standards and jurisdictions make integrating blockchain in cross-border payment mechanisms very challenging.

Technical limitations in scalability, transaction speed, and operation efficiency further reduce the pragmatic potential of blockchain solutions for large-volume and complex global payments. Besides, barely enough research is being conducted on security issues in transactions and the resilience of blockchain-based systems against rapidly developing cyber threats to build critical vulnerability.

Future studies should fill these gaps by conducting large-scale studies involving multiple stakeholders in order to assess the impact of blockchain beyond mere pilot projects, and ensure that the findings are relevant for practical applications. Interoperable frameworks and regulatory harmonization due to coordination among academia, industry, and policy makers will enable seamless cross-border adoptions. More fundamentally, technological advances are required to enhance scalability, efficiency, and security; longitudinal studies can be carried out to look at the effects of blockchain on long-term trade relationships.

3.4.2 Supply chain and Logistics

While blockchain technology applied to supply chains and logistics has immense potential, limitations and unresolved challenges are huge. The most important issues pertain to the absence of any empirical evidence and practical case studies exploring blockchain deployment in diverse contexts of supply chains. Theoretical benefits are the focus of most available literature, at the cost of practical issues such as scalability, interoperability, and other regulatory challenges in the way of implementation. Besides, there naturally arises a very strong human element through possible inputting errors and reluctance on the part of enterprises to share sensitive supply chain data.

Moreover, interoperability issues make integrating blockchain into current supply chain management systems even more complex, as a variety of standards and technologies have been implemented by different companies. Furthermore, most of the literature focuses on developed economies, while the specific challenges that developing countries face, including the low level of technological infrastructure and government support during the adoption process, have hardly been mentioned. The question of data privacy, especially regarding sensitive business data handling, is not fully addressed, which creates concerns about stakeholders' trust.

Future research should be directed more toward multi-stakeholder collaboration to ensure blockchain solutions meet the needs of all players, from private enterprise to governmental agencies and the regulatory bodies, from both operational and legal standpoints. Investigations should be done with a view toward surmounting technical barriers by enhancing scalability and developing an interoperable architecture that can interface with existing systems seamlessly. Furthermore, blockchain combined with IoT and AI would be able to enhance data accuracy to a much higher degree by reducing dependency on manual inputs and therefore errors, hence improving the overall system efficiency.

Equally worth pursuing, for the sake of wide applicability, are ways developing economies might adapt blockchain solutions to resource-constrained settings by uniquely identifying their needs. Technologies that can guarantee privacy, like zero-knowledge proofs or methods ensuring differential privacy, may turn out to be key components for dealing with data sensitivity. Longitudinal and application-oriented studies will be needed if one wants to find out about the possible long-term impacts on efficiency, transparency, and resilience in the supply chain, which thus provides a sound basis for the development of more robust, scalable systems that are globally inclusive.

3.4.3 Regulations and Standards

Regulatory and legal challenges remain one of the biggest barriers to the adoption of blockchain technology in international trade. Limitations identified in this cluster mostly relate to a lack of a robust and harmonized regulatory framework, leading to fragmented legal environments that make cross-border transactions complicated. Most of the existing laws still demand paper-based documentation and wet signatures, which are not in tune with the nature of blockchain solutions.

This mismatch between traditional legal systems and modern technologies underlines the need for more extensive research and intervention in regulatory adaptation.

Most of the current research in this cluster is either highly conceptual or focused on isolated case studies, which limits its practical applicability. Important topics such as asset-backed tokens, property law implications, and the transferability and rights of token holders receive little attention. Further, the literature is focused on developed economies, with limited examination of the regulatory challenges and opportunities that exist within developing countries, where infrastructure gaps and governmental support for digital trade transformation are most acute.

Future research should be interdisciplinary and empirical, with legal scholars, technologists, economists, and policymakers working together to generate actionable insights. Comparative studies may examine how different jurisdictions address blockchain-related regulatory challenges, indicating best practices and highlighting domains where international alignment is required. Particular attention must be given to Smart Contracts, their legal enforceability, and the potential role of asset-backed tokens in trade finance.

First, there is a need for speedy transposition of model laws already in existence, such as the UNCITRAL Model Law on Electronic Transferable Records, with a view to taking the regulatory field up a notch. Equally indispensable are collaborative international frameworks; without them, efforts at interoperability and predictability across borders will be hindered. By successfully addressing these gaps, substantial dividends will be felt beyond increased legal certainty and efficiency in their better-functioning facilitation of improved levels of trust among market actors, thus paving the path toward wider blockchain adoption for use within the context of international trade.

3.4.4 Sustainability

Some of the major limitations in integrating blockchain technology into international trade sustainability initiatives relate to underdeveloped and fragmented regulatory and legal frameworks, which pose a critical barrier to the adoption of blockchain-based solutions to enhance sustainability. In addition, technical issues like scalability and energy consumption linked with blockchain operations further complicate its application in sustainable trade practices, where resource efficiency is cardinal. Further, ethical issues in the distribution of costs and benefits to stakeholders and possible biases in technology implementation need deeper elaboration.

Most of the literature so far is based on the assumption of homogeneous consumer attitudes toward sustainability, which is far from realistic in real-world scenarios characterized by heterogeneous preferences and behaviors across regions and demographics. Besides, many studies are also constrained by static models that cannot capture the dynamic benefits of blockchain in evolving trade and supply chain environments. Most of the empirical and case-based validations are missing, which keeps the findings disconnected from practical implementation. The fast development area of energy-efficient blockchain solutions and its implication for sustainability is another continuous evaluation area.

From this perspective, future research should be more dynamic and empirical, properly illustrating how blockchain technology ensures practical effects on the realizability of sustainability performance. These multi-stakeholder collaboration projects among governments, private firms, and non-governmental organizations are necessary to solve the interlinked challenges regarding scalability, resource efficiency, and global coordination. Similarly, policymakers have to work toward harmonizing legal and regulatory frameworks that offer incentives for the adoption of blockchain solutions for sustainability, comprising energy-efficient consensus mechanisms and carbon-neutral infrastructure.

Moreover, integrating blockchain technology with other sustainability metrics, like virtual water flows, product life-cycle analysis, and emissions tracking, would provide even more actionable insights into reduction. Last but not least, studying some uncertainty factors characterizing global trade environments, such as fluctuations in disruption to demand or supply, could help design even more resilient and sustainable blockchain applications targeted specifically at international trade ecosystems.

3.4.5 Security, Trust and Privacy

The integration of blockchain into international trade also faces other challenges that seem intractable, touching on issues of security, trust, and privacy. The literature remains limited in focus, especially on privacy issues related to the secure handling and sharing of sensitive business and personal data across borders. Current research does not study comprehensively the trust dynamics of these key stakeholders-suppliers, regulators, and end-users-whose participation makes successful implementation of the blockchain possible. Lack of capturing a view from the perspective of a particular stakeholder, this hinders elaboration of unique solutions that consider different needs and expectations.

Furthermore, regulatory challenges continue to make the landscape trickier, since inconsistent mandates and responsibilities across jurisdictions impede adoption. An additional factor is that dependence on the accuracy and integrity of inputs, given blockchain, means that human-driven processes may lead to mistakes, which will undermine trust from a user's perspective. Although blockchain does provide effective cryptographic security methods, vulnerabilities in the form of breaches, cyberattacks, and ensuring seamless verification with external-to-the-blockchain supply chain stakeholders do persist. Moreover, consumer verification hardly enjoys any representation in the literature with regard to fraud detection and market integrity, thus leaving a gap that is very significant in understanding the participation of an end-user.

Future research should be directed more toward privacy-preserving mechanisms, such as zero-knowledge proofs or homomorphic encryption, which can be used to protect sensitive data without sacrificing the transparency of trade processes. The holistic framework for multi-stakeholder engagement also needs to be developed, considering the views of all stakeholders- manufacturers, regulators, and consumers- to address boundary constraints and build trust. Integration of blockchain with other advanced technologies, such as AI and IoT, may further enhance real-time security and automate data verification with minimal dependence on manual inputs.

They could now extend discussions toward regulatory harmonization between jurisdictions to mitigate legal barriers and support blockchain's scaling into mainstream applications globally. The empirical research that would assess the viability of blockchain solutions in building trust and maintaining data privacy within actual trade-related scenarios would be the last but a very important step toward establishing practical insights and closing the gap between theoretical considerations and practice.

3.5 Conclusions

Over the last 15 years, blockchain has undergone significant evolution in the economic and financial world and beyond. It was immediately easy to notice that due to its intrinsic characteristics, it was perfectly suited to the needs and activities of international trade. Thanks to its core features of transparency, decentralization, security, and efficiency, blockchain is capable of raising international trade practices to a level much more in line with modern standards both in the area of technology and operation, as it has the potential to modernize the processes which have been traditionally inefficient due to the outdated techniques and tools they rely on. The advantages of its adoption will be many and will positively affect both producers and consumers.

Against this background of an ever-increasing body of scientific literature on the use of blockchain technology in international trade, this systematic literature review provides a comprehensive overview of the state of the art by considering what already exists in terms of research findings In particular, this study categorizes the primary research areas, highlights significant results, identifies limitations, and uncovers gaps that future studies could address.

By analyzing the selected literature, it emerges that the sector of cross-border payments and financial technologies is one of the most consolidated and relevant research lines. Numerous studies emphasize the transformative potential of blockchain in trade finance, in particular in the digitalization and automation of instruments such as the letter of credit. Smart contract applications, recurrently described in the analyzed corpus, represent one of the most promising contributions, as they are capable of significantly reducing transaction times and cost, improving trust between the parties. However, the literature also highlights how many of these solutions are still in the experimental phase or limited to pilot projects, highlighting a gap between theoretical potential and practical implementation, often held back by regulatory and infrastructural barriers.

A second particularly developed thematic axis is that of supply chain and logistics, where blockchain is proposed as a key tool to improve traceability, safety and operational efficiency. The case studies analyzed show how technology can digitize fundamental documents such as bills of lading, guarantee the authenticity of products throughout the supply chain, and monitor transport conditions in real time thanks to the integration with IoT sensors. In this area, the literature highlights a strong convergence between theory and application, even if there are obstacles related to scalability, interoperability between different systems and the protection of sensitive data. Furthermore, the active participation of the actors in the value chain is crucial for the success of these initiatives, underlining the importance of a collaborative multi-stakeholder approach.

No less central is the issue of regulation and regulatory standards, where a tension between technological innovation and the slowness of legal adjustments is observed. The contributions in the literature analyzed highlight how the absence of an internationally harmonized regulatory framework constitutes one of the main barriers to the adoption of blockchain in global trade. Some studies focus on the concept of tokenization of rights and the challenges related to the legal framework of smart contracts and digital assets, especially in the context of European private law. In this sense, there is a strong need for shared technical and legal standards, which allow us to overcome regulatory fragmentation and promote transnational interoperability.

Sustainability also constitutes an emerging and particularly relevant trend, especially in relation to the ability of blockchain to trace the origin and life cycle of products, ensuring greater transparency and responsibility along the supply chain. The literature shows how this technology can contribute to the decarbonization of production processes, the decentralized management of energy and the implementation of more sustainable practices in sectors such as agri-food and the wood industry. However, important questions remain open related to the energy consumption of consensus protocols, the poor inclusiveness of benefits, and the lack of empirical studies that evaluate the actual impact of these solutions in real contexts.

Finally, the theme of security, trust and privacy pervades the entire panorama analyzed. Blockchain is often described as a powerful tool to strengthen information security, minimize dependence on third parties and improve transparency in international trade relations. Practical examples, such as application cases in food traceability or in the pharmaceutical supply chain, demonstrate the potential of the technology to strengthen consumer trust and ensure the quality of traded goods. However, the analysis also highlights critical issues related to the protection of personal data, vulnerability to certain cyber attacks and the accuracy of the data entered into the blockchain itself. In this context, technologies such as homomorphic cryptography or zero-knowledge proofs represent very promising research perspectives.

This approach provides a very valuable basis for further research because it allows scholars to focus only on issues that require deep analysis and provides guidance on methodological approaches.

It would act as an operational tool for policymaking, regulating, business persons, and stakeholders' interests in international trade in applying and developing the blockchain technology. Recognition of present status quo, combined with research, and known potentialities within the application scope, can indeed make creating policies and strategies, problems of encouraging the adoption feasible. This work seeks to highlight the transformative and potential role blockchain plays in enhancing efficiency, security, and transparency among global trade and the ways it leads to future contributions in the field.

A Appendix A

A.1 Included studies (SLR corpus)

Table A.1: Included studies in the systematic literature review (N=112).

ID	Ref.	Authors	Year	Title	Source
S1	[57]	Abidi et al.	2016	Proving chaotic behavior of CBC mode of operation	International Journal of Bifurcation and Chaos
S2	[56]	Abidi et al.	2021	Blockchain-based secure information sharing for supply chain management: Optimization assisted data sanitization process	International Journal of Intelligent Systems
S3	[58]	Agmon et al.	2022	Distributed Ledger Technology (DLT): A Game Changer for MNEs in Emerging Markets	Journal of Risk and Financial Management
S4	[59]	Ahi et al.	2022	Advanced technologies and international business: A multidisciplinary analysis of the literature	International Business Review
S5	[33]	Ahmad et al.	2021	Blockchain applications and architectures for port operations and logistics management	Research in Transportation Business and Management
S6	[60]	Ahmad et al.	2022	Blockchain in oil and gas industry: Applications, challenges, and future trends	Technology in Society
S7	[42]	Al-Amaren et al.	2020	The blockchain revolution: A game-changing in letter of credit (l/c)?	International Journal of Advanced Science and Technology
S8	[61]	Alonso et al.	2020	Flexibility services based on openadr protocol for dso level	Sensors (Switzerland)
S9	[29]	Alonso et al.	2020	An intelligent Edge-IoT platform for monitoring livestock and crops in a dairy farming scenario	Ad Hoc Networks
S10	[62]	Alsalim et al.	2023	Secure banking and international trade digitization using blockchain	Optik
S11	[63]	Andrews	2022	Reconceptualizing alternative dispute resolution ecosystem in the digital era: saudi arabia's online transactional engagements	International Journal of Development and Conflict
S12	[64]	Angara et al.	2022	Towards a virtual water currency for industrial products using blockchain technology	Water Policy
S13	[65]	Asaithambi et al.	2024	Enhancing enterprises trust mechanism through integrating blockchain technology into e-commerce platform for SMEs	Egyptian Informatics Journal

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ID	Ref.	Authors	Year	Title	Source
S14	[66]	Austin et al.	2021	Evaluating company adoptions of blockchain technology: How do management and auditor communications affect nonprofessional investor judgments?	Journal of Accounting and Public Policy
S15	[67]	Balaji et al.	2023	The non-fungible token (Nft) marketplace: technological innovation and opportunities for creators	Indian Journal of Marketing
S16	[68]	Balci et al.	2021	Blockchain adoption in the maritime supply chain: Examining barriers and salient stakeholders in containerized international trade	Transportation Research Part E: Logistics and Transportation Review
S17	[26]	Berdik et al.	2021	A Survey on Blockchain for Information Systems Management and Security	Information Processing and Management
S18	[69]	Bhat et al.	2021	Blockchain letter of credit: a transaction-level analysis	Journal of Engineering Science and Technology
S19	[39]	Biswas et al.	2023	Traceability vs. sustainability in supply chains: The implications of blockchain	European Journal of Operational Research
S20	[37]	Cao et al.	2021	Strengthening consumer trust in beef supply chain traceability with a blockchain-based human-machine reconcile mechanism	Computers and Electronics in Agriculture
S21	[70]	Cao et al.	2022	Adopting blockchain technology to block less sustainable products' entry in global trade	Transportation Research Part E: Logistics and Transportation Review
S22	[71]	Čerin et al.	2024	Enhancing Sustainability through the Development of Port Communication Systems: A Case Study of the Port of Koper	Sustainability (Switzerland)
S23	[35]	Chang et al.	2019	Exploring blockchain technology in international trade: Business process re-engineering for letter of credit	Industrial Management and Data Systems
S24	[40]	Chang et al.	2020	Blockchain-enabled trade finance innovation: A potential paradigm shift on using letter of credit	Sustainability (Switzerland)

Continued on next page

ID	Ref.	Authors	Year	Title	Source
S25	[72]	Chang et al.	2020	Blockchain in global supply chains and cross border trade: a critical synthesis of the state-of-the-art, challenges and opportunities	International Journal of Production Research
S26	[45]	Chen et al.	2021	A blockchain-based intelligent anti-switch package in tracing logistics system	Journal of Supercomputing
S27	[73]	Chen et al.	2021	Optimization Model of Cross-Border E-commerce Payment Security by Blockchain Finance	Wireless Communications and Mobile Computing
S28	[74]	Chen et al.	2022	A transaction cost perspective on blockchain governance in global value chains	Strategic Change
S29	[75]	Chuah	2023	Money Laundering Considerations in Blockchain-based Maritime Trade and Commerce	European Journal of Risk Regulation
S30	[76]	Compagnucci et al.	2022	Uncovering the potential of blockchain in the agri-food supply chain: An interdisciplinary case study	Journal of Engineering and Technology Management - JET-M
S31	[77]	Cozzi	2020	Will Blockchain Technologies Strengthen or Undermine the Effectiveness of Global Trade Control Regulations and Financial Sanctions?	Global Jurist
S32	[53]	D'Orazio et al.	2023	Application of a Blockchain Model in the Energy Market for Social Goodness: A Simulator to Generate Transactions	Periodica polytechnica Electrical engineering and computer science
S33	[78]	Davis et al.	2022	Can blockchain-technology fight corruption in MNEs' operations in emerging markets?	Review of International Business and Strategy
S34	[79]	Drozdz et al.	2019	Signatures of the crypto-currency market decoupling from the Forex	Future Internet
S35	[80]	Du et al.	2023	From Buzzword to Biz World: Realizing Blockchain's Potential in the International Business Context	California Management Review
S36	[81]	Dubovec et al.	2017	A proposal for UNCITRAL to develop a Model Law on Warehouse Receipts	Uniform Law Review

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ID	Ref.	Authors	Year	Title	Source
S37	[82]	Epps et al.	2019	Revolutionizing global supply chains one block at a time: Growing international trade with blockchain: Are international rules up to the task?	Global Trade and Customs Journal
S38	[43]	Ermakov et al.	2018	A letter of credit as an instrument to mitigate risks and improve the efficiency of foreign trade transaction	Espacios
S39	[48]	Farrell	2019	Blockchain standards in international banking: Understanding standards deviation	Journal of ICT Standardization
S40	[83]	Fridgen et al.	2021	Blockchain Won't Kill the Banks: Why Disintermediation Doesn't Work in International Trade Finance	Communications of the Association for Information Systems
S41	[84]	Ganne	2021	Blockchain for trade: When code needs law	AJIL Unbound
S42	[85]	Gao et al.	2022	Modeling and analysis of port supply chain system based on Fabric blockchain	Computers and Industrial Engineering
S43	[86]	Gao	2021	Study on the Intention of Foreign Trade Driven by Cross-Border E-Commerce Based on Blockchain Technology	Security and Communication Networks
S44	[36]	Gao et al.	2018	CoC: A Unified Distributed Ledger Based Supply Chain Management System	Journal of Computer Science and Technology
S45	[47]	Garcia-Teruel et al.	2021	The digital tokenization of property rights. A comparative perspective	Computer Law and Security Review
S46	[87]	Gigli et al.	2023	A Decentralized Oracle Architecture for a Blockchain-Based IoT Global Market	IEEE Communications Magazine
S47	[88]	Goli	2023	Integration of blockchain-enabled closed-loop supply chain and robust product portfolio design	Computers and Industrial Engineering
S48	[89]	Guarín et al.	2020	Enhancing E-Commerce through Blockchain (DLTs): The Regulatory Paradox for Digital Governance	Global Jurist

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ID	Ref.	Authors	Year	Title	Source
S49	[90]	Hamidi et al.	2022	Blockchain Capabilities to Improve the Productivity of Maritime Logistics Processes: Review, Taxonomy, Open Challenges and Future Trends	Journal of Information Technology Management
S50	[50]	Harkushenko	2022	Prospects of VAT Administration Improvement in Digitalized World: Analytical Review	Journal of Tax Reform
S51	[30]	Hasan et al.	2019	Smart contract-based approach for efficient shipment management	Computers and Industrial Engineering
S52	[91]	Hashimy et al.	2021	Distributed ledger technology as a catalyst for open innovation adoption among small and medium-sized enterprises	Journal of High Technology Management Research
S53	[92]	Hooper et al.	2020	Blockchain technology in international business: changing the agenda for global governance	Review of International Business and Strategy
S54	[93]	Hu et al.	2022	Cross-Border E-Commerce Business Model Based on Big Data and Blockchain	Mobile Information Systems
S55	[52]	Huang et al.	2020	A study on the development trends of the energy system with blockchain technology using patent analysis	Sustainability (Switzerland)
S56	[94]	Ioannou	2023	Relational trade networks	Cambridge Law Journal
S57	[95]	Irannezhad	2020	The Architectural Design Requirements of a Blockchain-Based Port Community System	Logistics
S58	[96]	Jaloliddin	2023	Digitalization in Global Trade: Opportunities and Challenges for Investment	Global Trade and Customs Journal
S59	[38]	Juma et al.	2019	A Survey on Using Blockchain in Trade Supply Chain Solutions	IEEE Access
S60	[97]	Kalejahi et al.	2021	Using blockchain technology in mobile network to create decentralized home location registry (HLR)	Computer Systems Science and Engineering
S61	[98]	Kassou et al.	2021	Digital transformation in flow planning: The case of container terminals at a smart port	Journal of Theoretical and Applied Information Technology

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ID	Ref.	Authors	Year	Title	Source
S62	[99]	Kim et al.	2023	Securing the Cyber Resilience of a Blockchain-Based Railroad Non-Stop Customs Clearance System	Sensors
S63	[32]	Kimani et al.	2020	Blockchain, business and the fourth industrial revolution: Whence, whither, wherefore and how?	Technological Forecasting and Social Change
S64	[55]	Komdeur et al.	2021	The potential of blockchain technology in the procurement of sustainable timber products	International Wood Products Journal
S65	[100]	Korneyko et al.	2019	Assessment of the Blockchain Capabilities to Combat the Global Trade in "Falsified" and "Illegal" Fish Products	ARPN Journal of Engineering and Applied Sciences
S66	[101]	Kramer et al.	2021	The Impact of Instrumental Stakeholder Management on Blockchain Technology Adoption Behavior in Agri-Food Supply Chains	Journal of Risk and Financial Management
S67	[44]	Lee et al.	2023	Dynamic Trade Finance in the Presence of Information Frictions and FinTech	Manufacturing and Service Operations Management
S68	[51]	Leelasantitham	2020	A Business Model Guideline of Electricity Utility Systems Based on Blockchain Technology in Thailand: A Case Study of Consumers, Prosumers and SMEs	Wireless Personal Communications
S69	[102]	Leelasantitham et al.	2024	Economic Pricing in Peer-to-Peer Electrical Trading for a Sustainable Electricity Supply Chain Industry in Thailand	Energies
S70	[49]	Lehmann	2021	National Blockchain Laws as a Threat to Capital Markets Integration	Uniform Law Review
S71	[103]	Lian	2022	Blockchain-Based Secure and Trusted Distributed International Trade Big Data Management System	Mobile Information Systems
S72	[104]	Lian	2022	Research on Credit Algorithm of International Trade Enterprises Based on Blockchain	Mathematical Problems in Engineering

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ID	Ref.	Authors	Year	Title	Source
S73	[105]	Lin	2022	Research on Optimization of Steel Foreign Trade Financial Transaction Based on Blockchain Technology	Mobile Information Systems
S74	[106]	Liu et al.	2023	Blockchain technology in maritime supply chains: applications, architecture and challenges	International Journal of Production Research
S75	[107]	Macedo	2018	Blockchain for trade facilitation: Ethereum, eWTP, COs and regulatory issues	World Customs Journal
S76	[28]	Mackey et al.	2017	A review of existing and emerging digital technologies to combat the global trade in fake medicines	Expert Opinion on Drug Safety
S77	[108]	Mathew et al.	2019	Exploration of blockchain for edifying safety and security in IoT based diamond international trade	International Journal of Innovative Technology and Exploring Engineering
S78	[109]	Mukherjee	2023	Blockchain: Contemporary Challenges and Future Application in International Trade	Manchester Journal of International Economic Law
S79	[110]	Murimi et al.	2023	Blockchains: A review and research agenda for international business	Research in International Business and Finance
S80	[111]	Nsour	2023	The WTO and Using Digital Economy Technologies: Surviving the Race With Preferential Trade Agreements	Journal of World Trade
S81	[112]	Patrickson	2021	What do blockchain technologies imply for digital creative industries?	Creativity and Innovation Management
S82	[113]	Pečarić et al.	2020	Application of "blockchain" and "smart contract" tehnology in international payments – The case of reimbursement banks	Pomorstvo
S83	[114]	Prasad et al.	2022	Analysing the Barriers for Implementation of Lean-led Sustainable Manufacturing and Potential of Blockchain Technology to Overcome these Barriers: A Conceptual Framework	International Journal of Mathematical, Engineering and Management Sciences

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ID	Ref.	Authors	Year	Title	Source
S84	[115]	Purwaningsih et al.	2024	Utilizing blockchain technology in enhancing supply chain efficiency and export performance, and its implications on the financial performance of SMEs	Uncertain Supply Chain Management
S85	[31]	Qian et al.	2020	Food traceability system from governmental, corporate, and consumer perspectives in the European Union and China: A comparative review	Trends in Food Science and Technology
S86	[116]	Rab	2020	Smart Contracts & Blockchain: the panacea to the unequal bargaining power of consumers?	International Journal on Consumer Law and Practice
S87	[117]	Rukanova et al.	2023	Public value creation through voluntary business to government information sharing enabled by digital infrastructure innovations: a framework for analysis	Government Information Quarterly
S88	[118]	Sharma	2023	Supply chain, geographical indicator and blockchain: provenance model for commodity	International Journal of Productivity and Performance Management
S89	[119]	Shen	2023	Design of internet of things service system for logistics engineering by using the blockchain technology	International Journal of Grid and Utility Computing
S90	[120]	Siddik et al.	2021	Blockchain Technology and Facilitation of International Trade: An Empirical Analysis	FIIB Business Review
S91	[121]	Sinha et al.	2021	Blockchain-based smart contract for international business – a framework	Journal of Global Operations and Strategic Sourcing
S92	[122]	SUAU	2021	Blockchain-based smart contracts and conflict rules for business-to-business operations	Revista Electronica de Estudios Internacionales
S93	[54]	Svitanko	2024	Who is Mr. H2? Or expanding the view on hydrogen economy	International Journal of Hydrogen Energy
S94	[123]	Tan et al.	2018	A blockchain model for less container load operations in China	International Journal of Information Systems and Supply Chain Management

Continued on next page

ID	Ref.	Authors	Year	Title	Source
S95	[124]	Tandra et al.	2022	Designing a new cryptocurrency with hard fork and stablecoin approach as a disruptive innovation in payment system of international trade	Journal of Theoretical and Applied Information Technology
S96	[125]	Thess et al.	2020	Global carbon surcharge for the reduction of anthropogenic emission of carbon dioxide	Energy, Sustainability and Society
S97	[126]	Tian et al.	2023	Pricing and redesign decisions for global supply chain of free trade port based on the complex system	Alexandria Engineering Journal
S98	[127]	Todd	2019	Electronic bills of lading, blockchains and smart contracts	International Journal of Law and Information Technology
S99	[41]	Toorajipour et al.	2022	Block by block: A blockchain-based peer-to-peer business transaction for international trade	Technological Forecasting and Social Change
S100	[128]	Valeria et al.	2022	The Impact of Blockchain Technology on International Trade and Financial Business	Universal Journal of Accounting and Finance
S101	[129]	Valle et al.	2021	Blockchain-based information management for supply chain data-platforms	Applied Sciences (Switzerland)
S102	[130]	Vilkov et al.	2019	Blockchain as a Solution to the Problem of Illegal Timber Trade between Russia and China: SWOT Analysis	International Forestry Review
S103	[131]	Wandhöfer	2022	The future of cross-border wholesale payments: Mobilising central bank money across borders	Journal of Payments Strategy and Systems
S104	[132]	Wang et al.	2023	Green development of the maritime industry: Overview, perspectives, and future research opportunities	Transportation Research Part E: Logistics and Transportation Review
S105	[133]	Wood et al.	2016	Trustless computing—The what not the how	New Economic Windows
S106	[134]	Yang et al.	2024	Blockchain technology and international countertrade	Journal of International Financial Markets, Institutions and Money
S107	[135]	Yang et al.	2022	An Efficient Identity-Based Aggregate Signcryption Scheme with Blockchain for IoT-Enabled Maritime Transportation System	IEEE Transactions on Green Communications and Networking

Continued on next page

ID	Ref.	Authors	Year	Title	Source
S108	[34]	Yoon et al.	2020	The value of Blockchain technology implementation in international trades under demand volatility risk	International Journal of Production Research
S109	[136]	Zakharkina et al.	2022	The Impact of Digital Transformation in the Accounting System of Fuel and Energy Complex Enterprises (International Experience)	International Journal of Energy Economics and Policy
S110	[137]	Zalan	2018	Born global on blockchain	Review of International Business and Strategy
S111	[138]	Zhang et al.	2022	Blockchain: An emerging novel technology to upgrade the current fresh fruit supply chain	Trends in Food Science and Technology
S112	[139]	Zheng	2022	Analysis of Computer-Based Blockchain Technology in Cross-Border E-commerce Platforms	Mobile Information Systems

Chapter 4

Interdependencies and seasonal patterns in the decentralized finance ecosystem: a time-series econometric analysis

4.1 Short-run interdependencies across DeFi categories: VAR and adaptive TVP–VAR evidence from category-level TVL

Abstract

We study short-run interdependencies across decentralized finance (DeFi) categories using monthly Total Value Locked (TVL) from the Cambridge DeFi Navigator (Jul-2018–Jun-2025). After documenting unit roots in log levels and no robust evidence of cointegration, we estimate a VAR(1) in $\Delta \log \mathrm{TVL}$ for four core categories: Lending & Borrowing (LB), Staking (STK), Decentralized Exchanges (DEX) and Service Providers (SVP), and complement it with an adaptive, RLS-based time-varying parameter VAR (TVP–VAR) to track connectedness over time. Three results stand out. First, staking shocks systematically precede broad positive responses in LB, DEX and SVP within 1–2 months. Second, forecast-variance decompositions indicate that lending-related shocks account for most short-run forecast uncertainty in STK and DEX, whereas SVP remains comparatively inward-driven. Third, interdependence is strongly state-dependent. An adaptive TVP–VAR with generalized forecast-error variance decompositions shows that total connectedness peaks in 2021–2022 and declines thereafter. In high-connectivity regimes, DEX appears as the most frequent net transmitter of shocks and LB as the main receiver, whereas in calmer phases STK regains structural influence. Our contribution to provide, to the best of our knowledge, the first category-level map of hierarchical, state-contingent linkages in DeFi, implying that risk monitoring should be state-dependent and centered on the credit channel and liquidity hubs rather than on individual protocols.

Keywords

Decentralized finance (DeFi); Total value locked (TVL); Vector autoregression (VAR); Time-varying parameter VAR (TVP-VAR); Connectedness; Systemic risk.

4.2 Introduction

The second revolution in the landscape of distributed ledger technologies (DLT), following that of cryptocurrencies inaugurated by Bitcoin between 2009 and 2010, can be seen in decentralized finance (DeFi). It stands as one of the most disruptive innovations in the era of financial digitalization, reshaping the way individuals and institutions access and manage resources. Using blockchain and smart contracts, DeFi has introduced a permissionless world of services, like lending and borrowing, exchanges and staking, challenging traditional intermediation [140]. The origins of DeFi are commonly traced back to the launch of Ethereum [2], which enabled programmability and the creation of self-executing, customizable financial applications. However, it was during the age of the so-called "DeFi Summer"[1] of 2020 that the space saw some exponential growth of a magnitude of a thousand times and more: during a span of a few months only, TVL[2] in the protocols of DeFi saw growth from a level of less than USD 1 billion to a level of more than USD 10 billion and secured first and foremost with protocols like Compound, Aave, and Uniswap. It created a sensation both among developers and investors and raised academic and regulatory concerns with regard to the future of world finance. To provide a structured view of the ecosystem, the Cambridge Centre for Alternative Finance [141] proposed a functional taxonomy that classifies DeFi protocols into operational categories. This classification offers a useful analytical framework to understand the variety and specialization of services and to study their evolutionary dynamics. The academic literature has begun addressing complex DeFi's nature at theoretical, regulatory, and quantitative levels. Schär [3] defines DeFi as an interoperable financial architecture that eliminates intermediaries, emphasizing the role of Automated Market Makers (AMM) and lending platforms. Arner et al. [4] report the democratizing promise of DeFi and warn of cybersecurity and regulatory risk. Aramonte et al. [5] criticize the actual level of decentralization of the sector and remark upon concentrations of power towards an "illusion of decentralization." Other authors [142], [143] have analyzed tokenization and quantitative regime shifts with reference to indicators such as TVL and trading volumes. However, none has yet conducted a systematic investigation of mutual dynamics across functional sectors with reference to how shocks are conveyed through the system. This paper aims to fill this gap by conducting an econometric analysis based on monthly TVL data disaggregated by functional category, obtained from the CCAF DeFi Navigator and covering the period 2018–2025. For comparability and complete coverage, the main analytical sample is 2020–2025. The research questions are: (i) how have DeFi categories evolved over time in terms of TVL and what structural trends can be identified? (ii) Are there significant dynamic relationships across the main functional categories? (iii) What economic-financial and regulatory implications arise from the observed interdependencies?

Methodologically, we combine descriptive tools with multivariate time-series models. We begin by characterizing TVL dynamics using STL decomposition, rolling correlations, and simple persistence measures. We then estimate a VAR in first log-differences for four core DeFi categories and use impulse responses, forecast-error variance decompositions, and Granger-causality tests to summarize short-run interdependencies. Finally, we develop an adaptive, RLS-based TVP–VAR on standardized growth rates and compute generalized FEVD-based connectedness measures over time following the Diebold–Yilmaz framework. This lightweight TVP–VAR provides a local linear approximation to time-varying linkages and is well suited to short, shock-intensive monthly samples such as 2020–2025.

The empirical evidence delivers three headline findings. Short-run dynamics in $\Delta \log \mathrm{TVL}$ display a hierarchical structure: staking shocks tend to precede increases in lending, decentralized exchanges, and service providers, while lending shocks explain a substantial share of the forecast-error variance of staking and DEX, and the service-provider layer remains comparatively inward-driven. At the same time, the four categories exhibit strong persistence but no robust evidence of cointegration in log levels, which is consistent with the absence of stable long-run equilibria over 2020–2025 and motivates an emphasis on short-run interactions. Time variation is pronounced: the adaptive RLS-based TVP–VAR indicates that connectedness is state-dependent, peaking around the 2021 boom and the 2022 Terra/UST and FTX episodes, with DEX most often acting as a net transmitter and lending as the main receiver of shocks, before declining as staking regains structural influence in calmer regimes.

We contribute on two fronts. Empirically, we provide a systematic category-level map of intra-DeFi interdependencies using functional TVL from the CCAF DeFi Navigator, documenting

[1] "DeFi Summer" is a market term commonly used to describe the mid-2020 surge in yield-farming and liquidity-mining activity.

[2] TVL is measured as the USD value of on-chain assets locked in DeFi smart contracts (collateral, liquidity pools, and protocol reserves). Because TVL is denominated in USD, it conflates quantity/flow changes with valuation effects from crypto-asset prices; we therefore focus on log-differences and interpret results as short-run co-movements in USD-valued activity rather than pure capital flows.

a tightly connected yet hierarchical and state-dependent DeFi stack. Methodologically, we offer a replicable pipeline for short monthly panels that combines STL decomposition, a parsimonious VAR(1) on $\Delta \log \mathrm{TVL}$ with wild-bootstrap IRFs and FEVDs, and an adaptive RLS-based TVP–VAR that delivers time-varying connectedness measures. The implications concern systemic-risk monitoring, regulatory policy (for example under the EU MiCA framework), and protocol design.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 describes the data and presents descriptive evidence on category-level TVL. Section 4 introduces the econometric methodology and reports the VAR and adaptive TVP–VAR connectedness results. Section 5 discusses economic and policy implications. Section 6 concludes with the main insights and directions for future research.

4.3 Literature Review

DeFi has often been captured as a potential revolution of the financial system. From the perspective of Harvey et al. [142], DeFi "Challenges the established system and suggests solutions to intrinsic issues of the conventional financial infrastructure," suggesting that decentralized initiatives are best positioned to define the future of finance. However, scholars and regulators highlight the diversity of risks and unresolved problems of this new paradigm and stress that certain benefits of centralization are unavoidable and that the elimination of traditional intermediaries poses a variety of problems with a view to stability and regulation.

Against this backdrop, this part of the chapter summarizes the recent literature on DeFi with an emphasis on its tech foundations, functional types, tech and regulation risks, and empirical methods of quantitative research.

From a technical perspective, DeFi can be described as a side-by-side financial system that runs with a foundational substratum of public blockchains (most commonly Ethereum) and with open, permissionless, and interoperable protocols that reflect financial services transparently and inclusively. In the place of intermediaries of the past, DeFi replaces smart contracts, programmatic mechanisms inscribed upon the blockchain that carry out agreements and regulate transactions securely and openly. This enables the creation of an immutable financial system in which rules are applied by code and every transaction is validated by the distributed network, thereby reducing the need for trust in centralized entities. Ethereum has been the pioneering and still dominant platform for DeFi development, owing to its ability to support Turing-complete smart contracts and its extensive user and developer base. Numerous studies confirm the centrality of Ethereum: for example, Schär [3] notes that Ethereum has emerged as the leading smart contract platform in terms of both capitalization and development activity. Although other blockchains (e.g., Binance Smart Chain, Solana, Avalanche) have also enabled DeFi, Ethereum provided the foundational ecosystem on which the first and most widespread DeFi protocols were built.

Jensen et al. [144] emphasize the growing interest of both investors and regulators in DeFi, introducing its key components and technological evolution. Zhou et al. [145] provide a more technical overview, analyzing the critical role of smart contracts in automating transactions and their implications in terms of security and protocol complexity. Computational techniques are applied by Ko et al. [146], as they also classify Ethereum accounts with the aid of Graph Neural Network (GNN) models and thereby enhance understanding of internal structures of DeFi. Similarly, Stepanova and Eriņš [147] also perform a survey of major DeFi applications with an emphasis on underlying tech infrastructures. Moreover, Auer et al. [148] also characterize DeFi as a nascent paradigm of finances with a definition of fundamental tech components and primary empirical adoption patterns.

The DeFi ecosystem has high heterogeneity of function measured as the broad spectrum of services offered, e.g., lending, staking, and exchanges. Maouchi et al. [149] carry out an empirical investigation of interlinkages of parts of crypto markets, including DeFi. From their findings, they assert that analyzing segments separately sheds light on system-level behavior and risk spillover. Aggregate metrics such as TVL are insightful at a finer level of detail once disaggregated at the category level.

For this reason, and due also to the explosive proliferation of protocols and applications, has come the necessity of classifying and ordering the heterogeneous universe of DeFi into operational categories. Of specific utility in this regard is the work of the Cambridge Centre for Alternative Finance [150], providing a dynamic multi-level classification deriving from the ISO 10962 classification of the traditional financial markets. The CCAF model divides the DeFi ecosystem along four main axes: Activities, Actors, Assets, and Architecture, and identifies, for each dimension, operational categories and static/dynamic attributes. These attributes include, for example, governance structures, yield generation mechanisms, settlement processes, and the type of collateral used in lending protocols.

This taxonomy, developed through the analysis of over 200 DeFi protocols with the highest TVL, represents a robust attempt to harmonize DeFi's description with the classification criteria of traditional finance (TradFi). It has a multi-level architecture that enables sophisticated and adaptive classification as time progresses, consistent with the quick changes that an ecosystem produces. Innovative features like restaking protocols or blockchain-derived derivatives are integrated into this semantic system, benefiting both research at the academic level and also at the level of monitoring and regulation.

The exponential growth of DeFi has prompted a heated academic argument about both transformative promise and structural risks of the phenomenon. Of special interest as a research topic are the protocols' tech security problems since smart contracts are famously vulnerable. Liang et al. [151] explore risks from poorly designed contracts, while Li et al. [152] perform a systematic review of significant threats like exploits, rug pulls, and flash loan attacks. Zhou et al. [153] counter with a taxonomic approach to classify attacks against DeFi and point out how protocol increasing complexities expand the attack surface. To confront the challenge, Su et al. [154] propose technical solutions intended to prevent token loss, while Lin et al. [105] propose an early-warning system intended for vulnerable contracts. Nguyen et al. [155] also counter with risk mitigation through a reputation system intended for lending protocols with the aim of discouraging opportunism.

On the regulatory side, Teichmann et al. [156] discuss the impact of the EU's MiCA regulation and suggest opportunities and implementation challenges. Barczentewicz and Gomes [157] reflect on issues of market abuse and transactional transparency. From a socio-institutional perspective, De Filippi and Merk [158] reflect on how social capital and trust mediate membership of DAOs. Finally, Fan et al. [159] and Harir and Bel Mkaddem [160] consider system-level implications of DeFi and tensions between innovation and stability of the traditional banking system.

These pieces emphasize the dual nature of DeFi: a platform of innovation and democratization at one level and a high-risk environment of both technical and institutional kinds that requires balancing operational autonomy and safeguards. From a quantitative viewpoint, current research has developed instruments to investigate DeFi's evolution and growth and gain access to the openness of on-chain data with classical instruments of finance redesigned for this new environment. One of the threads of empirical research revolves around growth and aggregate indicators and especially TVL as a yardstick of ecosystem size and adoption. Şoiman et al. [161] empirically examine the determinants of returns of the DeFi marketplace and use indicators of finance to evaluate the dynamics of economic gains across protocols and detect relevant associations between TVL and trading volumes and volatility. Opposite comes an approach from Bhambhwani and Huang [162], with a interest focused on protocol audits and configuring of evaluation metrics and giving a system of comparison of operating performance of a variety of DeFi services. Similarly, Yang and Cui [163] propose a system of lending protocol specific evaluation purely quantitative of reliability and sustainability and of security. Grande and Borondo [164] use a behavioral approach and model TVL as a function of indicators of trust derived from social sentiment and thus highlight the sensitivity of DeFi with respect to informational flows. Maouchi et al. [165] embed TVL into the digital bubble context and examine price dynamics during the pandemic and the contribution of DeFi protocols to speculative behavior.

Direct contributions to econometric analysis of DeFi include [166] and [167], who explore dynamic linkages between DeFi tokens and traditional equity sectors using time-varying parameter VAR and DCC-GARCH models during and after the COVID-19 crisis. Complementarily, Osman et al. [168] investigate bubble formation in DeFi markets driven by sentiment and contagion, highlighting the complexity of interdependencies across protocols. Even studies not directly focused on DeFi offer relevant methodological insights: Qiao et al. [169] use frequency-domain comovement analysis for cryptocurrencies, while Omane-Adjepong and Alagidede [170] employ multiresolution methods to measure market spillovers. Jana and Sahu [171] examine crypto market diversification using dynamic connectedness, offering tools potentially extendable to inter-category DeFi analysis.

Nevertheless, despite existing empirical work on token returns and protocol performance, no research to date has systematically explored the dynamic relationships and co-evolution among DeFi's functional categories over time, using multivariate econometric models based on TVL data. This is precisely the gap addressed by the present study.

4.4 Data and Descriptive Evidence

4.4.1 Data source and sample construction

The empirical analysis in this study is based on data from the DeFi Navigator [141], an interactive platform developed by the Cambridge Centre for Alternative Finance (CCAF). This tool systematically aggregates information on protocols operating in the DeFi ecosystem, with a particular focus on the metric of TVL. Data are collected at the protocol level on a daily basis and subsequently aggregated into monthly averages in order to obtain a more stable and interpretable time.[3]

The database spans July 2018 to June 2025. Descriptive statistics and long-run visual evidence are based on the full available (potentially unbalanced) panel of categories. For the econometric analysis, we restrict attention to the balanced sample starting in December 2020, the first month in which all functional categories are simultaneously observed. The resulting main analytical sample covers December 2020 to June 2025 and contains no missing observations. Following the taxonomy of protocols into functional categories developed by the CCAF (see Section 2), the DeFi Navigator distinguishes seven macro-categories: Staking Entities, Decentralized Exchanges, Lending and Borrowing Providers, Asset Managers, Decentralized Stablecoin Issuers, Service Providers, and Miscellaneous.

This functional classification reflects the structure of the DeFi ecosystem and allows us to analyze sectoral dynamics both in aggregate terms and at the level of specific segments. The number of active protocols in each category varies over time, depending on market evolution and on the amount of TVL allocated to each actor. For the purposes of this paper, we focus on TVL as the sole variable of interest. No additional variables are included. Statistical transformations (e.g., logarithms, differencing) and data cleaning procedures are introduced in subsequent sections as part of the descriptive and econometric analysis.

In the empirical estimation, three categories are excluded. First, Asset Managers are omitted because their TVL series displays markedly different time-series properties over the sample (stationary in levels), whereas the remaining categories exhibit non-stationary dynamics. Including Asset Managers would therefore require a separate transformation or modelling treatment, potentially weakening the comparability of the connectedness measures across categories. Second, Decentralised Stablecoin Issuers and Miscellaneous are excluded due to their marginal TVL share and heterogeneous composition. The final dataset used in the econometric analysis consists of four core categories: Lending and Borrowing, Staking Entities, Decentralized Exchanges, and Service Providers.

4.4.2 Descriptive statistics and aggregate TVL

The descriptive analysis provides a preliminary view of TVL's development over time throughout functional categories in DeFi with information regarding their statistical properties, averages, and volatility dynamics. Table 1 reports basic descriptive statistics (mean, standard deviation, coefficient of variation, in USD billions) computed from the first observation for each category, in order to maximize informational coverage of every series. The evidence registers strong heterogeneity across

[3]It uses monthly averages (rather than end-of-month snapshots) to reduce sensitivity to short-lived spikes and end-of-period window dressing, which are common in DeFi liquidity provisioning.

segments. Lending & Borrowing, Staking Entities, and Decentralized Exchanges have the highest TVL averages and therefore qualify as by far the foremost support columns of the DeFi system. On the contrary, newer or special purpose segments such as Asset Managers, Service Providers, and particularly Decentralized Stablecoin Issuers have lower average volumes and bigger discontinuities. With volatility in mind, standard deviation provides an absolute measure of dispersion but is not very useful for between-category comparisons with categories having scales in their mean. Thus, for such purposes, the coefficient of variation (CV) was calculated. Results indicate that Service Providers (CV = 1.24), Stablecoin Issuers (CV = 1.15), and Staking Entities (CV = 0.99) are relatively most volatile categories with sharp boom–bust cycles. Conversely, Miscellaneous (CV = 0.69), Decentralized Exchanges (CV = 0.83), and Lending & Borrowing (CV = 0.83) have relatively more stable dynamics compared to their mean size.

Table 4.1: Descriptive Statistics of TVL by DeFi Category (in USD billions).

Category	**First Available Date**	**Mean (USD B)**	**Standard Deviation (USD B)**	**Coefficient of Variation**
Lending and Borrowing	2018-10	23.45	19.40	0.83
Staking Entities TVL	2020-12	28.18	28.03	0.99
Asset Managers TVL	2019-02	8.86	8.61	0.97
Decentralized Exchanges	2018-12	17.16	14.29	0.83
Service Providers	2018-07	2.51	3.10	1.24
Miscellaneous	2020-02	3.86	2.67	0.69
Decentralized Stablecoin Issuers	2021-01	1.42	1.64	1.15

Figure 4.1 illustrates the time-series evolution of TVL across categories, revealing three distinct phases. The first phase (2020–2021) is characterized by explosive growth, largely driven by the "DeFi Summer" and the broader crypto bull market. This expansion was followed by a sharp contraction in 2022, coinciding with major market dislocations such as the collapse of Terra/UST and the failure of FTX. Finally, the period from 2023 to 2025 shows a phase of relative stabilization, with TVL remaining below previous peaks but exhibiting comparatively steady dynamics. Though these general cycles resemble one another across industries, variation in the timing of reactions indicates that dynamic interdependencies must exist, which are investigated econometrically in subsequent sections.

Figure 4.2 overlays all categories in a single comparative chart. The figure highlights large differences in absolute TVL levels: Staking and Lending& Borrowing dominate, whereas Stablecoin Issuers and Service Providers remain marginal. At the same time, the synchronicity of movements across the main categories suggests the presence of common shocks, though with heterogeneous magnitudes and transmission speeds.

Finally, Figure 4.3 shows the aggregated TVL of the entire DeFi economy. The chart justifies a phase of explosive growth till mid-2021 (over USD 200 billion), then declines sharply, followed by a phase of retrenchment till 2023–2025. The trend repeats broader crypto marketplace developments and triggers use of a multivariate econometric model to investigate co-evolution and interactions between functional segments.

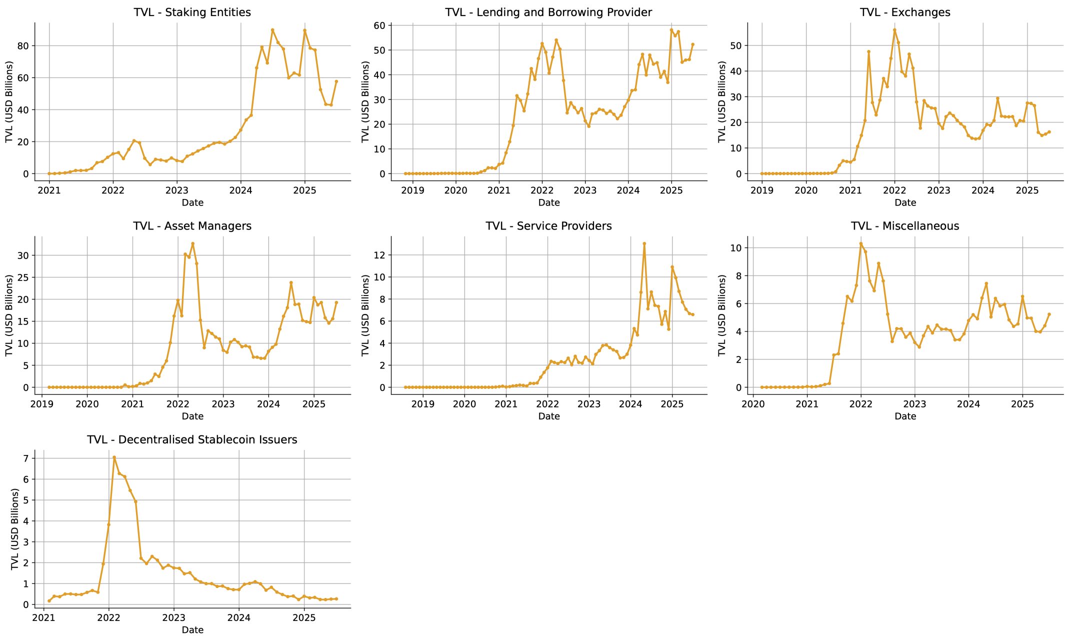


Figure 4.1: TVL by DeFi category, 2019–2025.

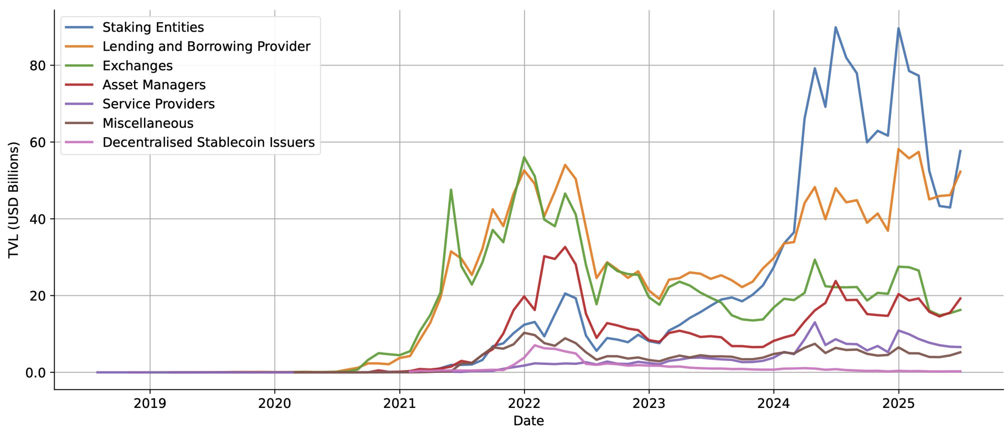


Figure 4.2: Comparative dynamics of DeFi total value locked across categories.

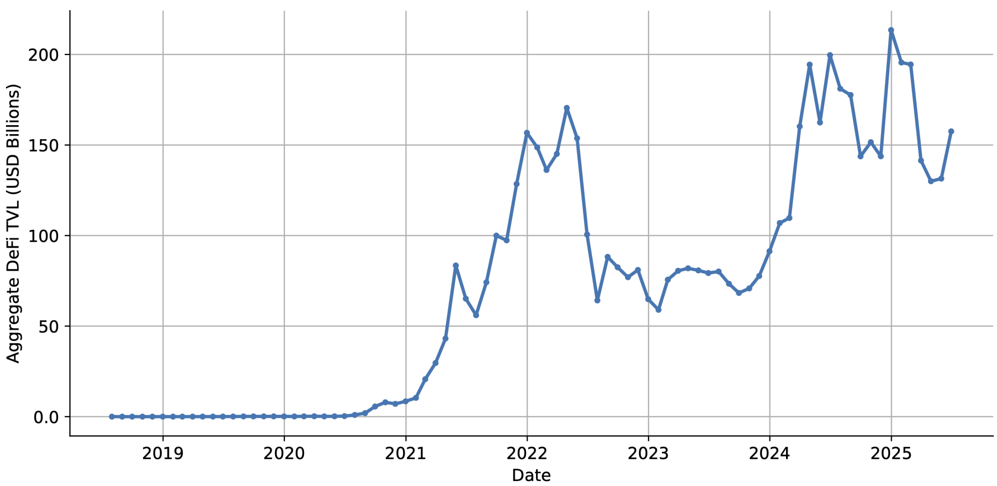


Figure 4.3: Aggregate TVL in the DeFi ecosystem.

4.4.3 Cross-sectional correlations and rolling volatility

Within the first stage of the empirical analysis, we analyze the linear dependency structure between the key functional groups of DeFi by computing a Pearson correlation matrix based on monthly TVL time series. Correlations are calculated using the maximum overlap available for each pair of time series, thus preserving all relevant information without unwarranted sample truncation. This approach allows us to include categories that emerged over time (e.g., Stablecoin Issuers), while ensuring comparability with longer-established segments (e.g., Lending or Decentralized Exchanges).

Results are shown in Figure 4.4. We observe some patterns. Very strong positive correlations exist among Lending & Borrowing, Asset Managers, Decentralized Exchanges, and Service Providers (ρ within the range 0.67–0.89). This suggests that these buckets co-move together very strongly over time, as they share common exposures such as aggregate inflows of liquidity into DeFi, aggregate market sentiment, as well as macro–crypto cycle effects.

Staking Entities exhibit a richer relationship: while they are very strongly related to Service Providers ($\rho = 0.94$), they exhibit weak, even slightly negative, correlations with Exchanges ($\rho = -0.11$). This inconsistency may reflect the specific economic role of staking, which captures yield opportunities through participation in consensus, as opposed to the liquidity-focused processes found within decentralized exchanges.

We see issuers of stablecoins showing a low correlation or even a negative relationship, as evidenced by $\rho = -0.26$ with Service Providers and $\rho = -0.30$ vis-à-vis Staking. This implies that stablecoins mostly act as transaction infrastructure, rather than yield-providing services. Moreover, their use is influenced by multiple factors, such as market conditions, regulatory constraints, and the need for on-chain settlement.

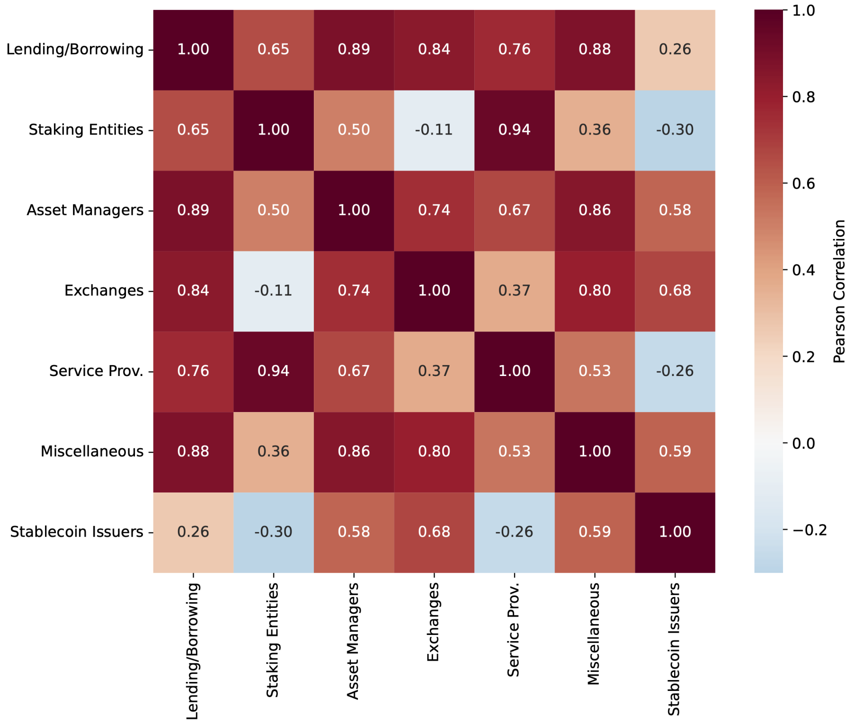
The Miscellaneous category exhibits intermediate correlations with most groups (ρ between 0.36 and 0.88), but its heterogeneous composition limits interpretative insight; these correlations may reflect idiosyncratic innovation effects rather than a coherent economic mechanism.

It is apparent from the correlation matrix that the DeFi ecosystem does not grow homogeneously. Instead, separate functional groups display diverse levels of co-movement, reflecting the stratified nature of the structure: a dense "core" (exhibiting strong co-movement) (Lending, Asset Management, DEX, Service Providers), a complementary, although separate, group (Staking), as well as more idiosyncratic groupings (Stablecoin Issuers, Miscellaneous). These preliminary insights motivate the multivariate econometric analysis developed in the next sections, which aims at tracing the dynamic propagation of shocks among groups.

Alongside the examination of cross-category correlations, we evaluate the comparative volatility of each segment within the DeFi ecosystem over time by computing the rolling coefficient of variation (CV) using a 12-month window. This metric, defined as the ratio between the rolling standard deviation and the rolling mean of TVL, provides a dimensionless indicator of internal stability that is not affected by the absolute magnitude of each category.

The resulting trajectories (Figure 4.5) highlight marked heterogeneity across categories. Asset Managers, Service Providers, and Miscellaneous protocols display pronounced volatility spikes, particularly during phases of market stress or structural adjustment (e.g., the 2022 crypto downturn and the post-FTX collapse). In contrast, Exchanges and Lending & Borrowing providers exhibit lower and more stable CV values, indicating greater relative resilience despite large swings in absolute TVL. Staking Entities show an intermediate pattern: initial instability during their rapid adoption phase (2021–2022), followed by a gradual convergence toward more stable dynamics after 2023. Decentralized stablecoin issuers, meanwhile, record sharp peaks in relative volatility around 2022, consistent with the fragility of algorithmic stablecoins exposed during crisis episodes (e.g., Terra/UST).

Overall, the rolling CV analysis suggests that while core sectors (Lending, Exchanges) have evolved as relatively stable centers, peripheral and more innovative segments remain more vulnerable and subject to idiosyncratic shocks. These observations complement the correlation analysis by capturing differences in maturity and structural fragility across functional groupings within the DeFi ecosystem.



	Lending/Borrowing	Staking Entities	Asset Managers	Exchanges	Service Prov.	Miscellaneous	Stablecoin Issuers
Lending/Borrowing	1.00	0.65	0.89	0.84	0.76	0.88	0.26
Staking Entities	0.65	1.00	0.50	-0.11	0.94	0.36	-0.30
Asset Managers	0.89	0.50	1.00	0.74	0.67	0.86	0.58
Exchanges	0.84	-0.11	0.74	1.00	0.37	0.80	0.68
Service Prov.	0.76	0.94	0.67	0.37	1.00	0.53	-0.26
Miscellaneous	0.88	0.36	0.86	0.80	0.53	1.00	0.59
Stablecoin Issuers	0.26	-0.30	0.58	0.68	-0.26	0.59	1.00

Figure 4.4: Pearson correlation matrix of DeFi categories.

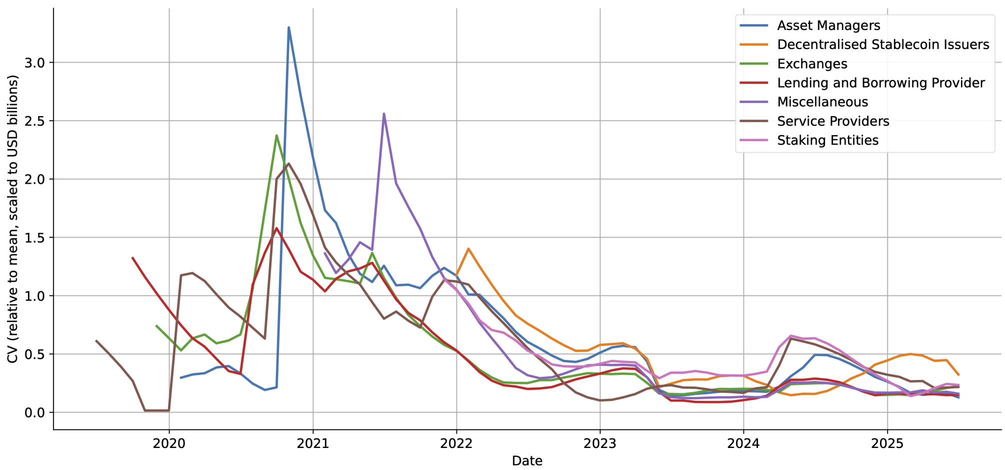


Figure 4.5: Rolling coefficient of variation (12-month window).

4.4.4 Time-varying correlations

We then proceed to dynamic analysis of the relationships between categories. While correlation based on the entire sample provides a mean estimate of pairwise linear association, this time-series variation due to market shocks, shifts in regulation, or internal dynamics within the ecosystem, is lost. We then estimate rolling Pearson correlation based on 6-monthly moving windows, through which we gain insight into the time-evolution of both the strength as well as the signed direction, of the relationships between category pairs.

Formally, for two time series $X = \{x_t\}$ and $Y = \{y_t\}$ and a rolling window width w, the rolling correlation at time t is:

$$\rho_t = \frac{\sum_{i=t-w+1}^{t}(x_i - \bar{x}_t)(y_i - \bar{y}_t)}{\sqrt{\sum_{i=t-w+1}^{t}(x_i - \bar{x}_t)^2}\sqrt{\sum_{i=t-w+1}^{t}(y_i - \bar{y}_t)^2}}, \tag{1}$$

where $\bar{x}_t$ and $\bar{y}_t$ denote rolling means over $[t - w + 1, t]$.

Each value ρ_t therefore reflects the degree of linear dependence between X and Y over the preceding w months, providing a dynamic and localized representation of the relationship.

The outcomes, as observed from Figures 4.6 to 4.9 , indicate significant variation among the pairs. Lending & Borrowing and Exchanges exhibit a rather stable positive correlation, also during expansion (2021) and contraction (2022) stages. This implies a functional complementarity between exchange venues and credit markets, as would be expected given liquidity shifts across sectors.

Staking Entities and Service Providers exhibit sporadic co-movements, where periods of high alignment are followed by divergence. This suggests weaker structural connections, likely influenced by reward campaigns or protocol-specific forces.

Asset Managers exhibit significantly positive but unstable correlations, reflecting the category's tendency to consolidate as well as its reactivity to sectoral reshufflings and external shocks.

Decentralized stablecoin issuers exhibit the most fragile and erratic correlations, often fluctuating into negative values. This observation suggests a predominant role of idiosyncratic factors, driven by specific events (e.g., the Terra/UST failure in 2022) rather than overarching systemic patterns.

Other protocols display transient and erratic correlations, with no clear signal of long-run synchronization. A common feature emerges during crisis periods: around 2022, amid the crypto market meltdown and the collapse of several CeFi entities, correlations among some pairs strengthened, indicating episodes of systemic contagion. This suggests that, under stress, the DeFi system becomes more interdependent, whereas under normal conditions idiosyncratic and specialized dynamics prevail.

More generally, these results show that relationships between DeFi categories are time-varying rather than constant and are highly context-specific. This motivates the multivariate econometric models developed in the following sections, which enable explicit modeling of dynamic relationships and the transmission of shocks across categories.

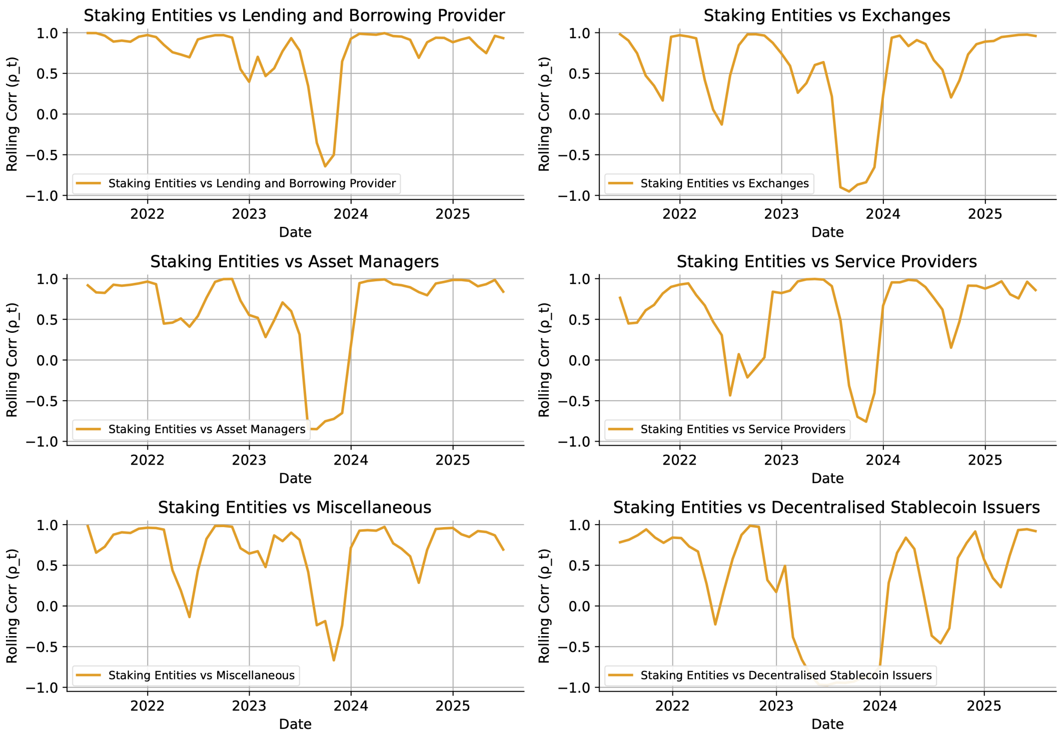


Figure 4.6: Rolling Pearson correlation (6-month window) – Group 1.

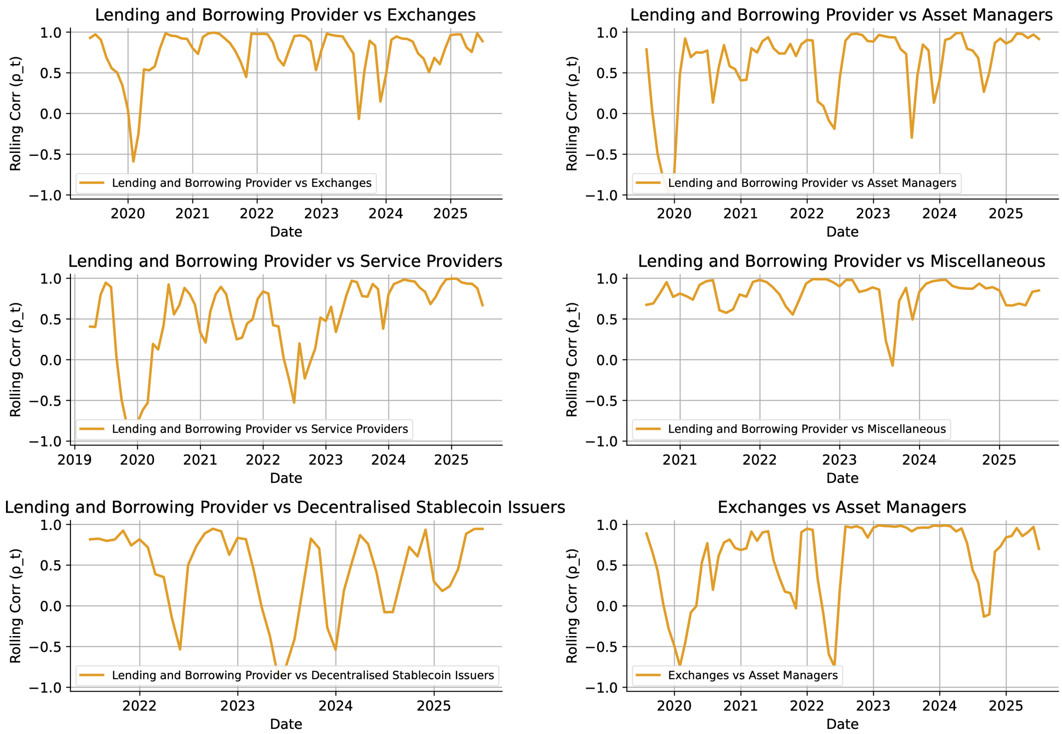


Figure 4.7: Rolling Pearson correlation (6-month window) – Group 2.

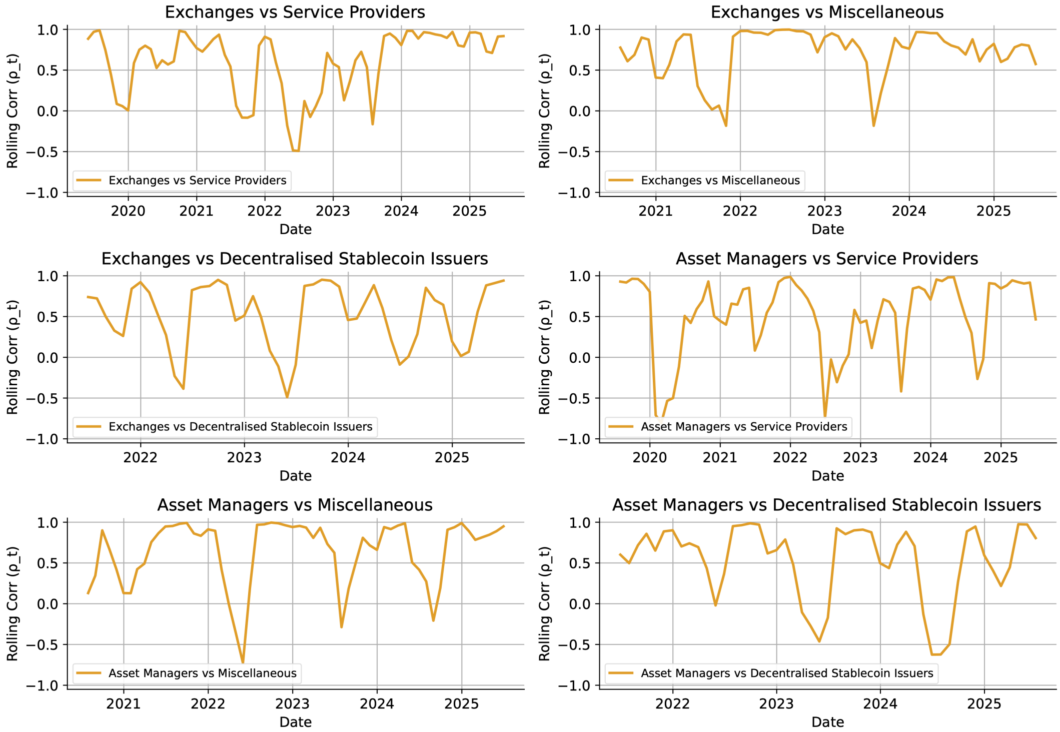


Figure 4.8: Rolling Pearson correlation (6-month window) – Group 3.

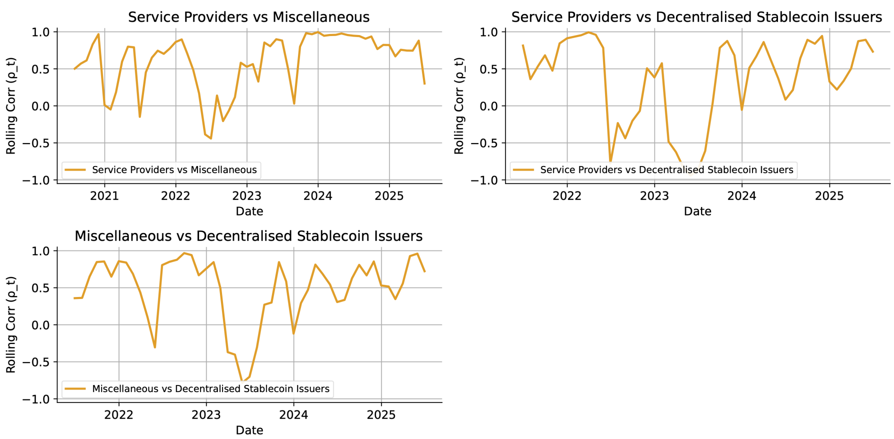


Figure 4.9: Rolling Pearson correlation (6-month window) – Group 4.

4.4.5 Trend, seasonality and persistence

To facilitate a better understanding of the dynamic parameters linked to DeFi activity, we apply Seasonal–Trend decomposition using LOESS (STL) to all TVL series [172]. This decomposition identifies three separate components: (i) a slow-moving long-term trend, (ii) a seasonal cycle with fixed annual periodicity (period = 12), and (iii) an irregular residual containing unsystematic shocks. We use the robust option to limit the influence of large outliers and shock episodes. The results are reported in Figure 4.10.

Trend components reveal divergent paths across categories. Staking Entities demonstrate the most vigorous and sustained expansion, with renewed acceleration in 2024–25 in line with liquid staking and restaking schemes. Lending & Borrowing Providers grow rapidly up to 2022, then experience a flattening and mild contraction in 2023 before a gradual rebound in 2024–25. Decentralized Exchanges peak in 2022 and then normalise, reflecting the post-bull-market adjustment in on-chain trading volumes. Service Providers follow an almost monotonic upward path, consistent with gradual infrastructural adoption (oracles, bridges, middleware). Miscellaneous protocols expand up to 2023 and then decline, signalling consolidation in less scalable niches. Decentralized Stablecoin Issuers display a sharp 2021–22 boom followed by a persistent downtrend, consistent with the collapse of algorithmic designs and tightening regulatory scrutiny.

Seasonal components are highly heterogeneous. STL attributes very large recurring components to Staking Entities and, to a lesser extent, to Service Providers (Appendix A, Table A.1). However, formal month-dummy tests do not detect calendar-type seasonality for any category (Appendix A, Table A.2). This indicates that part of what STL is capturing is likely protocol- or incentive-driven (reward epochs, restaking waves, liquidity-mining campaigns) rather than strictly tied to the month of the year. By contrast, Lending, DEX, and asset-management categories display only modest recurring movements, while Stablecoin Issuers and Service Providers exhibit weak or irregular seasonality, suggesting that their dynamics are driven more by discrete adoption steps or market events than by regular calendar forces.

Residuals capture episodic shocks, often coinciding with major crypto events. Large spikes in 2021–22 appear in Lending, DEX, and Stablecoin Issuers and align with the Terra/UST failure, subsequent liquidations, and the FTX collapse. Residual volatility increases again for Staking in 2024–25, reflecting new product releases and incentive campaigns. Service-type categories show smoother, trend-driven residuals, consistent with gradual infrastructure roll-out.

Taken together, the decomposition points to a bifurcation of DeFi functional groups. Pro-cyclical segments (staking, lending, DEX) display visible recurrent patterns and are shock-sensitive, whereas infrastructural or consolidating segments (services, stablecoin issuers) follow smoother, trend-dominated paths. A simple parametric check based on OLS with monthly dummies does not reject the null of no month-of-year effects for any category. This supports interpreting DeFi "seasonality" as recurrent intra-year, incentive-driven behaviour rather than classical calendar seasonality: STL remains useful as a descriptive tool to visualise those cycles, but the underlying mechanism is economic and institutional rather than purely temporal.

To characterize serial dependence beyond the trend–seasonal patterns, we compute autocorrelation (ACF) and partial autocorrelation (PACF) functions for monthly TVL (up to 24 lags; Figure 4.11). Across categories, the ACFs are strongly positive at short horizons and decay only gradually, indicating pronounced persistence consistent with the trend components recovered by STL. The PACFs, by contrast, display only a few significant low-order spikes, suggesting that once the series are rendered stationary (e.g., via log-differencing) their short-run dynamics are parsimonious.

At the category level, Staking Entities exhibit a slowly declining ACF and a PACF dominated by a single spike at lag 1, the hallmark of a near-AR(1) process after de-trending. Lending & Borrowing Providers also display high persistence, but the PACF shows small, repeated signals at the first few lags, pointing to a slightly richer adjustment (low-order AR/ARMA once stationary). Decentralized Exchanges combine a strong lag-1 correlation with a faster subsequent decay and a PACF concentrated at lag 1, consistent with short memory once trends are removed. Asset Managers present steady ACF tapering and PACF activity at lags 1–2, compatible with a compact

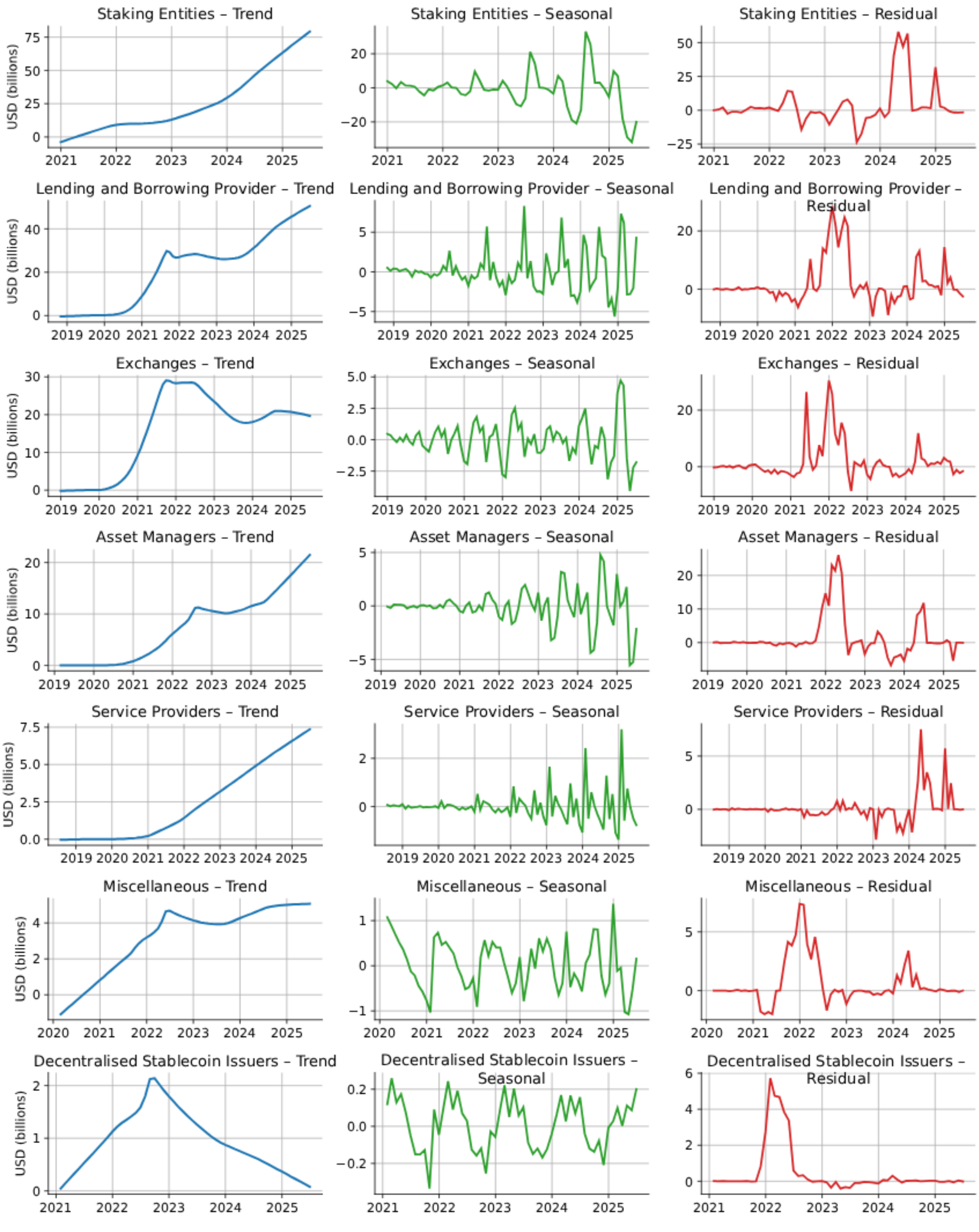


Figure 4.10: STL decomposition by category (period=12, robust=true).

AR(2) representation on stationary transforms. Service Providers are the most persistent: the ACF remains elevated deep into the lag order while the PACF is largely featureless, a pattern typical of integrated behaviour driven by a strong trend component. Miscellaneous shows a declining ACF that turns mildly negative at medium horizons and a PACF with small, scattered early-lag signals, suggestive of a damped-cycle element once stationary. Finally, Decentralized Stablecoin Issuers exhibit a rapid drop of the ACF toward zero and alternating, near-zero PACF coefficients, indicating weak persistence and dominance of idiosyncratic shocks.

Overall, the correlograms corroborate the STL evidence: core segments (Staking, Lending, DEX, Asset Managers) are trend-dominated yet admit compact short-run representations after stationarization, whereas Stablecoin Issuers display comparatively low persistence. These properties justify working with log-differences (or otherwise stationarized series) and motivate parsimonious lag orders when specifying the multivariate model in the next section.

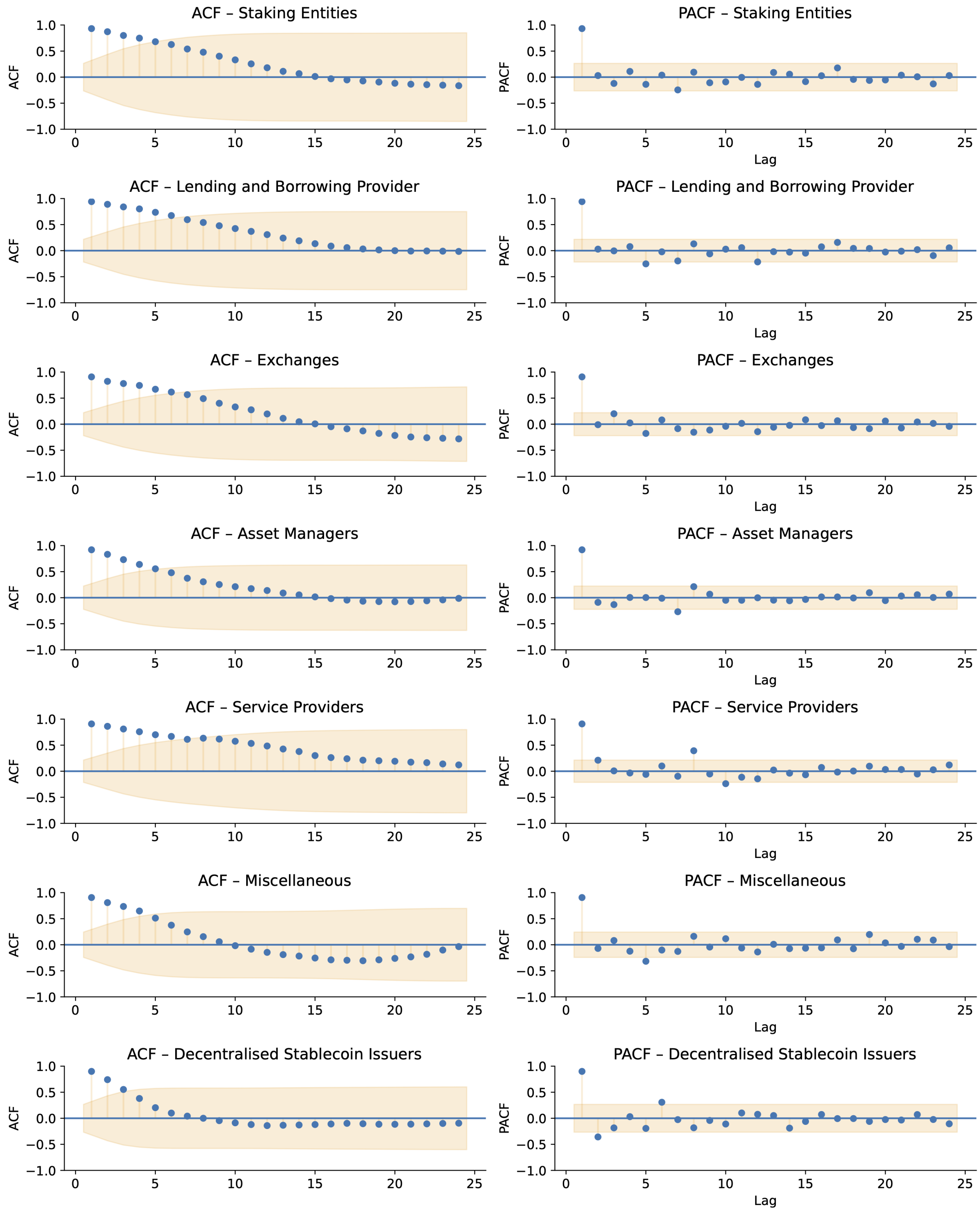


Figure 4.11: ACF & PACF by category (max lag = 24).

4.5 Methodology and Results

4.5.1 Unit-root and cointegration tests

To test the degree of integration of the series, we applied tests with opposing null hypotheses: Augmented Dickey–Fuller (ADF, H_0: unit root) and KPSS (H_0: stationarity in levels), on monthly data with intercepts. In the ADF, the lag length is selected via AIC, while for the KPSS the Newey–West bandwidth follows standard practice.

At levels, i.e., on the logarithms of TVL,

$$y_{i,t} = \ln\bigl(\mathrm{TVL}_{i,t}\bigr),$$

the ADF p-values are high (Lending 0.163; Staking 0.705; Exchanges 0.254; Service 0.871), so the presence of a unit root is not rejected. The KPSS results are around 0.05–0.10 (with borderline Staking), outlining a picture consistent with strong trend components and possible structural breaks.

Turning to logarithmic differences,

$$\Delta y_{i,t} = y_{i,t} - y_{i,t-1},$$

the evidence is reversed: the ADF systematically rejects the unit-root hypothesis (Lending $p = 2 \times 10^{-6}$; Staking $p < 10^{-6}$; Exchanges $p \approx 3.9 \times 10^{-4}$; Service $p < 10^{-6}$), while the KPSS does not reject stationarity for Lending ($p = 0.098$) and Exchanges ($p = 0.086$) and reports slight deviations for Staking ($p = 0.030$) and Service ($p = 0.021$).

Overall, monthly changes in $\Delta \log$ can be considered weakly stationary: joint tests indicate mean reversion with possible residual heteroskedasticity, a typical finding for monthly growth rates in financial contexts.

In light of these findings, and following econometric practice [9, 10, 173], we adopt natural logarithms of TVL and estimate the models on their first differences. Furthermore, to ensure statistical and interpretive consistency of the system, we limit the analysis to four core categories—Lending & Borrowing, Staking Entities, Decentralized Exchanges, and Service Providers—excluding Decentralized Stablecoin Issuers and Miscellaneous due to their marginal weight and heterogeneous composition, as well as Asset Managers due to a clear integration mismatch with the other series. This choice maximizes the common timeframe (December 2020–June 2025) and reduces the risk of instability due to unrepresentative or misaligned segments.

We specify a VAR in first log-differences for the four core categories. Before estimation, to test for the possible presence of long-run equilibrium relationships between the four core categories, we apply the Johansen cointegration test on log levels, using the standard specification with a deterministic constant and the same lag choice adopted in the next section for the VAR. The results show that neither the trace statistic nor the max-eigenvalue statistic exceeds its respective 5% critical threshold for any rank hypothesis: for $r \leq 0$, the trace statistic equals 43.81 (critical 47.85) and the max-eigenvalue equals 20.59 (critical 27.59); for $r \leq 1$, the statistics drop further (trace 23.22 vs. 29.80; max-eigen 13.14 vs. 21.13), and similarly for $r \leq 2$ and $r \leq 3$. Overall, the null-rank hypothesis is not rejected ($r = 0$), indicating the absence of cointegrating vectors in the sample period. This evidence is consistent with unit-root tests on levels and reinforces the choice of estimating a VAR on log differences, focusing the analysis on short-run interdependencies between categories without an error-correction term.

Given the short and shock-intensive sample, Johansen tests have limited power; we therefore interpret the absence of statistically significant cointegration as a lack of robust evidence for cointegration rather than as a definitive statement. Our main results are, however, robust to estimating a VAR(1) in monthly log-differences (Appendix B, Table B.3).

We set the maximum lag to six months. Information criteria deliver mixed guidance on the appropriate lag length: the AIC and Final Prediction Error (FPE) favour $p = 3$, whereas the BIC and HQIC prefer $p = 0$. To retain short-run dynamics and enable impulse-response analysis while preserving parsimony, we adopt a baseline VAR(1).

4.5.2 Baseline VAR specification

We estimate a monthly VAR on log-differences of TVL for four core DeFi categories—LB, STK, DEX, and SVP—over 2020–2025. Guided by information criteria and by the monthly frequency of the data, we set $p = 1$. Orthogonalized impulse responses are identified through a Cholesky decomposition with the ordering [LB, STK, DEX, SVP], reflecting the credit–staking–trading–infrastructure flow within the DeFi ecosystem. Robustness to alternative orderings and to generalized (Pesaran–Shin) IRFs is reported in Appendix A.5.

The VAR is stable (all companion roots < 1) and residuals are white up to lag 12 (Ljung–Box $p \approx 0.42$). Residual correlations are high within the LB–STK–DEX block and moderate with SVP, consistent with the descriptive evidence.

Across equations, a clear short-run hierarchy emerges, with staking acting as the most influential transmitter of dynamics. (i) Lending & Borrowing (LB) responds positively to STK_{t-1} (≈ 0.36, $p < 0.001$), indicating that staking expansions systematically precede increases in lending activity. (ii) In the Staking equation, the own-lag is strongly persistent (≈ 0.85, $p < 0.001$). The Lending lag enters negatively and significantly in the baseline specification on raw $\Delta \log$ TVL ($p \approx 0.03$). Given the much higher volatility of Staking ($\sigma \approx 0.48$) relative to Lending ($\sigma \approx 0.20$), a scaling robustness check using standardized series reduces the magnitude to ≈ -0.40 ($p \approx 0.03$) while preserving sign and significance. We interpret this as partial substitution in short-run capital allocation between lending-type yields and staking yields, rather than a near one-for-one reallocation. (iii) DEX activity also loads positively on STK_{t-1} (≈ 0.35, $p \approx 0.001$), suggesting that staking-led expansions spill over into trading volume and liquidity provision. The own-lag term is small and short-lived, consistent with transient bursts of activity rather than persistent growth. (iv) Service Providers depend positively on STK_{t-1} (≈ 0.50, $p < 0.001$) and negatively on DEX_{t-1} (≈ -0.80, $p \approx 0.008$). This asymmetric response indicates that infrastructure adoption tends to follow staking-led growth phases but contracts after trading surges, consistent with temporary liquidity rotations.

Moderate multicollinearity among lagged regressors (pairwise ρ up to 0.87; VIF ≤ 5.1) may inflate some magnitudes but does not affect signs or significance. Full coefficient tables are reported in Appendix A.

4.5.3 Impulse responses and forecast variance decomposition

Figure 4.12 plots the orthogonalized impulse response functions (IRFs) over a 10-month horizon, with wild-bootstrap confidence intervals. Own-shock responses are sizable on impact and decay within 3–4 months, as expected for stationary growth rates. In our VAR specification, STK shocks are associated with positive responses in LB, DEX, and SVP within 1–2 months, with economically meaningful and statistically significant effects on impact and moderate persistence thereafter. LB shocks also relate to subsequent movements in STK and DEX, but with smaller amplitude and faster mean reversion. DEX shocks are short-lived and partly negative for STK and SVP, consistent with temporary liquidity or volatility bursts followed by normalisation. SVP shocks have limited outward effects, with most of the adjustment taking place within the service/infrastructure layer. Cumulative IRFs reported in Appendix A.5 corroborate the positive longer-run contributions of staking innovations in this reduced-form setting.

Figure 4.13 reports the 1–10 month forecast-error variance decomposition (FEVD) implied by the Cholesky-identified VAR. Lending is mostly self-driven ($\approx 91\%$ own share at 10 months), with a non-trivial contribution from staking ($\approx 9\%$). The forecast uncertainty of staking is primarily attributed to lending shocks ($\approx 62\%$), despite its high own persistence, suggesting a prominent role of the DeFi credit cycle in shaping short-run fluctuations in staking activity. DEX variance is strongly associated with lending shocks ($\approx 65\%$) and only modestly with staking ($\approx 6\%$), whereas SVP remains largely idiosyncratic ($\approx 74\%$ own share), with secondary exposure to DEX ($\approx 12\%$) and LB ($\approx 9\%$). Complete FEVD tables are provided in Appendix B.

Overall, the VAR points to a tightly connected yet hierarchical DeFi stack. Within our reduced-form specification, staking emerges as the main transmitter of positive growth pulses, in the sense that staking shocks precede expansions in lending, trading, and infrastructure. Lending shocks, however, account for most of the forecast uncertainty in the system, indicating that the

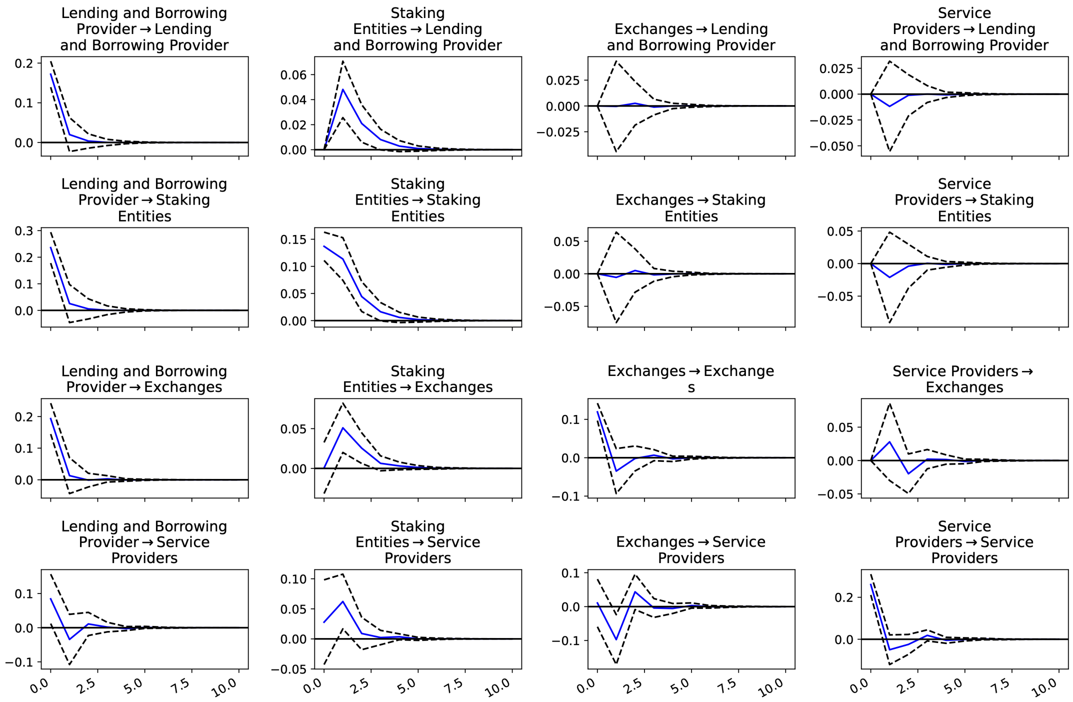


Figure 4.12: Impulse response functions (orthogonalized).

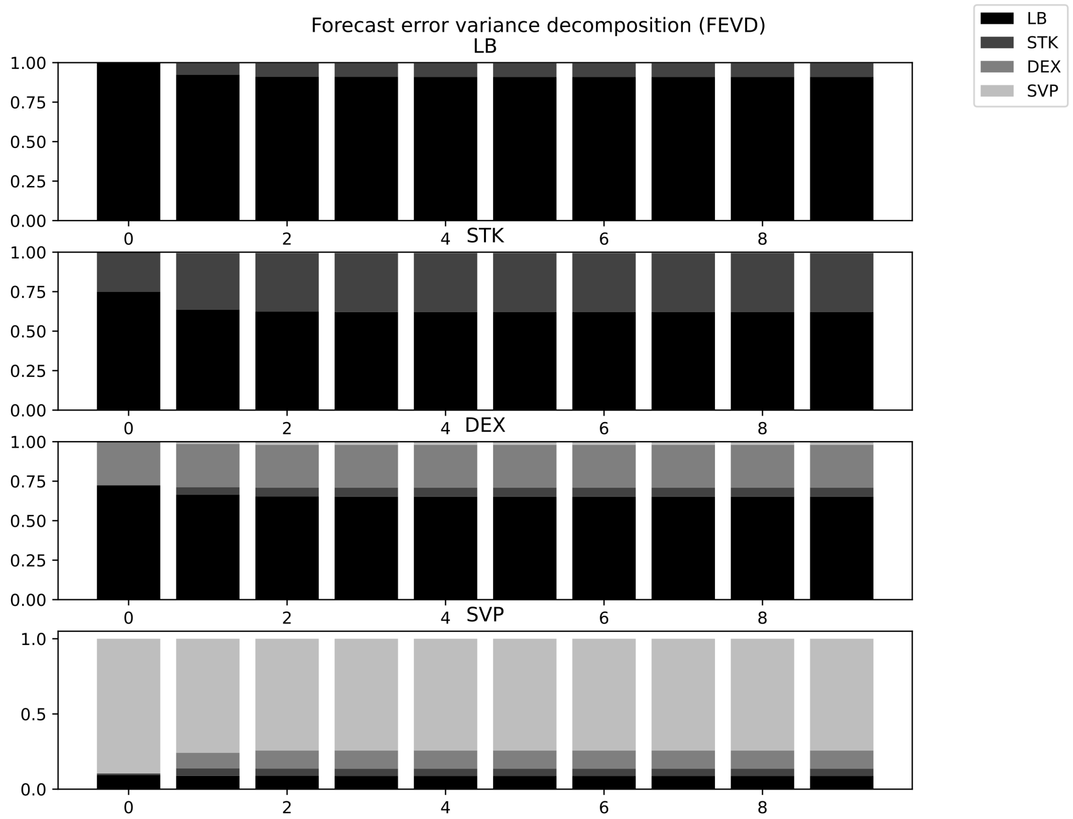


Figure 4.13: Forecast error variance decomposition across DeFi categories.

credit/leverage cycle plays a central role in short-run co-fluctuations across categories. DEX shocks are transient and largely mean-reverting, while the service/infrastructure layer is more inward-driven, adjusting mainly to utilisation rather than propagating shocks outward. These patterns are robust to alternative identification schemes and consistent with the descriptive evidence (rolling coefficients of variation; STL decomposition).

4.5.4 Adaptive RLS-based TVP–VAR and dynamic connectedness

As a dynamic robustness exercise, we extend the baseline VAR(1) by allowing both the coefficients and the innovation covariance matrix to evolve over time. Rather than estimating a fully fledged Bayesian/Kalman-filter TVP–VAR in the spirit of Primiceri [174], which is demanding in terms of both computation and sample size, we adopt a parsimonious online, RLS-based TVP–VAR that is suitable for short monthly panels with large shocks.

We start from a VAR(1) in standardized monthly log-differences of the four DeFi categories.[4] Let

$$\mathbf{y}_t = \big(y_{LB,t},\, y_{STK,t},\, y_{DEX,t},\, y_{SVP,t}\big)', \qquad N = 4,$$

and define the regressor vector

$$\mathbf{x}_t = (1, \mathbf{y}_{t-1}')' \in \mathbb{R}^{N+1}.$$

We write the time-varying VAR(1) as

$$\mathbf{y}_t = \mathbf{A}_{0,t} + \mathbf{A}_{1,t}\mathbf{y}_{t-1} + \mathbf{u}_t, \qquad \mathbb{E}[\mathbf{u}_t] = \mathbf{0}, \quad \mathbb{V}[\mathbf{u}_t] = \boldsymbol{\Sigma}_t, \tag{2}$$

and equivalently in "regression" form

$$\mathbf{y}_t = \mathbf{B}_t\mathbf{x}_t + \mathbf{u}_t, \qquad \mathbf{B}_t = \big[\mathbf{A}_{0,t} \;\; \mathbf{A}_{1,t}\big] \in \mathbb{R}^{N\times(N+1)}.$$

The i-th equation is $y_{i,t} = \mathbf{x}_t'\boldsymbol{\beta}_{i,t} + u_{i,t}$, where $\boldsymbol{\beta}_{i,t}'$ is the i-th row of $\mathbf{B}_t$.

We update coefficients equation-by-equation via recursive least squares with forgetting factor $\lambda_\beta \in (0,1)$. Let $\mathbf{P}_{i,t}$ denote the RLS covariance matrix for equation i. Given $(\boldsymbol{\beta}_{i,t-1}, \mathbf{P}_{i,t-1})$ and $\mathbf{x}_t$, form the one-step-ahead prediction error

$$\hat{y}_{i,t|t-1} = \mathbf{x}_t'\boldsymbol{\beta}_{i,t-1}, \qquad e_{i,t} = y_{i,t} - \hat{y}_{i,t|t-1}.$$

The RLS gain and updates are

$$\mathbf{k}_{i,t} = \frac{\mathbf{P}_{i,t-1}\mathbf{x}_t}{\lambda_\beta + \mathbf{x}_t'\mathbf{P}_{i,t-1}\mathbf{x}_t}, \qquad \boldsymbol{\beta}_{i,t} = \boldsymbol{\beta}_{i,t-1} + \mathbf{k}_{i,t}e_{i,t}, \tag{3}$$

$$\mathbf{P}_{i,t} = \frac{1}{\lambda_\beta}\Big(\mathbf{P}_{i,t-1} - \mathbf{k}_{i,t}\mathbf{x}_t'\mathbf{P}_{i,t-1}\Big). \tag{4}$$

Our baseline specification sets $\lambda_\beta = 0.98$, implying a half-life of about 35 months at monthly frequency. We adopt a diffuse initialization, setting $\boldsymbol{\beta}_{i,0} = \mathbf{0}$ and $\mathbf{P}_{i,0} = 100\,\mathbf{I}$ for all i, so as to reflect weak prior information and allow the data to rapidly dominate the recursion. Given this diffuse start, the earliest months can partly reflect a short warm-up phase; our interpretation therefore focuses on persistent patterns over the sample.

Time variation in the innovation covariance matrix is modelled via an EWMA-type update in the spirit of RiskMetrics [175]. Crucially, in the online recursion we use the stacked one-step-ahead prediction errors

$$\mathbf{u}_t = (e_{1,t}, \ldots, e_{N,t})' = \mathbf{y}_t - \mathbf{B}_{t-1}\mathbf{x}_t,$$

and update

$$\boldsymbol{\Sigma}_t = \lambda_\Sigma \boldsymbol{\Sigma}_{t-1} + (1-\lambda_\Sigma)\,\mathbf{u}_t\mathbf{u}_t', \tag{5}$$

[4]Standardization is performed component-wise as $z_{i,t} = (\Delta \log TVL_{i,t} - \overline{\Delta \log TVL_i})/s_i$, with moments computed over the full sample (in the implementation, s_i is the population standard deviation, i.e. ddof = 0).

with $\lambda_\Sigma = 0.97$ in the baseline and initialization $\mathbf{\Sigma}_0 = \mathbf{I}$. This specification trades some statistical efficiency for transparency and robustness in a short, shock-intensive sample, and provides a local linear approximation to a fully parametric TVP–VAR.

At each month t, the procedure delivers a local VAR representation $(\mathbf{A}_{1,t}, \mathbf{\Sigma}_t)$, with $\mathbf{A}_{1,t}$ extracted from the updated coefficient matrix $\mathbf{B}_t$. To avoid near-explosive local dynamics in the FEVD step, we apply a mild stabilization: if $\rho(\mathbf{A}_{1,t}) \geq 0.999$ (spectral radius), we rescale $\mathbf{A}_{1,t} \leftarrow \mathbf{A}_{1,t}/(\rho(\mathbf{A}_{1,t}) + 10^{-6})$.

From each time-indexed system we compute generalized forecast-error variance decompositions (GFEVD) over horizon $H = 10$ months and map them into time-varying connectedness measures à la Diebold and Yilmaz [11, 12]. Because of first-differencing and the one-month lag, connectedness measures are available from the second transformed observation onward.

Let $\Psi_{0,t} = \mathbf{I}$ and $\Psi_{h,t} = \mathbf{A}_{1,t}^h$ for $h = 1, \dots, H$. The (unnormalized) generalized FEVD share is computed as

$$\theta_{ij,t}(H) = \frac{\frac{1}{\sigma_{jj,t}} \sum_{h=0}^{H} \left(\mathbf{e}_i' \Psi_{h,t} \mathbf{\Sigma}_t \mathbf{e}_j\right)^2}{\sum_{h=0}^{H} \mathbf{e}_i' \Psi_{h,t} \mathbf{\Sigma}_t \Psi_{h,t}' \mathbf{e}_i}, \qquad \sigma_{jj,t} = (\mathbf{\Sigma}_t)_{jj}, \tag{6}$$

and we then row-normalize to enforce

$$\tilde{\theta}_{ij,t}(H) = \frac{\theta_{ij,t}(H)}{\sum_{m=1}^{N} \theta_{im,t}(H)}, \qquad \sum_{j=1}^{N} \tilde{\theta}_{ij,t}(H) = 1 \quad \forall i, t.$$

The Total Connectedness Index (TCI) is

$$\mathrm{TCI}_t = \frac{1}{N} \sum_{i \neq j} \tilde{\theta}_{ij,t}(H). \tag{7}$$

Directional connectedness measures (scaled as in the implementation) are

$$C_{i,t}^{\mathrm{TO}} = \frac{1}{N} \sum_{j \neq i} \tilde{\theta}_{ji,t}(H), \qquad C_{i,t}^{\mathrm{FROM}} = \frac{1}{N} \sum_{j \neq i} \tilde{\theta}_{ij,t}(H), \tag{8}$$

and net connectedness is

$$C_{i,t}^{\mathrm{NET}} = C_{i,t}^{\mathrm{TO}} - C_{i,t}^{\mathrm{FROM}}. \tag{9}$$

Time-varying connectedness: results

Figure 4.14 displays the time profile of the Total Connectedness Index (TCI) computed from the RLS-based TVP–VAR with $H = 10$. After a brief warm-up phase due to diffuse initialization, the TCI peaks around mid-2021 at approximately 0.73, then remains elevated through 2022 (average around 0.59), coinciding with major stress episodes such as the Terra/UST event and the FTX collapse. From 2023 onward, interconnectedness gradually declines, reaching about 0.50–0.52 by 2025. Overall, spillovers across DeFi categories strengthen in turbulent periods and weaken as conditions normalize, consistent with state-dependent amplification during systemic stress and a more segmented structure in calmer regimes.

Figures 4.15–4.16 report the directional connectedness indices. Directional "TO" measures the share of forecast error variance transmitted by category i to the others, whereas "FROM" captures the share of forecast error variance of category i attributable to shocks originating in the other categories (both scaled by $1/N$ in line with the implementation). Over most of the sample, DEX are the dominant shock transmitters, with a persistently high "TO" profile, while Lending & Borrowing (LB) is the main net receiver, displaying the largest "FROM" component throughout the period. Service Providers (SVP) show a pronounced decline in transmission over time and absorb a sizeable portion of spillovers when overall connectedness is high, consistent with an infrastructural "shock-absorber" role. Staking (STK) remains comparatively less connected than DEX and LB, with a gradual increase in its transmission component toward the end of the sample.

Finally, Figure 4.17 plots the time-varying coefficient $\beta_{\mathrm{STK}\to\mathrm{LB},t}$, i.e. the lagged effect of staking growth on lending growth within the standardized TVP–VAR. Following a brief initialization-driven

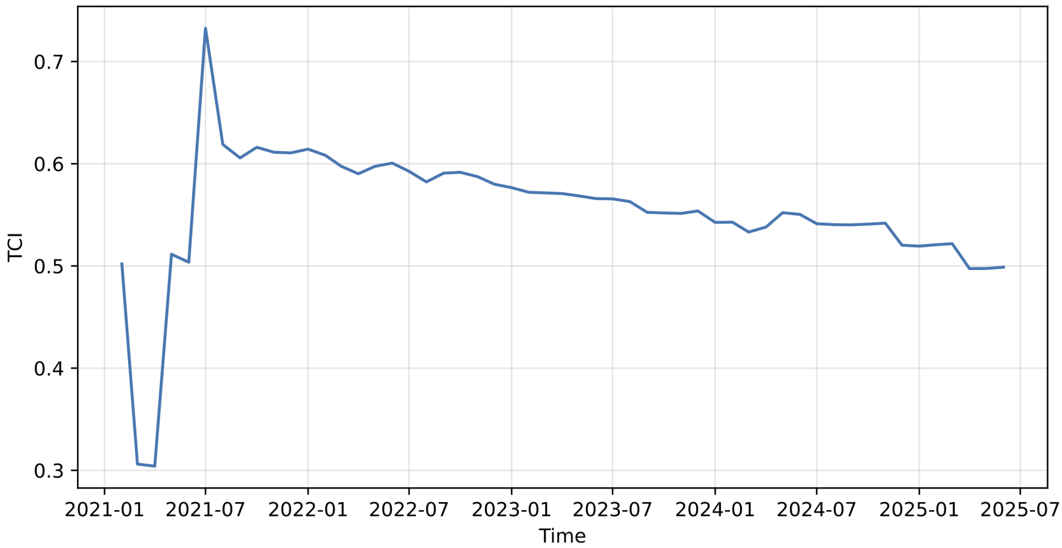


Figure 4.14: Total Connectedness Index (time-varying, $H = 10$). RLS-based TVP–VAR with diffuse initialization $\boldsymbol{\beta}_0 = \mathbf{0}$, $\mathbf{P}_0 = 100\mathbf{I}$, $\boldsymbol{\Sigma}_0 = \mathbf{I}$; baseline $\lambda_\beta = 0.98$, $\lambda_\Sigma = 0.97$.

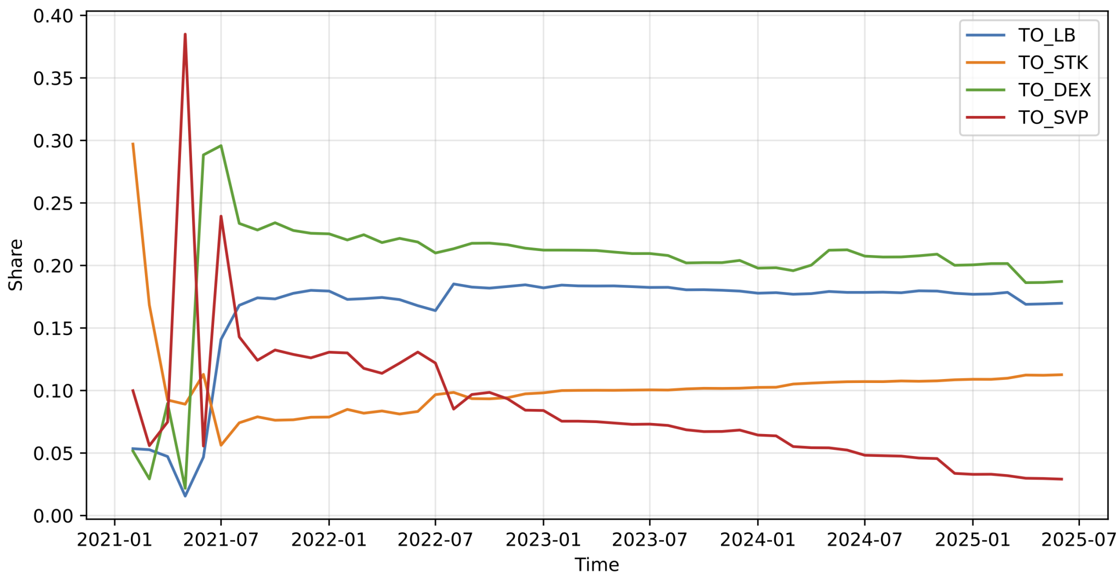


Figure 4.15: Directional connectedness — TO others (time-varying, $H = 10$). Notes: diffuse initialization $\boldsymbol{\beta}_0 = \mathbf{0}$, $\mathbf{P}_0 = 100\mathbf{I}$, $\boldsymbol{\Sigma}_0 = \mathbf{I}$; baseline $\lambda_\beta = 0.98$, $\lambda_\Sigma = 0.97$.

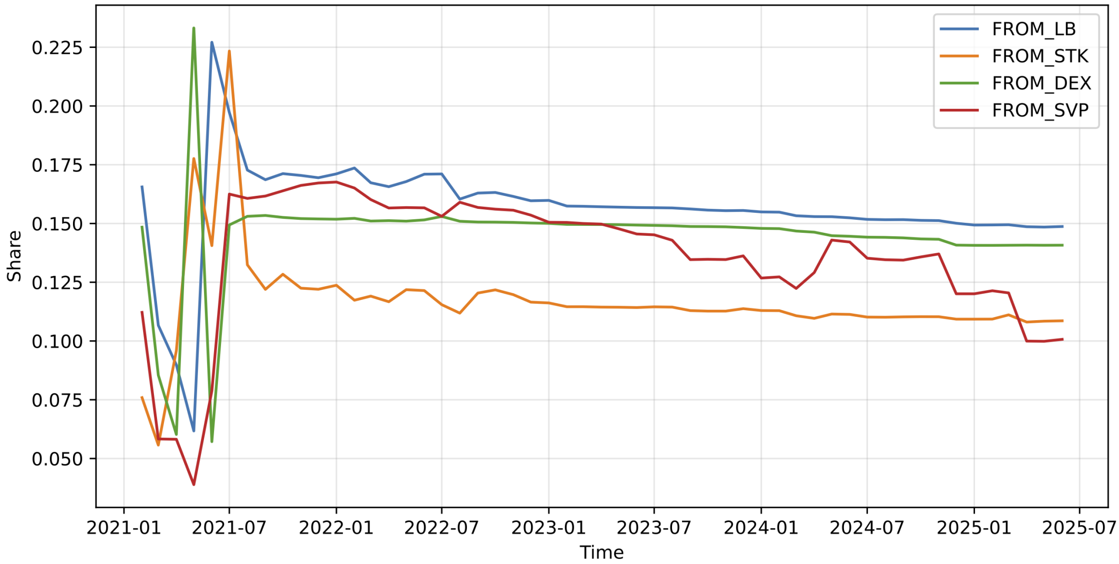


Figure 4.16: Directional connectedness — FROM others (time-varying, $H = 10$). Notes: diffuse initialization $\boldsymbol{\beta}_0 = \mathbf{0}$, $\mathbf{P}_0 = 100\mathbf{I}$, $\boldsymbol{\Sigma}_0 = \mathbf{I}$; baseline $\lambda_\beta = 0.98$, $\lambda_\Sigma = 0.97$.

adjustment early in the sample, the coefficient is predominantly positive and exhibits a steady upward drift from 2022 onward, reaching values close to one by 2024–2025. This pattern suggests that increases in staking activity tend to precede expansions in lending, with an intensity that strengthens over time.

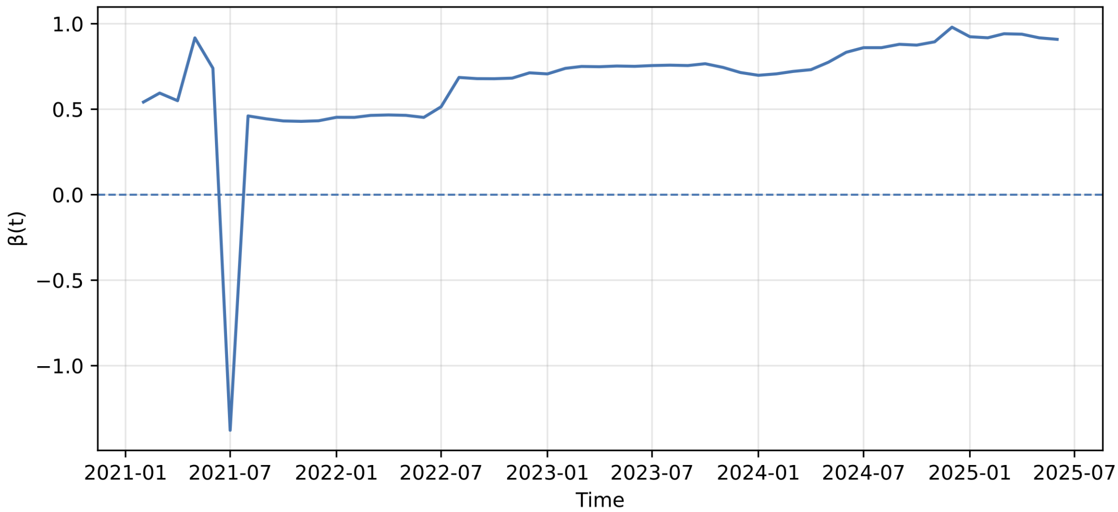


Figure 4.17: Time-varying coefficient $\beta_{\mathrm{STK}\to\mathrm{LB},t}$ from the RLS-based TVP–VAR. Notes: diffuse initialization $\boldsymbol{\beta}_0 = \mathbf{0}$, $\mathbf{P}_0 = 100\mathbf{I}$, $\boldsymbol{\Sigma}_0 = \mathbf{I}$; baseline $\lambda_\beta = 0.98$, $\lambda_\Sigma = 0.97$.

4.5.5 Robustness Checks

In order to determine whether the baseline VAR(1) is statistically adequate and that the main findings are not driven by misspecification, small-sample artefacts, or scale-induced elasticities, we ran a set of robustness checks. Multivariate portmanteau tests for residual autocorrelation up to lag 12 fail to reject the null of whiteness ($\chi^2 = 179.0 < 207.9$, $p = 0.42$), and all companion roots lie inside the unit circle, indicating dynamic adequacy at the monthly frequency. Because lagged DeFi categories are moderately to highly correlated (pairwise ρ up to 0.87; VIF up to ≈ 5.1), we additionally re-estimate the VAR on standardized (z-score) series to control for cross-series variance differences. The negative effect from LB to STK survives this transformation but with a reduced magnitude (≈ -0.40 vs. -0.93 in raw $\Delta \log$ TVL), confirming that the sign is robust while part of the baseline elasticity is scale-driven. Full results are reported in Appendix B.

Tests of conditional heteroskedasticity using multivariate ARCH–LM statistics do not indicate significant second-moment dependence for any category (LB $p = 0.27$; STK $p = 0.19$; DEX $p = 0.59$; SVP $p = 0.62$). Residual normality is weakly rejected in some equations, especially for STK ($p = 0.04$) and marginally for LB ($p = 0.08$), due to slight right-skewness and excess kurtosis (around 3.7 on average). These departures appear moderate and consistent with heavy-tailed DeFi processes; accordingly, IRFs and FEVDs are computed using 1,000 wild-bootstrap replications[5].

System stability is further assessed using recursive-residual CUSUM and CUSUMSQ tests, as well as Chow tests around major events such as the Terra/UST collapse (May 2022) and the FTX insolvency (November 2022). The recursive-residual statistics remain within the 95% confidence bands throughout. Chow test F-statistics range from 0.6 to 2.3 and do not indicate statistically significant breaks at conventional levels for any series (e.g., LB $p = 0.06$; STK $p = 0.43$; DEX $p = 0.26$; SVP $p = 0.28$).

Furthermore, extending the lag order to a VAR(2) yields no qualitative differences in impulse responses or variance decompositions. Granger-causality and block-exogeneity tests corroborate the key relationships in the baseline specification: STK activity Granger-causes both LB and DEX at the 1% level, while SVP exhibits limited causal influence. Taken together, these diagnostics indicate that the baseline VAR(1) is statistically sound, dynamically stable, and robust to alternative specifications. Residuals are approximately white and homoskedastic, the model remains stable through major market disruptions, and the leading role of staking activity in transmitting shocks across the DeFi ecosystem is consistently supported by both static and dynamic evidence.

Building on these constant-parameter checks, we assess whether the time-varying connectedness results are robust to the adaptive TVP–VAR's smoothing and forecasting choices. The adaptive TVP–VAR is estimated by recursive least squares with exponential forgetting for the coefficients and an EWMA-type update for the innovation covariance matrix. In line with the online nature of the algorithm and the diffuse initialization adopted in Section 4.5.4, the EWMA covariance recursion uses one-step-ahead prediction errors.

We re-estimate the model over a grid of parameters $\lambda_\beta \in \{0.96, 0.98, 0.99\}$, $\lambda_\Sigma \in \{0.96, 0.97, 0.99\}$, and horizons $H \in \{8, 10, 12\}$ for the generalized FEVD. Across all 27 combinations, TCI trajectories remain highly correlated with the baseline specification ($\lambda_\beta = 0.98$, $\lambda_\Sigma = 0.97$, $H = 10$), with pairwise correlations typically above ≈ 0.97. Sample-wide average TCI levels under alternative parameterizations vary moderately (roughly in the 0.49–0.58 range), while the timing of the main peaks—including the 2021 boom and the 2022 Terra/UST and FTX episodes—remains essentially unchanged.

Finally, we verify that the qualitative connectedness patterns are not driven by the diffuse prior scale by varying $\kappa \in \{10, 100, 1000\}$ in the initialization $\mathbf{P}_0 = \kappa \mathbf{I}$. While the overall level of TCI shifts with κ, the cyclical profile and the main stress-period peaks remain qualitatively similar.

4.6 Discussion and Implications

This section synthesises the descriptive and econometric evidence into a coherent view of how the main functional layers of DeFi move, interact, and transmit shocks. The data consistently portray a tightly connected yet hierarchical system in which short-run co-movements are strong but not uniform across categories, and where linkages intensify in periods of market stress.

A first message emerges from the cross-sectional and time-varying correlations. The Pearson matrix based on monthly TVL (Figure 4.4) reveals a dense core formed by LB, STK, and DEX, with

[5] Wild bootstrap procedures are employed to mitigate small-sample distortions and conditional heteroskedasticity that are typical of crypto and DeFi time series, thereby yielding more reliable inference for impulse response functions and forecast-error variance decompositions.

SVP comparatively more idiosyncratic. That structure is not static: rolling correlations fluctuate substantially across the sample, and the 12-month rolling coefficient of variation (Figure 4.5) peaks during 2021–2022 before converging lower. Together, these patterns indicate state-dependent interdependence: when market conditions tighten, correlations compress and relative volatility rises; in calmer phases the system partially segments and idiosyncratic dynamics re-emerge.

The STL decomposition (Figure 4.10) clarifies the sources of persistence and cyclicality. All categories exhibit pronounced trend components, but the strength and regularity of recurring movements differ markedly. Staking and Service Providers show the largest STL oscillations, though formal tests detect no fixed calendar-type seasonality (Appendix A), suggesting that these cycles are protocol- or incentive-driven rather than calendar-based. Residual components align with salient events (deleveraging waves in 2022; incentive-driven inflows in 2024–2025), suggesting that shocks are episodic rather than continuous. Correlograms (Figure 4.11) corroborate this reading: ACFs are high and slowly decaying at levels, while PACFs concentrate at low lags, implying that once stationarity is imposed the short-run law of motion is parsimonious. Formal tests confirm the modelling choice. On log levels, ADF fails to reject a unit root, whereas KPSS tends to reject stationarity; Johansen's trace and max-eigen statistics do not exceed the 5% critical values for any rank (e.g., for $r \leq 0$, trace = 43.81 vs. 47.85; max-eigen = 20.59 vs. 27.59). Estimating a VAR in first log-differences is therefore appropriate to study short-run interdependencies without an error-correction term.

Within that framework, a clear hierarchy emerges. The baseline monthly VAR(1) on $\Delta \log$ TVL over 2020–2025 is dynamically well-specified (all roots inside the unit circle; portmanteau $p \approx 0.42$). Across equations, staking is the most systematic short-run driver: the coefficient on lagged STK $(t-1)$ loads significantly in lending, exchanges, and services. Orthogonalized impulse responses over a 10-month horizon (Figure 4.12) show sizeable impact effects that dissipate within 3–4 months, as expected with stationary growth rates. A one-standard-deviation staking shock precedes increases in lending, trading activity, and infrastructure with lags of one to two months; in contrast, lending shocks feed back into staking and DEX with smaller amplitudes and faster mean reversion than the reverse; DEX shocks are transient and partly negative for staking and services, consistent with short-lived liquidity/volatility bursts that normalise quickly; service-layer shocks mostly remain internal. The forecast-error variance decomposition (Figure 4.13) quantifies the hierarchy. After nine months, lending's uncertainty is $\approx 91\%$ self-driven with a non-trivial $\approx 9\%$ component from staking; the uncertainty of staking is largely explained by lending shocks ($\approx 62\%$) despite high own persistence; DEX variance is strongly tied to lending ($\approx 65\%$) and only mildly to staking; the service layer remains mostly idiosyncratic ($\approx 74\%$ own). These magnitudes are economically meaningful: they imply that the credit/leverage cycle is the principal short-run source of forecast uncertainty for both staking and trading, while staking innovations act as broad positive transmitters in expansions. This distinction between impulse responses and forecast-error variance is important: staking innovations are the main positive transmitter in terms of average responses, whereas lending shocks dominate the decomposition of forecast uncertainty.

Allowing for time variation in parameters and shock covariances confirms and nuances this picture. The TVP–VAR delivers a Total Connectedness Index that peaks in mid-2021 and again throughout 2022, precisely when the crypto market faced systemic stress, and then declines toward 2025 (Figure 4.14). In high-connectedness regimes, DEX emerges as the dominant transmitter and lending as the principal receiver, consistent with liquidity–volatility spirals and collateral constraints; in tranquil regimes, the structural influence of staking reasserts itself, with expansions in staking preceding measured increases in credit and utilisation of infrastructure. This regime dependence reconciles the strong average co-movement in the Pearson matrix with the episodic divergences seen in rolling statistics.

The combined evidence is consistent with three economic mechanisms. First, a leverage–collateral channel: increases in staking and collateral valuation relax borrowing capacity, feeding a subsequent expansion in lending and, via market-making and arbitrage, into DEX activity. The significant coefficient on lagged STK $(t-1)$ in the lending equation, together with IRFs showing positive responses of LB and DEX to shocks in STK, speaks directly to this mechanism. Second, incentive- and composability-driven cycles: reward programmes, (re)staking and governance epochs generate seasonal-looking inflows into staking and short-lived liquidity migrations across categories; this explains the marked cyclicality in STK, the transience of DEX shocks, and the spikes in the rolling coefficient of variation around incentive-heavy periods. Third, plumbing and inertia in infrastructure: SVP exhibits an almost monotonic trend with limited outward spillovers, absorbing shocks rather than propagating them, consistent with middleware and oracle services whose adoption is gradual and whose TVL is only weakly sensitive to short-horizon risk appetite.

From a risk-management and policy perspective, these results call for state-contingent monitoring. The combination of (i) the Total Connectedness Index, (ii) rolling CV, and (iii) category-level drawdowns provides a practical early-warning dashboard: simultaneous spikes in connectedness and relative volatility identify phases when shocks are likely to propagate quickly and widely. Because the FEVD attributes most uncertainty in STK and DEX to lending shocks, stress testing should prioritise the credit channel: scenarios with collateral haircuts, oracle outages, abrupt changes in incentive schedules, or liquidity withdrawals from money markets are likely to produce the largest system-wide effects. At the protocol-design margin, our short-run responses favour circuit breakers, withdrawal throttling, dynamic collateral factors, and oracle redundancy, particularly in periods when the TCI approaches previous extremes. For investors, the message is that intra-DeFi diversification is fragile in crises: diversification benefits exist in calm regimes but attenuate rapidly as connectedness rises; liquidity management and hedging become paramount precisely when they are hardest to implement.

Several limitations temper the interpretation. The sample is short and shock-intensive (2020–2025); cointegration tests may have limited power, and some parameters may be regime-specific. TVL measured in USD conflates price and quantity; where feasible, future work should separate token-denominated TVL from valuation effects. Category-level aggregation hides intra-category heterogeneity (e.g., AMMs vs. order-book DEX; over- vs. under-collateralized lending). The VAR is linear and symmetric by construction, whereas crypto markets often display non-linearities and asymmetries (liquidation cascades, kinked liquidity curves). Finally, the analysis is deliberately endogenous: we do not include exogenous drivers such as BTC/ETH returns or volatility; part of the common component we attribute to within-DeFi linkages may reflect broader crypto-market conditions.

These caveats shape the research agenda. Extending the framework to VARX or TVP–VARX with crypto-market covariates would help distinguish internal spillovers from market-wide shocks. Regime-switching VARs could formalise crisis vs. calm states and capture asymmetries to positive vs. negative innovations. Higher-frequency data on TVL flows (or flow proxies) would allow for lead–lag analysis across categories and a closer link to DEX microstructure. Finally, moving from categories to protocol-level networks and computing FEVD-based spillover matrices would enable exposure maps and centrality rankings that are more actionable for systemic-risk oversight.

4.7 Conclusions

We document a tightly connected yet hierarchical DeFi stack in which short-run interdependencies are strong and state-dependent. Staking innovations act as broad positive transmitters, lending governs forecast uncertainty and mediates stress, DEX transmits primarily in turbulent regimes, and the infrastructure layer is comparatively inward-driven.

Allowing for time variation through an adaptive, RLS-based TVP–VAR suggests that interdependence itself is cyclical. Generalized FEVD-based connectedness indices peak during the mid-2021 boom and the 2022 Terra/UST and FTX crises, and decline thereafter, indicating that the DeFi stack becomes more tightly coupled precisely when the system is under stress. In high-connectedness regimes, DEX acts as the most frequent net transmitter and Lending & Borrowing as the main receiver of shocks, while in calmer periods staking retains a leading role and the infrastructure layer remains comparatively inward-driven. We view these time-varying measures as a local linear approximation to the evolution of intra-DeFi linkages in a short, shock-intensive sample, rather than as a fully structural account of regime changes.

Methodologically, the paper proposes a replicable pipeline: STL decomposition, a parsimonious VAR(1) on $\Delta \log$ TVL with wild-bootstrap IRFs and FEVDs, and an adaptive TVP–VAR with generalized FEVD-based connectedness measures, which can be applied to other short monthly panels in decentralized finance. At the same time, the analysis is deliberately endogenous: our system includes only DeFi category-level TVL and omits external crypto-market and macro-financial drivers. Extending the framework to VARX/TVP–VARX with market-wide covariates is therefore a natural next step to better disentangle intra-DeFi spillovers from common external shocks.

A Appendix A

A.1 STL seasonal amplitude (as % of mean TVL)

Table A.1: STL seasonal amplitude as a percentage of mean TVL

Category	STL seasonal amplitude (% of mean TVL)
Staking Entities	230.17*
Service Providers	182.59*
Asset Managers	116.47
Miscellaneous	63.41
Lending & Borrowing Providers	59.40
Decentralised Exchanges (DEX)	51.26
Decentralised Stablecoin Issuers	41.82

* For staking and service providers the STL-based amplitude exceeds 100% of the mean. This reflects the short, shock-intensive sample (2021–2025) and the presence of protocol-level incentive waves (e.g. restaking campaigns) that STL partly attributes to the seasonal component rather than pure calendar seasonality.

A.2 Seasonality tests (OLS with monthly dummies)

Table A.2: Tests for monthly seasonality

Category	F-stat	p-value
Service Providers	0.31	0.9814
Decentralised Stablecoin Issuers	0.26	0.9898
Asset Managers	0.18	0.9982
Lending & Borrowing Providers	0.16	0.9991
Miscellaneous	0.15	0.9993
Decentralised Exchanges (DEX)	0.10	0.9999
Staking Entities	0.05	0.999997

Notes: The null hypothesis of no monthly seasonality cannot be rejected for any category (all $p \gg 0.10$).

A.3 Multicollinearity diagnostics (VAR(1) regressors)

Table A.3: Multicollinearity diagnostics

Lagged regressor	Highest pairwise correlation	VIF
L1. Lending & Borrowing (LB)	corr(L1.DEX, L1.LB) = 0.87	5.09
L1. Exchanges (DEX)	corr(L1.LB, L1.DEX) = 0.87	4.14
L1. Staking Entities (STK)	corr(L1.LB, L1.STK) = 0.75	2.62
L1. Service Providers (SVP)	–	1.41

A.4 Cumulative impulse response functions

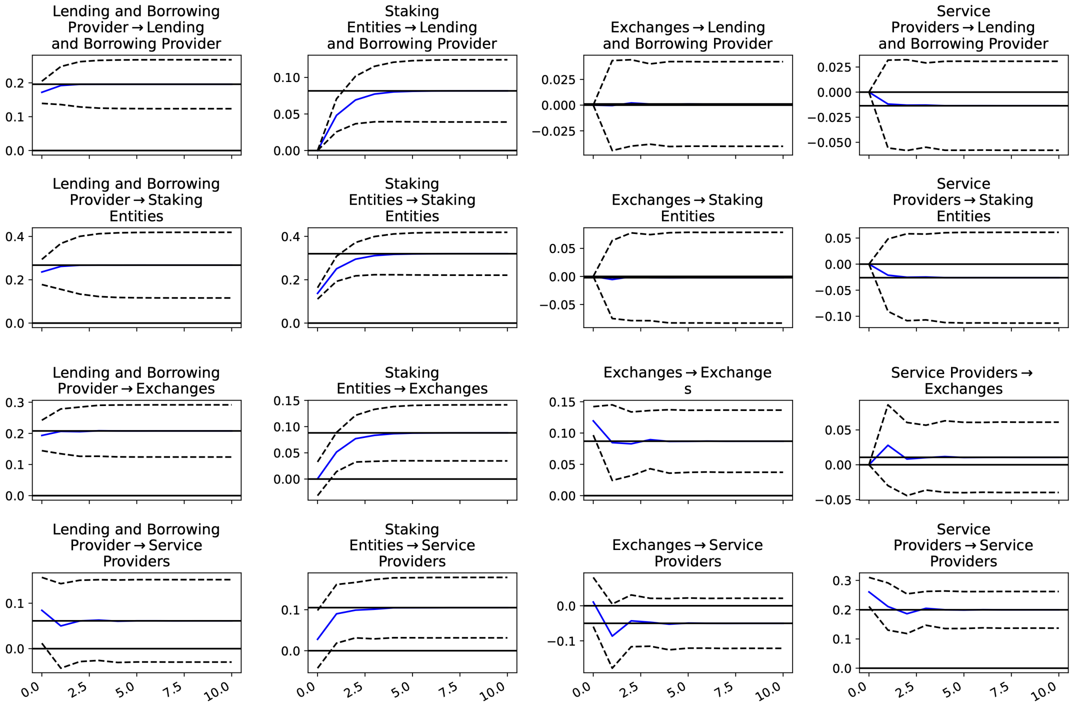


Figure A.1: Cumulative impulse response functions from the baseline VAR(1).

A.5 Impulse response robustness: generalized IRFs and alternative Cholesky orderings

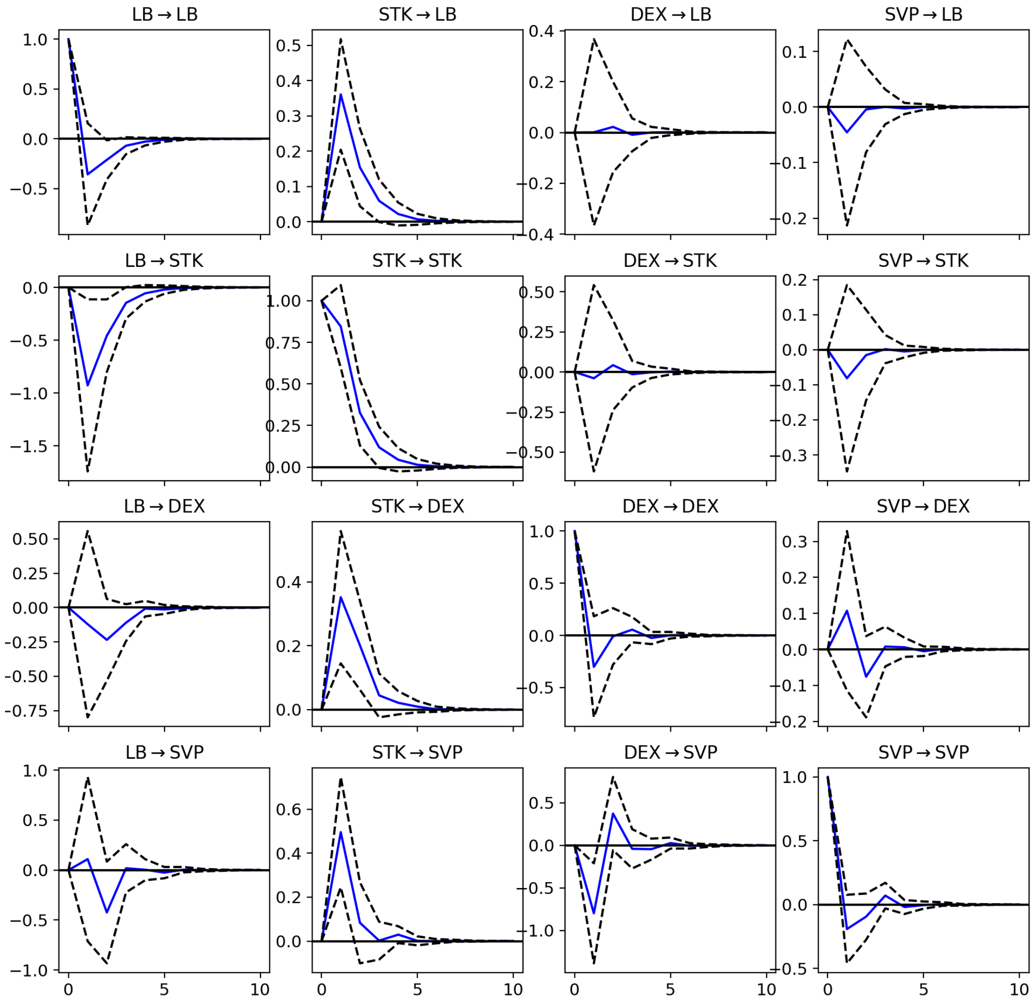


Figure A.2: Generalized impulse response functions (Pesaran–Shin). Responses are invariant to variable ordering.

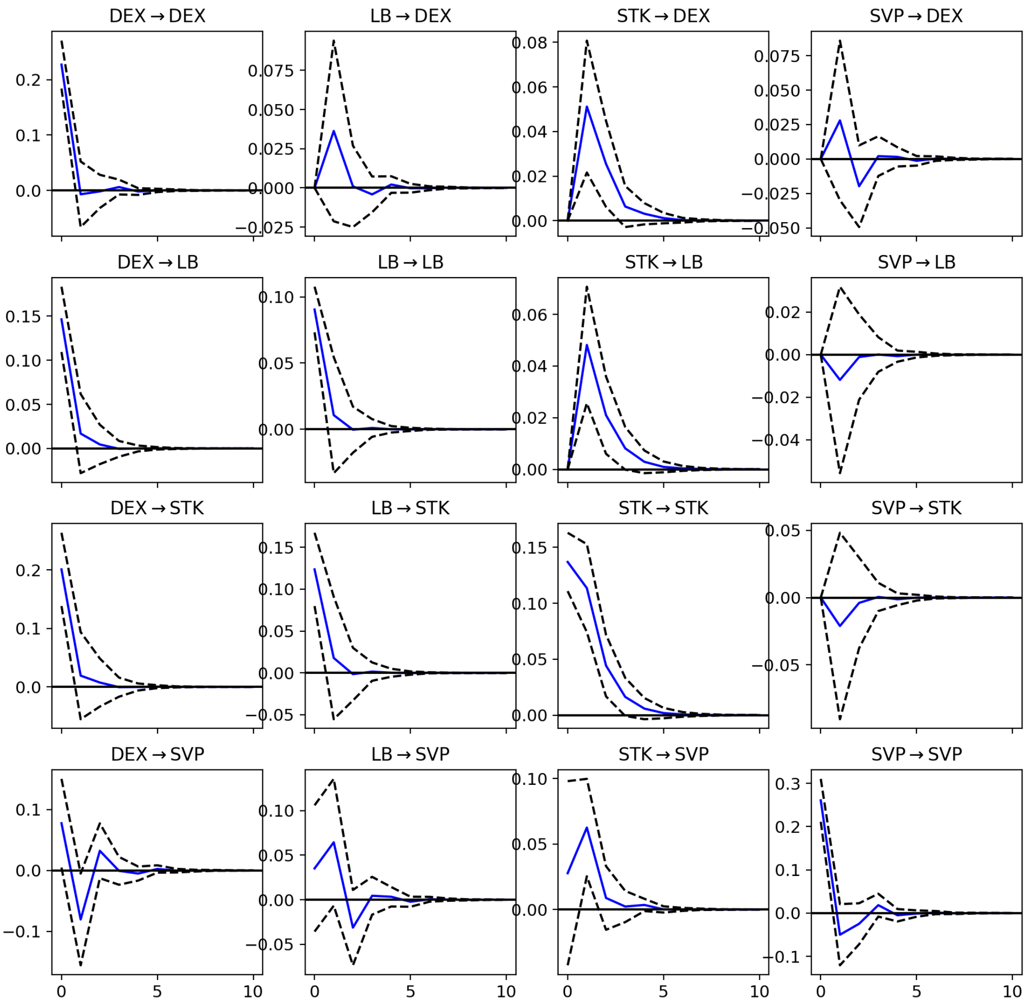


Figure A.3: Orthogonalized impulse responses under Cholesky ordering: [DEX, LB, STK, SVP].

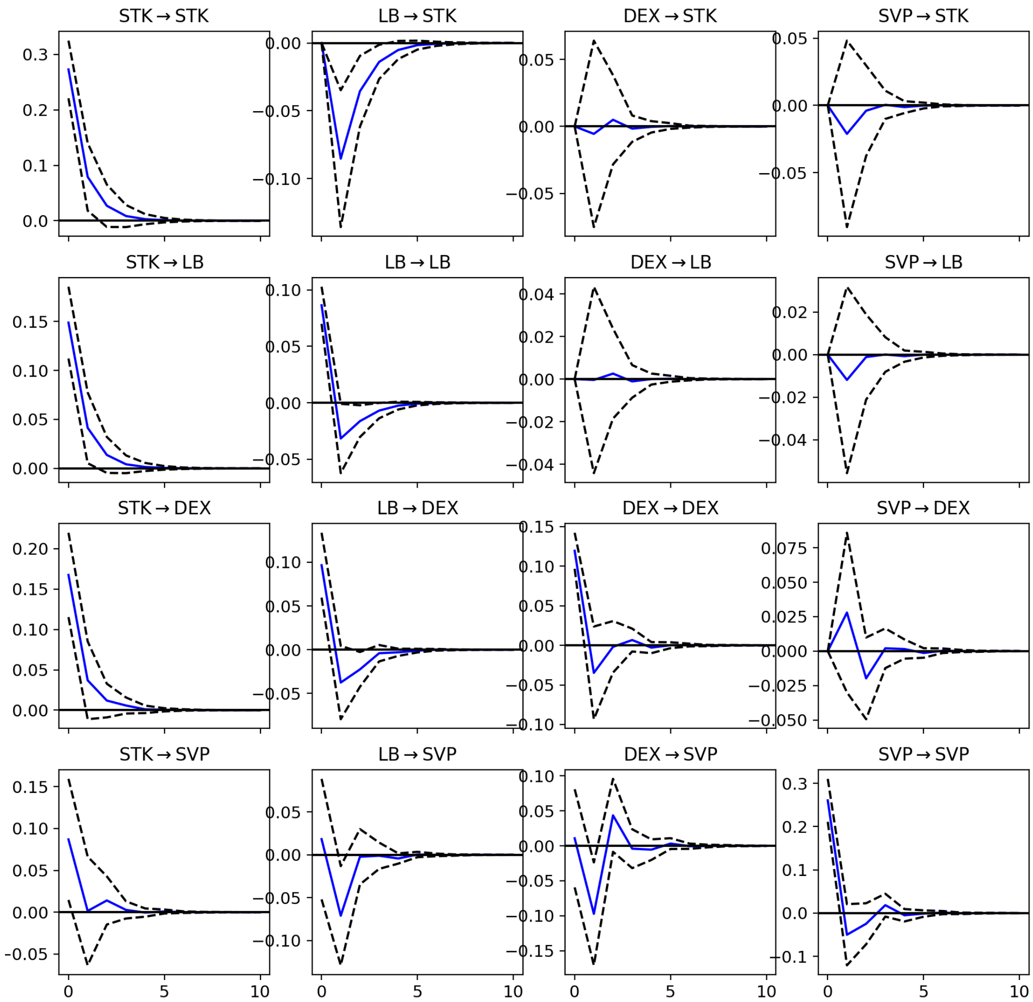


Figure A.4: Orthogonalized impulse responses under Cholesky ordering: [STK, LB, DEX, SVP].

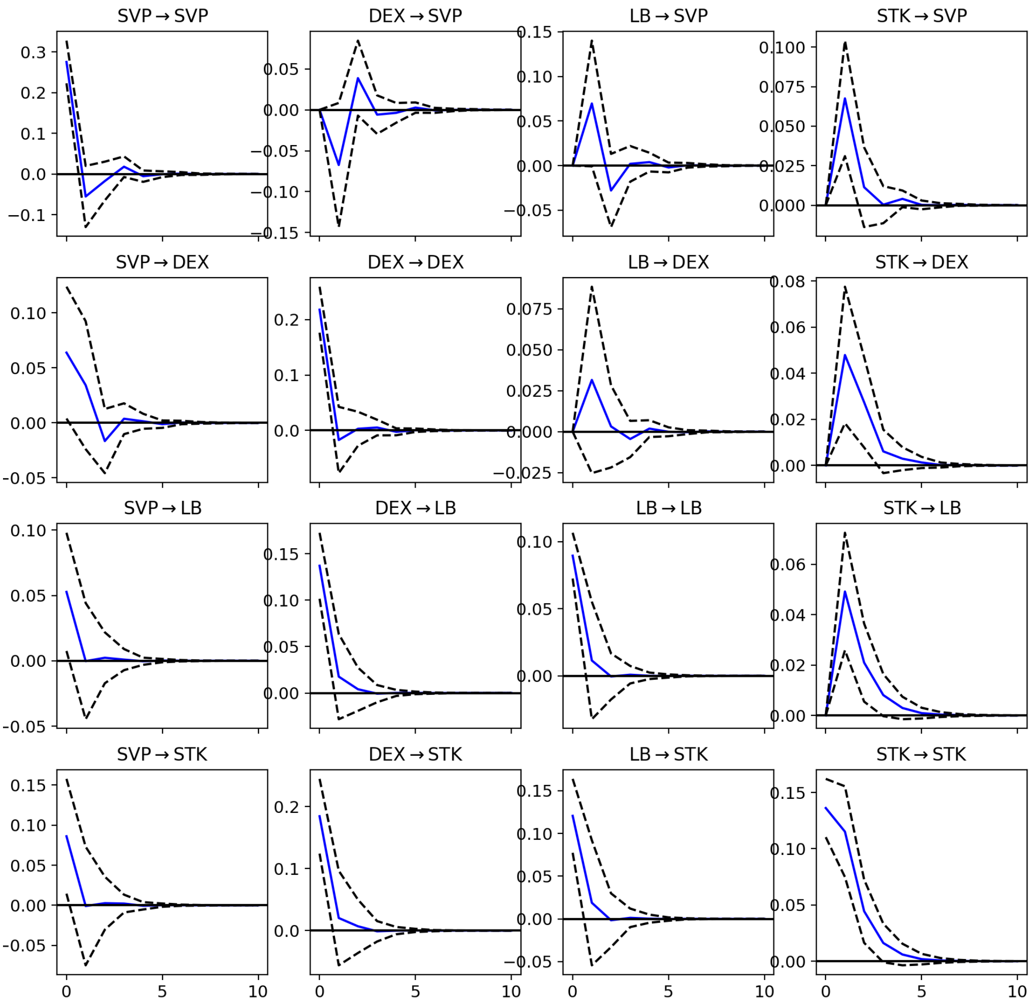


Figure A.5: Orthogonalized impulse responses under Cholesky ordering: [SVP, DEX, LB, STK].

A.6 Forecast error variance decomposition (FEVD)

Baseline VAR(1), monthly $\Delta \log$ TVL, Dec 2020 – Jun 2025

Panel A — FEVD of Lending & Borrowing

Table A.4: FEVD of Lending & Borrowing

Horizon	LB	STK	DEX	SVP
0	1.0000	0.0000	0.0000	0.0000
1	0.9242	0.0715	0.0000	0.0043
2	0.9117	0.0838	0.0002	0.0043
3	0.9098	0.0856	0.0002	0.0043
9	0.9095	0.0859	0.0002	0.0043

Notes: 9-month share: 90.9% own | 8.6% STK | ≈ 0% DEX | 0.4% SVP.

Panel B — FEVD of Staking Entities

Table A.5: FEVD of Staking Entities

Horizon	LB	STK	DEX	SVP
0	0.7481	0.2519	0.0000	0.0000
1	0.6369	0.3577	0.0003	0.0051
2	0.6229	0.3713	0.0006	0.0051
9	0.6208	0.3734	0.0006	0.0051

Notes: 9-month share: 62.1% LB | 37.3% own | ≈ 0% DEX/SVP.

Panel C — FEVD of Decentralised Exchanges (DEX)

Table A.6: FEVD of Decentralised Exchanges (DEX)

Horizon	LB	STK	DEX	SVP
0	0.7237	0.0000	0.2763	0.0000
1	0.6655	0.0462	0.2744	0.0139
2	0.6535	0.0566	0.2695	0.0205
9	0.6522	0.0574	0.2698	0.0206

Notes: 9-month share: 65.2% LB | 5.7% STK | 27.0% own | 2.1% SVP.

Panel D — FEVD of Service Providers (SVP)

Table A.7: FEVD of Service Providers (SVP)

Horizon	LB	STK	DEX	SVP
0	0.0938	0.0102	0.0015	0.8945
1	0.0893	0.0499	0.1031	0.7576
2	0.0881	0.0494	0.1201	0.7425
9	0.0878	0.0493	0.1201	0.7428

Notes: 9-month share: 8.8% LB | 4.9% STK | 12.0% DEX | 74.3% own.

B Appendix B — Additional econometric tests and outputs

Table B.1: Unit root tests on TVL series (levels and log-differences)

Category	ADF p-val (Levels)	KPSS p-val (Levels)	ADF p-val ($\Delta \log$)	KPSS p-val ($\Delta \log$)
Lending & Borrowing	0.163	0.090	0.0000	0.098
Staking Entities	0.705	0.052	0.0000	0.030
Exchanges (DEX)	0.254	0.100	0.0004	0.086
Service Providers	0.871	0.100	0.0000	0.021

Table B.2: Johansen cointegration test (levels, 4 core categories)

$r \leq$	Trace stat	Trace 5% crit	Max-eig stat	Max-eig 5% crit
0	43.81	47.85	20.59	27.59
1	23.22	29.80	13.14	21.13
2	10.09	15.49	9.45	14.26
3	0.63	3.84	0.63	3.84

Table B.3: Baseline VAR(1) estimation results (monthly $\Delta \log$ TVL)

Regressor	LB	STK	DEX	SVP
Const	0.005 (0.026)	0.043 (0.042)	-0.040 (0.035)	0.036 (0.042)
L1.Lending & Borrowing	-0.357 (0.262)	-0.928 (0.415)**	-0.121 (0.346)	0.110 (0.419)
L1.Staking	0.361 (0.080)***	0.846 (0.127)***	0.352 (0.106)***	0.496 (0.128)***
L1.Exchanges	0.001 (0.187)	-0.039 (0.297)	-0.301 (0.247)	-0.798 (0.300)***
L1.Service Providers	-0.045 (0.086)	-0.081 (0.136)	0.107 (0.113)	-0.191 (0.137)
R^2	0.49	0.68	0.41	0.53
Adj. R^2	0.42	0.63	0.34	0.45
F-statistic (p-val)	4.9 (0.002)	10.7 (< 0.001)	3.7 (0.012)	6.1 (0.001)

Notes: Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table B.4: Baseline vs standardized VAR coefficients

Dependent	Regressor	Baseline	Standardized	p-value
STK_t	LB_{t-1}	-0.93	-0.40	0.026
LB_t	STK_{t-1}	$+0.36$	$+0.85$	0.000
DEX_t	STK_{t-1}	$+0.35$	$+0.65$	0.001
SVP_t	STK_{t-1}	$+0.50$	$+0.72$	< 0.001
SVP_t	DEX_{t-1}	-0.80	-0.63	0.008

Table B.5: Residual serial correlation (multivariate Ljung–Box / Portmanteau test)

Lag (h)	Test statistic	5% critical value	p-value	Decision (5%)
6	82.54	95.75	0.613	Fail to reject H_0
12	179.02	207.96	0.422	Fail to reject H_0

Null hypothesis: no residual autocorrelation up to the given lag.

Table B.6: Correlation matrix of VAR(1) residuals

	LB	STK	DEX	SVP
Lending & Borrowing (LB)	1.000	0.865	0.851	0.306
Staking (STK)	0.865	1.000	0.737	0.316
Exchanges (DEX)	0.851	0.737	1.000	0.281
Service Providers (SVP)	0.306	0.316	0.281	1.000

Table B.7: Residual normality and heteroskedasticity tests

Test	Statistic	*p*-value	Decision (5%)
Jarque–Bera (multivariate)	6.84	0.335	Fail to reject normality
Doornik–Hansen	8.92	0.258	Fail to reject normality
ARCH–LM (lag 6)	54.70	0.472	Fail to reject heteroskedasticity

Table B.8: Pairwise Granger causality tests (sorted by *p*-value)

Caused	Causing	F-stat	*p*-value
Lending & Borrowing Providers	Staking Entities	20.37	0.0000
Service Providers	Staking Entities	14.99	0.0001
Exchanges (DEX)	Staking Entities	11.10	0.0010
Service Providers	Exchanges (DEX)	7.09	0.0084
Staking Entities	Lending & Borrowing Providers	4.99	0.0267
Exchanges (DEX)	Service Providers	0.90	0.3429
Staking Entities	Service Providers	0.36	0.5499
Lending & Borrowing Providers	Service Providers	0.28	0.5954
Exchanges (DEX)	Lending & Borrowing Providers	0.12	0.7269
Service Providers	Lending & Borrowing Providers	0.07	0.7936
Staking Entities	Exchanges (DEX)	0.02	0.8957
Lending & Borrowing Providers	Exchanges (DEX)	0.00	0.9974

Null hypothesis: the causing variable does not Granger-cause the caused variable.

B.1 FEVD VAR(2)

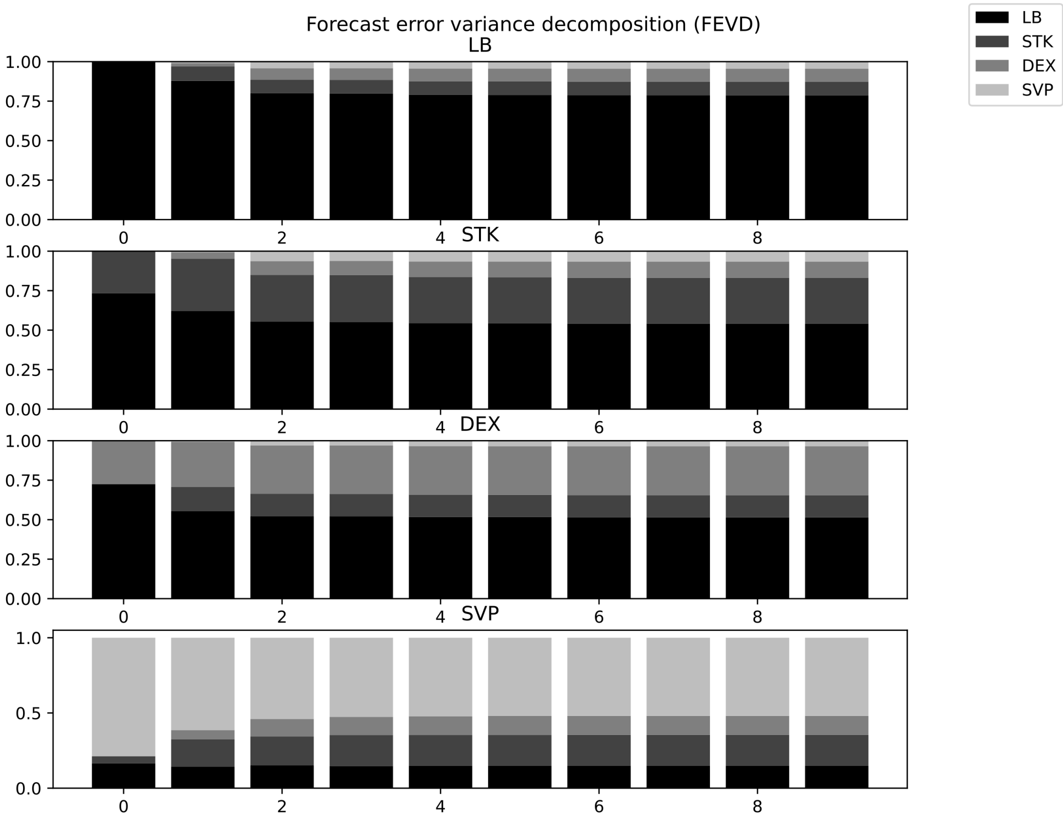


Figure B.1: Forecast error variance decomposition from VAR(2).

B.2 IRF VAR(2)

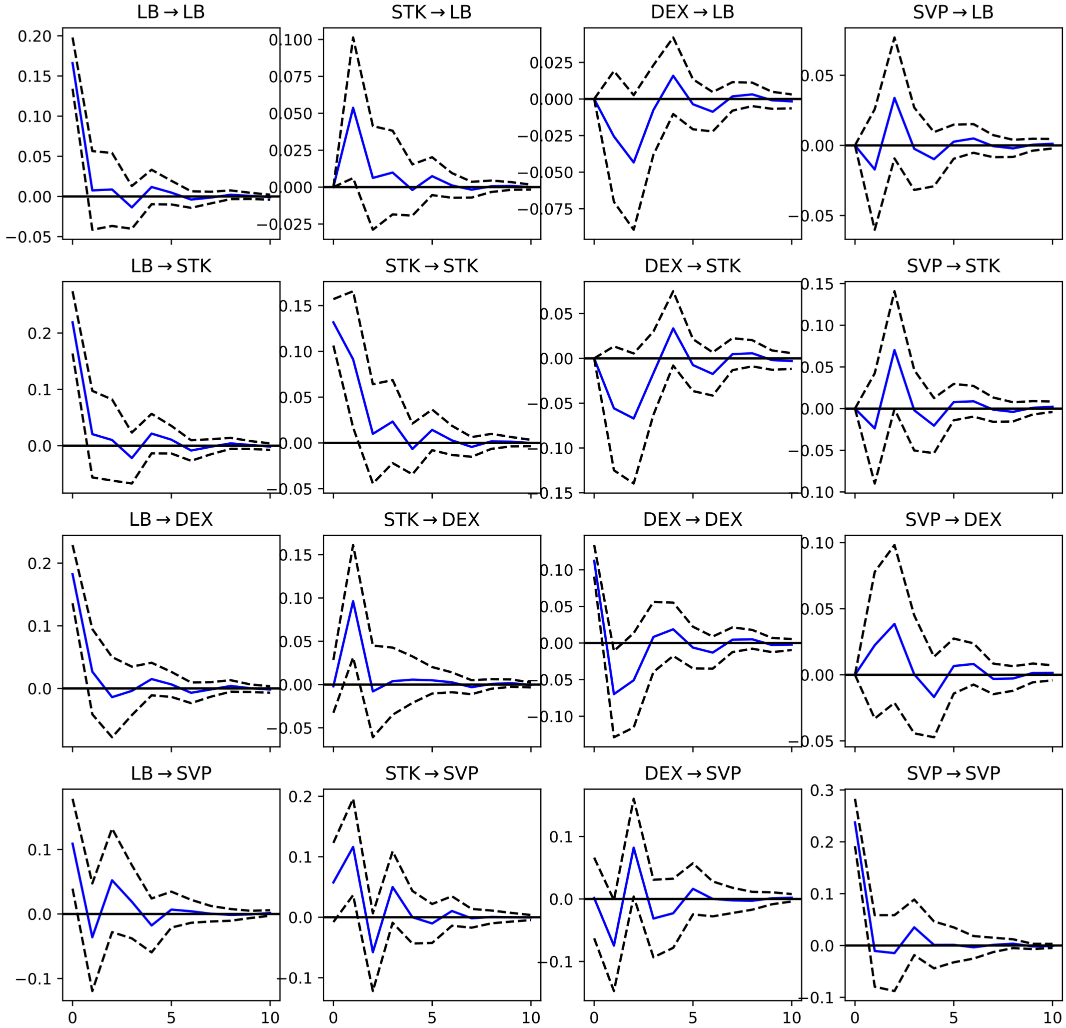


Figure B.2: Impulse response functions from VAR(2).

Chapter 5

USD Stablecoins, Monetary Substitution, and Policy Transmission in Small Open Economies

Abstract

USD-pegged stablecoins have expanded access to dollar-denominated liquidity outside domestic banking systems, raising questions about their implications for domestic money demand and monetary policy transmission in small open economies. This paper develops a portfolio model in which households allocate liquidity between domestic money and a USD stablecoin. The model highlights two core mechanisms: monetary substitution, through which tokenized dollars displace domestic liquid balances, and monetary-policy leakage, through which access to a foreign-currency liquidity substitute weakens the response of domestic money demand to local policy conditions. The framework emphasizes features specific to USD stablecoins, including low-friction access, cross-border transferability, and reduced reliance on traditional banking channels. The paper then presents cross-country evidence on the monetary margin. Using a monthly panel for 24 countries over 2018–2025, we estimate local projections of M1 growth on the interaction between changes in global stablecoin capitalization and a country-level indicator of relatively high retail crypto exposure. The results show a negative dynamic response of M1 growth in high-exposure economies at several horizons, consistent with the model's monetary-substitution channel. Taken together, the findings suggest that USD stablecoins can already affect domestic monetary conditions even if broader forms of dollarization remain limited. The main empirical support for the model emerges on the monetary margin: greater stablecoin-market expansion is associated with weaker subsequent M1 growth in relatively high-exposure economies. These results point to the importance of improved measurement, monitoring, and policy design aimed at preserving domestic monetary transmission as tokenized dollar use expands.

Keywords: USD-pegged stablecoins; Monetary substitution; Monetary policy transmission; Small open economies; Money demand; Local projections

5.1 Introduction

USD-pegged stablecoins have evolved from instruments used primarily within crypto markets into increasingly accessible vehicles for holding and transferring U.S. dollar value across borders.[1] Their appeal is especially evident in small open economies, where residents may seek dollar liquidity outside domestic banking systems for savings, transfers, or portfolio reallocation. Unlike conventional bank-based dollar assets, USD stablecoins combine low-friction access, near-continuous transferability, and interoperability with digital platforms, making them a distinctive form of foreign-currency liquidity. At the same time, they remain privately issued claims subject to credit, liquidity, and regulatory risk rather than risk-free public money.

These developments raise a narrower but economically important question for non-U.S. economies. If households can reallocate part of their liquid balances into tokenized dollars at relatively low cost,

[1] In this chapter, USD-pegged stablecoins refers to fiat-backed, reserve-based tokens that aim to maintain par convertibility into U.S. dollar assets.

how does this affect domestic money demand and the transmission of monetary policy? In financially dollarized settings, the availability of foreign-currency liquid assets can already weaken monetary control by reducing the stability of money demand and increasing the sensitivity of portfolios to external conditions. USD stablecoins may intensify these pressures by making foreign-currency liquidity easier to access outside traditional banking channels. Their potential relevance therefore lies less in a broad claim about full "digital dollarization" and more in the possibility that they alter the composition of liquid portfolios and weaken the link between domestic policy rates and domestic money holdings.

This paper studies these issues in the context of small open economies. Its focus is intentionally narrower than a full theory of dollarization in domestic transactions, goods pricing, or credit denomination. Rather than modelling all dimensions of foreign-currency use, the paper isolates the monetary margin: how access to USD stablecoins changes liquid-portfolio allocation between domestic money and tokenized dollars, and how this reallocation may attenuate the response of domestic money demand to local monetary-policy conditions. This narrower focus is both analytically tractable and closely aligned with the type of macroeconomic evidence that can currently be brought to the data.

The paper builds on three related strands of literature. First, it connects to the literature on financial dollarization and currency substitution, where foreign-currency assets serve as hedges against inflation and exchange-rate risk and can weaken domestic monetary control. Second, it relates to work on global digital currencies and currency competition, which shows that access to an external liquidity instrument can constrain domestic policy autonomy. Third, it contributes to the growing literature on stablecoins, which has mostly emphasized peg stability, reserve management, run risk, and interactions with crypto and money markets. What remains less developed is a tractable portfolio framework tailored specifically to USD stablecoins in small open economies and focused on domestic money demand and policy transmission.

Our analysis is motivated by the idea that USD stablecoins are not simply another label for offshore dollars. Relative to traditional bank-based dollar instruments, they can offer faster access, lower transfer frictions, and weaker reliance on domestic banking intermediaries. These features make them potentially relevant even when the use of foreign-currency deposits or other conventional dollar instruments is constrained by cost, limited access, or regulatory frictions. The relevant question is therefore not whether stablecoins have already displaced domestic currencies across all dimensions of economic activity, but whether they are beginning to matter along the monetary margin that is most directly connected to money demand and policy transmission.

The paper makes three contributions. First, it develops a minimal portfolio model in which households allocate liquidity between domestic money and a USD stablecoin. The model delivers two central mechanisms. The first is monetary substitution: as the relative attractiveness of the stablecoin rises, households shift liquid balances away from domestic money. The second is monetary-policy leakage: because a close foreign-currency liquidity substitute is available, changes in the domestic policy rate have a weaker effect on domestic money demand than in an otherwise comparable economy without stablecoins. The framework also clarifies what is specific about USD stablecoins in this context, namely low-friction access, cross-border transferability, and reduced reliance on traditional banking channels.

Second, the paper brings the model to the data on the monetary margin. Using a monthly panel of 24 countries over 2018–2025, we estimate local projections of M1 growth on the interaction between changes in global stablecoin capitalization and a country-level indicator of relatively high retail crypto/stablecoin exposure. The exposure measure is not a direct observation of resident stablecoin holdings or flows; rather, it is a ranking-based proxy for relative cross-country exposure intensity in retail centralized crypto channels, where stablecoin usage is more likely to be salient. Within this framework, the local-projection estimates reveal a negative dynamic response of M1 growth in relatively higher-exposure economies at several horizons. This pattern is consistent with the monetary-substitution mechanism highlighted by the model.

Third, the paper draws policy implications from this combination of theory and evidence. The results do not imply that broad forms of dollarization through stablecoins are already fully developed. They do suggest, however, that tokenized dollars may already begin to shape domestic monetary conditions in more exposed economies. This points to the importance of better measurement of resident exposure to stablecoins, closer monitoring of their monetary relevance, and policy design aimed at preserving domestic monetary transmission as private dollar-based digital instruments continue to expand.

The rest of the paper is organized as follows. Section 2 reviews the related literature and outlines the paper's monetary focus. Section 3 presents the portfolio model and derives the implications for domestic money demand and monetary policy transmission. Section 4 provides cross-country evidence on the monetary margin using local projections of M1 growth. Section 5 discusses policy implications for monitoring, measurement, and domestic monetary resilience. Section 6 concludes.

5.2 Literature Review

One strand of the literature treats stablecoins as privately issued monetary instruments and studies the institutional mechanisms that support, and sometimes destabilize, their peg. Lyons and Viswanath-Natraj [7] show how arbitrage and reserve management help maintain the peg of leading USD stablecoins, while Gorton and Zhang [176] interpret stablecoins as privately issued money-like claims that remain exposed to credit and liquidity risk. Recent empirical work further documents the importance of reserve structure, market-making frictions, and run dynamics for stablecoin stability (Ma et al. [177]; Ahmed et al. [178]). We take these institutional and market-structure features as given and focus on a more specific question: how access to USD-pegged stablecoins as foreign-currency liquidity instruments affects domestic money demand and monetary-policy transmission in small open economies.

A closely related literature studies financial dollarization and currency substitution. Ize and Levy Yeyati [6] show how foreign-currency assets arise as hedges against inflation and exchange-rate risk, while Levy Yeyati [179] emphasizes that dollarization weakens the stability of money demand and constrains domestic monetary control. USD-pegged stablecoins fit naturally into this tradition as foreign-currency-denominated liquid claims that can be accessed globally at low cost. Our framework extends the portfolio logic of financial dollarization to a setting in which the foreign-currency asset is a tokenized private dollar that competes directly with domestic money in household liquidity portfolios.

A further literature examines competition between national currencies and globally accessible digital currencies. Benigno et al. [13] show that the availability of an external digital currency can constrain domestic monetary autonomy. This perspective is useful here, but our paper takes a more targeted view: rather than modelling a general currency-competition environment, we study USD-pegged stablecoins as a specific foreign-currency liquidity instrument and examine how their availability modifies domestic money demand and policy transmission in small open economies.

Recent contributions also examine stablecoins and foreign digital money in emerging and developing economies. Empirical and theoretical work suggests that adoption tends to be higher where inflation is elevated, exchange restrictions are tighter, or trust in domestic financial institutions is weaker. Murakami and Viswanath-Natraj [180], in particular, develop a small-open-economy framework in which foreign stablecoins can improve risk sharing but also weaken monetary control under fragile domestic conditions. Aldasoro et al. [181] further show that stablecoin capitalization responds distinctively to monetary and crypto-specific shocks. These contributions show that stablecoins may matter for open-economy monetary conditions, but they often focus on welfare, crypto-market dynamics, or mechanisms other than domestic money demand. Our contribution is more focused: we develop a tractable portfolio framework centered on monetary substitution and monetary-policy leakage, and relate these mechanisms to cross-country evidence on the monetary margin.

A related policy-oriented literature studies central bank digital currencies and tokenized bank money as domestic digital alternatives. Andolfatto [182] shows that a well-designed interest-bearing CBDC need not crowd out bank lending, while Agur et al. [183] analyze how CBDC design affects money holdings and financial intermediation. Ferrari Minesso et al. [184] extend the discussion to open-economy spillovers. This literature is relevant for our discussion of policy implications, because domestic digital monetary instruments may help preserve monetary transmission if private dollar-based instruments become more widely used. In this paper, however, these issues remain secondary to the central question of how USD stablecoins affect domestic money demand and policy transmission.

Taken together, the literature points to two monetary mechanisms through which USD stablecoins may matter in small open economies. First, they can induce monetary substitution by providing a foreign-currency liquidity instrument that competes directly with domestic money in household portfolios. Second, they can generate monetary-policy leakage by weakening the response of domestic money demand to local policy conditions when a close dollar liquidity substitute is readily available. Other macro-financial channels may also exist, but they lie outside the core monetary focus of this paper. Section 3 formalizes these two mechanisms in a tractable portfolio model of liquidity allocation between domestic money and a USD stablecoin, and Section 4 examines whether they leave a detectable footprint in cross-country evidence on the monetary margin.

5.3 A Minimal Theoretical Model

Our theoretical framework builds on the portfolio approach to financial dollarization of Ize and Levy Yeyati [6], in which residents allocate liquid portfolios across currencies to hedge domestic monetary and exchange-rate risk. We adapt this logic to a setting where the foreign-currency liquid asset is a USD-pegged stablecoin with distinct access frictions and usage costs, and we embed it in a small-open-economy environment to study monetary-policy transmission and currency substitution (Benigno et al. 2022).

This section develops a small open economy model in which agents choose between domestic money and a USD-pegged stablecoin as alternative sources of liquidity. The objective is not to capture all institutional details or all dimensions of dollarization, but to obtain transparent conditions under which: (i) USD-backed stablecoins gain a positive share in liquid portfolios, (ii) this share responds to interest differentials, access and usage costs, and (iii) the presence of stablecoins weakens domestic money demand and attenuates the effectiveness of local monetary policy. The resulting predictions guide the empirical analysis in Section 4.

5.3.1 Environment

Consider a small open economy populated by a representative household that lives in discrete time and discounts the future at factor $\beta \in (0, 1)$. In each period t, the household chooses consumption C_t and real holdings of two liquid assets: (i) domestic money M_t, issued by the local central bank; (ii) USD-pegged stablecoins S_t, issued abroad and redeemable at par against U.S. dollar reserves.

Let P_t be the domestic price level and e_t the nominal exchange rate (domestic currency per U.S. dollar). We define real balances as:

$$m_t \equiv \frac{M_t}{P_t}$$

$$s_t \equiv \frac{e_t S_t}{P_t}$$

Both assets provide liquidity services that facilitate transactions. Domestic money is frictionless within the local monetary system. USD stablecoins provide foreign-currency liquidity that is transferable across borders, but their attractiveness depends on two reduced-form features. The first is an access and credibility parameter $\varphi_t \in (0, 1]$, which captures the effective usability of the stablecoin, combining ease of access, on- and off-ramping conditions, perceived peg credibility, and the ability to acquire, transfer, and redeem balances across platforms and jurisdictions. The second is a per-unit cost $\kappa \geq 0$, which summarizes the effective cost of holding and using stablecoins, including transaction fees, conversion frictions, operational inconvenience, and regulatory impediments[2].

[2] Formally, φ_t and κ capture a reduced-form composite of technological, regulatory and institutional frictions. They can be micro-founded as the outcome of fixed participation costs and per-transaction fees in richer models with explicit financial intermediation, which we abstract from here.

Relative to traditional bank-based USD instruments, stablecoins may be associated with a higher effective access parameter (φ_t) and lower effective transaction costs (κ) when they provide cheaper, faster, and more continuous cross-border transferability.[3]

The household derives utility from consumption and liquidity services according to a money-in-utility specification[4]:

$$U = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t [u(C_t) + \psi_M \ln(m_t) + \psi_S \varphi_t \ln(s_t) - \kappa s_t]$$

where $u(\cdot)$ is increasing and concave, $\psi_M > 0$ and $\psi_S > 0$ measure the strength of liquidity services from domestic money and stablecoins respectively. The term φ_t scales the liquidity services provided by stablecoins, while the linear term κs_t captures proportional holding or usage costs.

We work with real variables throughout. Let y_t denote real income. Denote by R_t^E and R_t^U the gross real returns on domestic money and on the USD risk-free asset, respectively. The representative household's real budget constraint is:

$$C_t + m_t + s_t \leq y_t + R_t^E m_{t-1} + (R_t^U - \delta_t) s_{t-1}.$$

where $\delta_t \geq 0$ captures any yield discount between stablecoin reserves and the U.S. risk-free asset, including fees, foregone interest, or spreads.

5.3.2 Portfolio Choice and Monetary Substitution

To isolate the portfolio decision, consider the intratemporal problem of allocating a given amount of real liquidity l_t between domestic money and stablecoins, where $l_t \equiv m_t + s_t$.

Given l_t, the relevant part of period utility is:

$$\Psi(m_t, s_t) = \psi_M \ln(m_t) + \psi_S \varphi_t \ln(s_t) - \kappa s_t,$$

subject to:

$$m_t + s_t = l_t, m_t > 0, s_t > 0.$$

Substituting $m_t = l_t - s_t$, we can write the problem as:

$$\max_{0<s_t<l_t} \psi_M ln(l_t - s_t) + \psi_S \varphi_t ln(s_t) - \kappa s_t.$$

The first-order condition for an interior solution is:

$$-\frac{\psi_M}{l_t - s_t} + \frac{\psi_S \varphi_t}{s_t} - \kappa = 0.$$

Let $\omega_t \equiv s_t / l_t$ denote the stablecoin share in liquid portfolios. Using $s_t = \omega_t l_t$, the first-order condition can be rewritten as:

$$F(\omega_t; \varphi_t, \kappa, l_t) \equiv -\frac{\psi_M}{1 - \omega_t} + \frac{\psi_S \varphi_t}{\omega_t} - \kappa l_t = 0.$$

For given (φ_t, κ, l_t), this equation implicitly defines a unique interior share $\omega_t \in (0, 1)$. We do not need a closed-form solution for ω_t; comparative statics follow directly from this implicit equation.

Proposition 1 (Monetary substitution).
Suppose the interior solution $\omega_t \in (0, 1)$ to

[3]This comparison is only interpretative in the baseline specification, which does not explicitly model bank-based USD instruments. An extension introduced in 3.4 makes this distinction explicit by allowing households to choose among domestic money, traditional bank-based USD assets, and USD stablecoins.

[4]A cash-in-advance or transactions-cost specification would deliver similar portfolio trade-offs under standard assumptions. We adopt a money-in-utility formulation solely for tractability and transparency of the comparative statics.

$$F(\omega_t; \varphi_t, \kappa, l_t) = 0$$

exists and is unique. Then:

$$\frac{\partial \omega_t}{\partial \varphi_t} > 0, \quad \frac{\partial \omega_t}{\partial \kappa} < 0.$$

That is, better access and perceived credibility of stablecoins (higher φ_t) raise their portfolio share, while higher usage costs (higher κ) reduce it.

Sketch of proof. By the implicit function theorem,

$$\frac{\partial \omega_t}{\partial \varphi_t} = -\frac{\partial F/\partial \varphi_t}{\partial F/\partial \omega_t}.$$

Since $\partial F/\partial \varphi_t = \psi_S/\omega_t > 0$ and $\partial F/\partial \omega_t < 0$ for $\omega_t \in (0,1)$, it follows that $\partial \omega_t/\partial \varphi_t > 0$. Analogously,

$$\frac{\partial \omega_t}{\partial \kappa} = -\frac{\partial F/\partial \kappa}{\partial F/\partial \omega_t},$$

and because $\partial F/\partial \kappa = -l_t < 0$, we obtain $\partial \omega_t/\partial \kappa < 0$.

To incorporate the opportunity costs of holding the two assets, define an effective net cost term:

$$\widetilde{\kappa}_t \equiv \kappa - (i_t^U - i_t^E) + \delta_t,$$

We use $\widetilde{\kappa}_t$ as a reduced-form measure of all factors that affect the relative cost of holding stablecoins.[5]

Treating ω_t as a function of $\widetilde{\kappa}_t$, we have $\partial \omega_t/\partial \widetilde{\kappa}_t < 0$. By the chain rule:

$$\frac{\partial \omega_t}{\partial i_t^U} = \frac{\partial \omega_t}{\partial \widetilde{\kappa}_t}\frac{\partial \widetilde{\kappa}_t}{\partial i_t^U} = \frac{\partial \omega_t}{\partial \widetilde{\kappa}_t}(-1) > 0, \quad \frac{\partial \omega_t}{\partial i_t^E} = \frac{\partial \omega_t}{\partial \widetilde{\kappa}_t}\frac{\partial \widetilde{\kappa}_t}{\partial i_t^E} = \frac{\partial \omega_t}{\partial \widetilde{\kappa}_t}(1) < 0.$$

Thus, an increase in i_t^U – interpreted as an improvement in the relative attractiveness of USD safe assets – raises the stablecoin share, while a higher domestic rate i_t^E has the opposite effect. This provides a simple formalization of monetary substitution: when stablecoins become more attractive in effective cost terms, residents allocate a larger fraction of their liquid portfolios to tokenized dollars, and the demand for domestic money falls relative to a given liquidity need l_t.

5.3.3 Monetary Policy Leakage

Aggregate real money demand can be written as:

$$m_t = (1 - \omega_t)\, l_t,$$

where l_t is the desired real liquidity and ω_t is the stablecoin share implicitly defined by the portfolio condition in Section 3.2.

In a standard setting without a stablecoin alternative, real money demand is simply $m_t = l_t(i_t^E)$, a decreasing function of the domestic policy interest rate i_t^E: raising the policy interest rate increases the opportunity cost of holding money and reduces desired liquidity. With a USD-pegged stablecoin,

[5] In the spirit of Ize and Levy Yeyati [6], we interpret i_t^U and i_t^E as reduced-form indices of the attractiveness of short-term safe assets in USD and in domestic currency. In addition to policy interest rates, they proxy expected real returns and perceived safety, including expected exchange-rate movements and inflation risk. The term δ_t captures fees and the extent to which the interest on reserves is not passed through to stablecoin holders, so that i_t^U - δ_t can be read as the effective return associated with holding tokenized dollars relative to domestic money. In current markets, most fiat-backed stablecoins do not explicitly remunerate end users, so in practice δ_t may absorb a large part of i_t^U. The comparative statics with respect to i_t^U should therefore be interpreted more broadly as capturing changes in the relative attractiveness of USD-denominated safe assets, including environments in which residents value stablecoins primarily as a store of value or inflation hedge rather than as an explicitly interest-bearing instrument.

the response of m_t to the domestic rate has two components: a change in total desired liquidity and a reallocation between domestic money and stablecoins.

Differentiating $m_t = (1-\omega_t)l_t$ with respect to the domestic policy interest rate i_t^E gives:

$$\frac{\partial m_t}{\partial i_t^E} = (1-\omega_t)\frac{\partial l_t}{\partial i_t^E} - l_t\frac{\partial \omega_t}{\partial i_t^E}$$

The first term,

$$(1-\omega_t)\ \partial l_t/\partial i_t^E,$$

is the conventional channel: higher policy interest rates reduce desired liquidity, so $\partial l_t/\partial i_t^E < 0$. The second term,

$$-l_t\ \partial \omega_t/\partial i_t^E,$$

captures portfolio reallocation between domestic money and stablecoins. From Section 3.2 we know that higher domestic rates increase the effective cost of holding stablecoins, so $\partial \omega_t/\partial i_t^E < 0$. Hence:

$$-l_t\frac{\partial \omega_t}{\partial i_t^E} > 0.$$

This term partially offsets the standard contraction in money demand: when the domestic policy interest rate rises, agents both reduce total liquidity (standard effect) and shift part of their liquid balances from stablecoins back into domestic money (offsetting effect).

Proposition 2 (Monetary policy leakage).
Suppose that desired liquidity is decreasing in the domestic policy interest rate, $\partial l_t/\partial i_t^E < 0$, and that the stablecoin share responds negatively to the domestic rate, $\partial \omega_t/\partial i_t^E < 0$, as implied by the effective-cost formulation in Section 3.2. Then the response of domestic money demand to a change in the policy interest rate can be decomposed as:

$$\frac{\partial m_t}{\partial i_t^E} = (1-\omega_t)\frac{\partial l_t}{\partial i_t^E} - l_t\frac{\partial \omega_t}{\partial i_t^E}$$

where the second term is positive and reflects portfolio reallocation from stablecoins into domestic money. Relative to an otherwise identical economy without stablecoins, where $m_t = l_t(i_t^E)$ and

$$\frac{\partial m_t}{\partial i_t^E} = \frac{\partial l_t}{\partial i_t^E},$$

the presence of a stablecoin alternative introduces an offsetting component that attenuates the contraction of domestic money for a given change in i_t^E. In many empirically relevant configurations this leads to a smaller semi-elasticity of m_t with respect to i_t^E.

The proposition provides a decomposition rather than a full ranking of elasticities, which would require additional structure on $l_t(i_t^E)$. The key point is that, in the presence of a close USD substitute, policy-induced changes in the opportunity cost of liquidity are absorbed not only through changes in total liquid balances, but also through shifts between domestic money and stablecoins. This is the "monetary policy leakage" channel.

The same logic implies a stronger role for foreign monetary conditions. Real money demand can also be differentiated with respect to the U.S. short-term rate i_t^U:

$$\frac{\partial m_t}{\partial i_t^U} = (1-\omega_t)\frac{\partial l_t}{\partial i_t^U} - l_t\frac{\partial \omega_t}{\partial i_t^U}$$

If desired liquidity l_t reacts only weakly to foreign rates, the main effect of i_t^U on m_t operates through the stablecoin share ω_t. Since higher U.S. rates increase the attractiveness of USD stablecoins (lower effective cost), we have $\partial \omega_t/\partial i_t^U > 0$ and therefore:

$$\frac{\partial m_t}{\partial i_t^U} \approx -l_t\frac{\partial \omega_t}{\partial i_t^U} < 0.$$

Domestic money demand becomes more sensitive to U.S. monetary conditions and stablecoin-specific shocks, and less tightly linked to the domestic policy interest rate. This is the core of the policy-leakage mechanism emphasized in the empirical and policy sections of the paper.

5.3.4 Stablecoins versus Bank-Based USD Assets

The core model above treats USD-pegged stablecoins as the only foreign-currency liquid asset. In practice, residents of small open economies also have access to more traditional USD instruments, such as offshore bank deposits or bank-mediated USD accounts. This section extends the framework to distinguish between bank-based USD assets, which are subject to capital controls and banking frictions, and tokenized USD stablecoins, which typically offer 24/7 access and lower transaction costs. The goal is to show, in a simple way, that stablecoins naturally become a circumvention channel when capital controls and banking frictions make traditional USD assets expensive or difficult to use.

We focus on the allocation within foreign-currency liquidity and abstract from domestic money in this subsection. Let s_t denote real holdings of USD-pegged stablecoins and b_t real holdings of bank-based USD assets, such as offshore deposits or foreign-currency accounts. Total real liquidity in USD-denominated instruments is therefore given by

$$f_t \equiv s_t + b_t.$$

Stablecoins deliver liquidity services that are more easily transferable and accessible at high frequency. We capture this with a higher effective access parameter φ_t^S (e.g. 24/7 availability, integration with global platforms, and ease of on/off-ramping) and a lower per-unit usage cost κ_S. Bank-based USD assets provide liquidity as well, but access is mediated by the banking channel and domestic regulations, captured by a lower access parameter φ_t^B (e.g. banking hours, documentation requirements, and operational frictions) and a higher per-unit cost κ_B. In addition, bank USD assets are subject to capital controls. We capture these frictions through an additional proportional cost $\tau_c \geq 0$ that applies to holdings of bank USD and summarizes taxes, administrative restrictions, or delays on cross-border movements; in reduced form, τ_c raises the effective cost of using bank-based USD relative to stablecoins.

To isolate the portfolio choice between s_t and b_t, consider the following within-USD liquidity subproblem. Conditional on a given level of USD liquidity f_t, the relevant part of period utility is

$$\Psi_F(s_t, b_t) = \psi_S \varphi_t^S \ln(s_t) + \psi_B \varphi_t^B \ln(b_t) - \kappa_S s_t - (\kappa_B + \tau_c) b_t,$$

subject to

$$s_t + b_t = f_t, \qquad s_t > 0, \qquad b_t > 0.$$

Substituting $b_t = f_t - s_t$, the problem becomes

$$\max_{0 < s_t < f_t} \ \psi_S \varphi_t^S \ln(s_t) + \psi_B \varphi_t^B \ln(f_t - s_t) - \kappa_S s_t - (\kappa_B + \tau_c)(f_t - s_t).$$

The first-order condition for an interior solution is

$$\frac{\psi_S \varphi_t^S}{s_t} - \frac{\psi_B \varphi_t^B}{f_t - s_t} - \kappa_S + (\kappa_B + \tau_c) = 0.$$

Define the stablecoin share in USD liquidity as

$$\omega_t^S \equiv \frac{s_t}{f_t}, \qquad s_t = \omega_t^S f_t, \qquad b_t = (1 - \omega_t^S) f_t.$$

Using this, the first-order condition can be rewritten as

$$G(\omega_t^S; \varphi_t^S, \varphi_t^B, \kappa_S, \kappa_B, \tau_c, f_t) \equiv \frac{\psi_S \varphi_t^S}{\omega_t^S f_t} - \frac{\psi_B \varphi_t^B}{(1 - \omega_t^S) f_t} - \kappa_S + (\kappa_B + \tau_c) = 0.$$

For given $(\varphi_t^S, \varphi_t^B, \kappa_S, \kappa_B, \tau_c, f_t)$, this equation implicitly defines a unique interior share $\omega_t^S \in (0,1)$. Under standard regularity conditions, the stablecoin share among USD assets is increasing in the intensity of capital controls on bank-based USD (a higher τ_c), and it is higher when stablecoins enjoy a greater access and cost advantage over bank USD (higher φ_t^S, lower κ_S, lower φ_t^B, and higher κ_B). These comparative statics follow directly from the first-order condition and the implicit function theorem. A formal derivation is provided in Appendix B.

Intuitively, tightening restrictions on the banking channel increases the effective cost of holding and moving bank-based USD, reallocating USD liquidity toward tokenized dollars. This mechanism provides a stablecoin-specific channel through which digital dollarization can accelerate even when formal controls are in place: as τ_c rises, the composition of foreign-currency portfolios shifts in favour of stablecoins.

In the empirical sections, this motivates focusing on economies where both capital-account frictions and stablecoin usage are high, and where tightening of banking or FX regulations is likely to redirect flows toward tokenized USD rather than toward traditional bank-based instruments. The model is deliberately stylised and is meant to organize mechanisms rather than to deliver quantitative predictions.

5.4 Empirical Evidence

This section examines whether the monetary mechanisms highlighted by the model leave a detectable footprint in cross-country macroeconomic data. The focus is on the monetary margin: if USD stablecoins act as a foreign-currency liquidity substitute, stablecoin-market expansion should be associated with weaker subsequent domestic money growth in relatively more exposed economies. To study this dynamic relationship, we use local projections on a monthly panel of 24 countries over 2018–2025. The empirical analysis is designed to capture differential dynamic responses rather than fully identified causal effects.

Before presenting the empirical strategy, it is worth noting that the theoretical mechanisms in Section 3 are particularly relevant for the economies in our sample with relatively high stablecoin adoption, many of which are characterized by elevated inflation, currency depreciation risk, or restricted access to formal dollar intermediation. In these contexts, the relative attractiveness of USD stablecoins is likely driven primarily by their role as a store of value and inflation hedge rather than by explicit yield remuneration, consistent with the broader interpretation of i_t^U as an index of USD asset attractiveness that rises whenever domestic monetary conditions deteriorate.

5.4.1 Empirical Strategy and Data

The empirical analysis is based on a monthly macro panel used to examine the dynamic relationship between global USD stablecoin capitalization and domestic narrow money (M1) dynamics in economies with relatively high stablecoin exposure. The identification approach exploits variation across countries in their degree of retail crypto and stablecoin adoption, combined with time variation in global stablecoin market capitalization, to estimate the differential dynamic response of M1 growth in high-exposure economies following stablecoin-market expansions.

The panel covers March 2018 to October 2025. We start from a universe of 30 countries and classify them into two groups based on the *Chainalysis Global Crypto Adoption Index 2025*[6], using the retail centralized services sub-index as a proxy for non-professional crypto and stablecoin activity.[7] The *high-usage* group consists of the 15 highest-ranked countries in our selection frame,

[6]The Chainalysis Global Crypto Adoption Index 2025, including the retail centralized services sub-index used here, is publicly available at: `https://www.chainalysis.com/blog/2025-global-crypto-adoption-index/`. The index covers 151 countries and is constructed from estimated transaction volumes across different types of crypto services, weighted by population size and purchasing power parity. It is the most comprehensive cross-country ranking currently available for this purpose.

[7]The retail centralized services sub-index is used rather than the overall index or the institutional sub-index because it specifically captures non-professional, individual cryptocurrency activity (transactions below USD 10,000) which is more directly relevant to the household portfolio reallocation mechanism modelled in Section 3.

while the *low-usage* group consists of 15 countries from the lower part of the ranking. The full country list is reported in Appendix Table A1. While the Chainalysis index is not a direct measure of resident stablecoin holdings or flows — it captures relative adoption intensity in retail centralized channels and may under-represent OTC or informal activity — it provides the most comprehensive cross-country ranking currently available and is used here as a ranking-based proxy for relative exposure intensity. This proxy is nonetheless informative because stablecoins are deeply embedded in the broader crypto ecosystem: USDT and USDC alone recorded a combined trading volume of USD 23 trillion in 2024, a 90 percent increase relative to 2023[8], with stablecoins accounting for approximately 30 percent of all on-chain crypto transaction volume as of mid-2025[9]. Countries with higher retail crypto activity therefore tend to have systematically greater exposure to stablecoin flows, making the Chainalysis ranking a reasonable, if imperfect, basis for grouping economies by stablecoin exposure intensity. In robustness checks, we replace the binary high/low classification with a continuous adoption score based on the normalised Chainalysis ranking, exclude the Covid-19 period from March 2020 to December 2021, and drop the three most volatile countries in the sample to assess the sensitivity of the results to sample composition.

The main empirical exercise uses local projections rather than a static fixed-effects panel. This choice is motivated by the model's mechanism of monetary substitution, which operates through gradual shifts in the composition of liquid balances: if households adjust portfolios in response to changes in the relative attractiveness of tokenized dollars, the effect on domestic money demand may emerge with lags rather than within the same month. Local projections trace the dynamic response of M1 growth at horizons from zero to twelve months following a stablecoin-market expansion, capturing this gradual adjustment in a way that a contemporaneous specification cannot. Throughout, we interpret the results as evidence on whether economies with relatively higher stablecoin exposure display systematically different dynamic M1 responses when global stablecoin capitalization expands, rather than as fully identified causal effects of stablecoins on money demand.

To be included in the monthly panel, a country must have continuous monthly series for M1, CPI, the main domestic policy interest rate, and the bilateral exchange rate vis-à-vis the USD. This yields a working sample of 24 countries — 12 high-usage and 12 low-usage — listed in Appendix Table A2. M1, CPI and policy interest rates are collected at the country level from Trading Economics and cross-checked against the underlying official sources when needed; exchange-rate series are taken from standard financial data providers.[10]

Global stablecoin adoption is proxied by the logarithm of the aggregate USD market value of major fiat-backed USD stablecoins in circulation (Stablecap).[11]

The key explanatory variable is the monthly change in global stablecoin capitalization, $\Delta \log StableCap_t$, rather than its level. This choice is deliberate: the level of $\log StableCap_t$ grows almost monotonically over the sample period, creating a risk of spurious correlation with any variable that also trends upward. Using the change instead isolates genuine expansions and contractions in global stablecoin markets from the underlying secular trend.

5.4.2 Baseline Local-Projection Specification

This section investigates whether the rise of global USD stablecoin markets is associated with a measurable impact on narrow money in high-usage economies. Building on the portfolio model in Section 3, one would expect that as tokenized dollars become more attractive, residents substitute away from domestic monetary aggregates, leading over time to weaker growth of M1 in countries where stablecoins are more widely used. We assess this hypothesis using local projections, which

Institutional-sized transactions primarily reflect trading and arbitrage activity rather than monetary substitution by resident households.

[8] Adrian, T., Bains, P., Bechara, M., Cerutti, E., et al. (2025), "Understanding Stablecoins", IMF Departmental Paper No. 2025/009

[9] "2025 Crypto Adoption and Stablecoin Usage Report", available at: https://www.trmlabs.com/reports-and-whitepapers/2025-crypto-adoption-and-stablecoin-usage-report.

[10] All variables, sources, and transformations are summarized in Appendix Table A3.

[11] Stablecap is based on publicly available circulating-supply disclosures aggregated into a single historical series.

allow us to trace the dynamic response of M1 growth over time rather than estimating a single contemporaneous association.

We use the monthly macro panel described in Section 4.1, covering March 2018 to October 2025. The working sample includes 24 countries (12 high-usage and 12 low-usage), reported in Appendix Table A2. Variable definitions, sources, and transformations are summarized in Appendix Table A3. The resulting panel is unbalanced and contains 2,061 country–month observations.

The baseline specification follows the local projection approach of Jordà [185]. For each horizon $h = 0, 1, \ldots, 12$, we estimate a separate regression of the form:

$$\Delta \log M1_{i,t+h} = \alpha_i + \tau_t + \beta_h \left(HighStable_i \times \Delta \log Stablecap_t \right) + \gamma_1 \pi_{i,t} + \gamma_2 i_{i,t} + \gamma_3 \Delta \log FX_{i,t} + \varepsilon_{i,t},$$

Where $\Delta \log M1_{i,t+h}$ is the monthly growth rate of narrow money in country i at horizon h months ahead; $HighStable_i$ is a time-invariant binary indicator equal to one for countries in the high-usage group and zero otherwise; $\Delta \log StableCap_t$ is the monthly change in the log of global USD stablecoin market capitalization; $\pi_{i,t}$ is domestic inflation, $i_{i,t}$ is the main domestic policy interest rate, and $\Delta \log FX_{i,t}$ is the monthly change in the log bilateral exchange rate against the USD. Country fixed effects α_i absorb time-invariant differences in monetary regimes and financial structure across economies. Month-year fixed effects τ_t absorb global shocks common to all countries in the same period. All regressions are estimated by OLS with standard errors clustered at the country level.

The coefficient of interest at each horizon is β_h, which captures the differential dynamic response of M1 growth in high-usage economies relative to low-usage economies following a unit shock to global stablecoin capitalization. A negative and statistically significant sequence of β_h coefficients across horizons would indicate that high-usage economies experience systematically weaker M1 growth in the months following a stablecoin-market expansion, consistent with the monetary substitution channel of the model. The full sequence $\{\beta_0, \beta_1, \ldots, \beta_{12}\}$ constitutes an impulse response function that traces the dynamic adjustment of domestic money growth over time.

The controls $\pi_{i,t}$, $i_{i,t}$, and $\Delta \log FX_{i,t}$absorb domestic macroeconomic conditions that affect M1 growth independently of stablecoin developments. The month-year fixed effects further absorb any remaining global confounders, including U.S. monetary policy shocks, global risk sentiment, and commodity price movements

Figure 1 provides a time-series overview of the underlying data. Panel A shows the rapid expansion of aggregate USD stablecoin capitalization over the sample period. Panel B plots the average monthly growth rate of M1 for high- and low-usage countries. The two series co-move closely at the contemporaneous level and do not display an obvious divergence, a pattern that motivates the shift to a dynamic local-projection framework capable of detecting delayed substitution effects rather than same-month correlations.

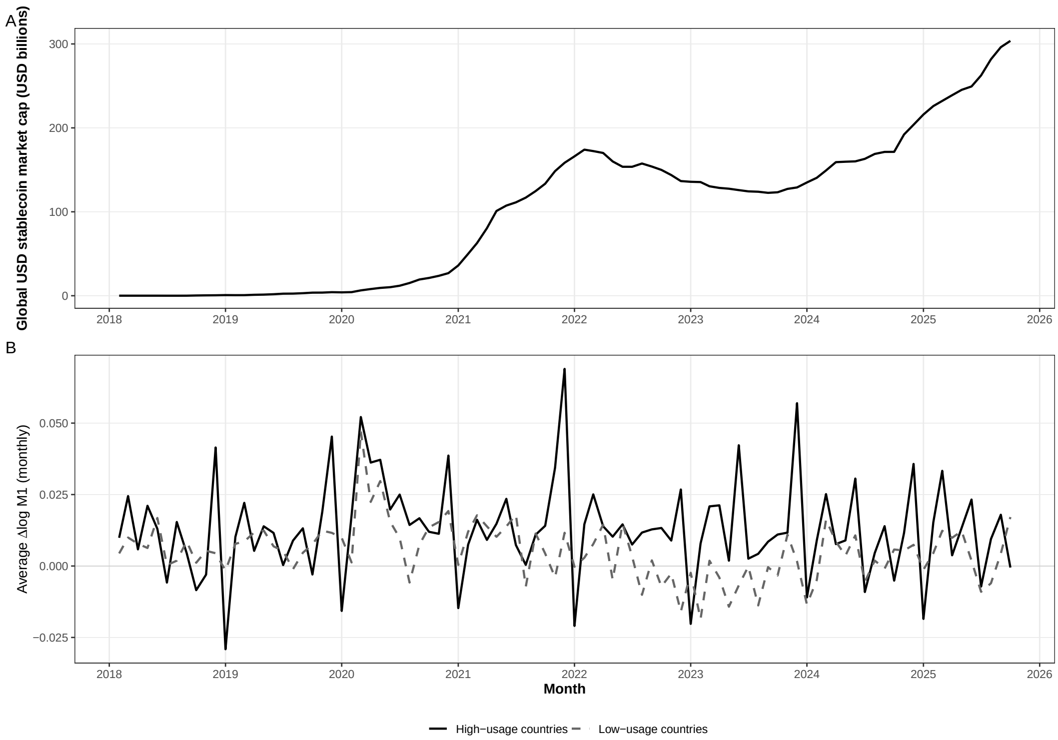


Figure 5.4.1: Global stablecoin capitalization and M1 growth in high- vs low-usage countries.

5.4.3 Main Results: Dynamic M1 Response to Stablecoin-Market Expansion

Table 2 reports the estimated coefficients β_h from the baseline local-projection specification for horizons $h = 0, 1, \ldots, 12$ months, and Figure 2 plots the full impulse response function together with 95 percent confidence bands.

At most horizons, the estimated coefficients are negative, with the exception of $h = 0$ and $h = 2$, where they are close to zero and statistically indistinguishable from zero. A clear negative pattern emerges from $h = 1$ onward and persists, with some oscillation, through $h = 12$. The mild rebound at $h = 2$ is likely a transitory mean-reversion component and does not alter the dominant negative pattern across the full horizon. That no significant contemporaneous effect appears at $h = 0$ is consistent with the presence of adjustment frictions (including onboarding costs, information diffusion lags, and the measurement of monetary aggregates at monthly frequency) that prevent instantaneous portfolio reallocation at the aggregate level. While the theoretical model predicts an immediate adjustment in the optimal stablecoin share ω_t in response to changes in the effective cost κ_t^e, this abstracts from the operational and informational frictions that characterise real-world adoption. The emergence of a significant negative effect from $h = 1$ onward is therefore the empirically relevant prediction, and the one that the data support.

Turning to statistical significance, the interaction coefficient $HighStable_i \times \Delta \log StableCap_t$ is significant at the five percent level or better at $h = 1$, $h = 3$, $h = 4$, $h = 6$, $h = 7$, $h = 9$, and $h = 12$, and marginally significant at $h = 5$. Significance is notably strong at $h = 3$ (p = 0.005) and $h = 7$ (p = 0.017), suggesting that the differential response of M1 growth in high-usage economies is most pronounced at a quarterly to half-yearly horizon following a stablecoin-market expansion. Confidence bands widen at longer horizons, as expected given the shorter effective sample available for forward projections, but point estimates remain consistently negative throughout.

In terms of magnitude, the estimated effects are statistically significant but modest in absolute terms, consistent with the current scale of stablecoin adoption relative to domestic monetary aggregates. At $h = 1$, where the effect is largest, $\widehat{\beta}_1 = -0.0216$. To give a sense of economic scale, a ten percent increase in global stablecoin capitalization, corresponding to $\Delta \log StableCap_t \approx 0.095$, is associated with a differential decline in monthly M1 growth of approximately 0.2 percentage points in high-usage economies relative to low-usage economies one month later. A doubling of stablecoin capitalization would imply a differential decline of roughly 1.5 percentage points at the same horizon. These magnitudes are non-trivial relative to the typical monthly volatility of M1 growth in the sample, but fall well short of suggesting that stablecoins are currently a dominant driver of monetary dynamics in high-usage economies.

Two sources of variation identify the differential dynamic response. Cross-sectional variation in $HighStable_i$ captures the fact that some economies have a larger latent demand for USD substitutes (typically driven by higher inflation, exchange-rate instability, or weaker monetary credibility) making them more responsive to changes in stablecoin accessibility. Time variation in $\Delta \log StableCap_t$ captures changes in the global attractiveness and accessibility of stablecoin platforms, which lower effective access costs and trigger substitution in countries where the underlying demand already exists. Together, these two sources of variation identify whether high-exposure economies display a systematically different dynamic M1 response when global stablecoin markets expand.

Overall, the results are consistent with the monetary substitution mechanism of Section 3. Following an expansion of global USD stablecoin markets, residents in high-usage economies gradually reallocate a portion of their liquid balances away from domestic money and toward tokenized dollars. This reallocation takes one to several months to materialize in aggregate M1 data, reflecting the time needed for households and firms to adjust their portfolio composition, access stablecoin platforms, and complete on-ramp transactions. When global stablecoin markets expand — signalling broader adoption, lower effective access costs, or improved platform integration — the relative attractiveness of tokenized dollars increases and residents in high-exposure economies respond by gradually reducing their domestic money holdings over the following months. As the stablecoin share $\omega_t$rises in response to lower effective access costs κ_t^e, domestic money demand falls relative to a given liquidity need, exactly as the model predicts. These results also connect naturally to the monetary-policy leakage channel: as residents hold a larger fraction of their liquid balances in stablecoins, the semi-elasticity of domestic money demand with respect to the domestic policy rate declines, attenuating monetary transmission at the margin. While we do not directly test this channel here, the documented negative response of M1 growth in high-usage economies is consistent with a setting in which monetary transmission is being gradually attenuated.

Table 2. Local Projection: Differential M1 Response to Stablecoin Shock.

Horizon	**Coefficient**	**SE**	**p-value**	**N**
0	-0.0034	(0.0127)	0.789	1907
1	-0.0216**	(0.0084)	0.017	1885
2	0.0023	(0.0046)	0.631	1863
3	-0.0133***	(0.0042)	0.005	1841
4	-0.0102**	(0.0037)	0.011	1819
5	-0.0091	(0.0053)	0.101	1797
6	-0.0089**	(0.0036)	0.023	1775
7	-0.0088**	(0.0034)	0.017	1753
8	-0.0057	(0.0046)	0.226	1731
9	-0.0084**	(0.0032)	0.017	1709
10	0.0017	(0.0037)	0.657	1687
11	-0.0002	(0.0039)	0.952	1665
12	-0.0092**	(0.0044)	0.047	1643

Notes: Dependent variable is M1 growth at horizon h, i.e. $\Delta \log M1_{i,t+h}$. The coefficient reported is on the interaction term $HighStable_i \times \Delta \log StableCap_t$. All regressions include country and month–year fixed effects. Cluster-robust standard errors at the country level are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

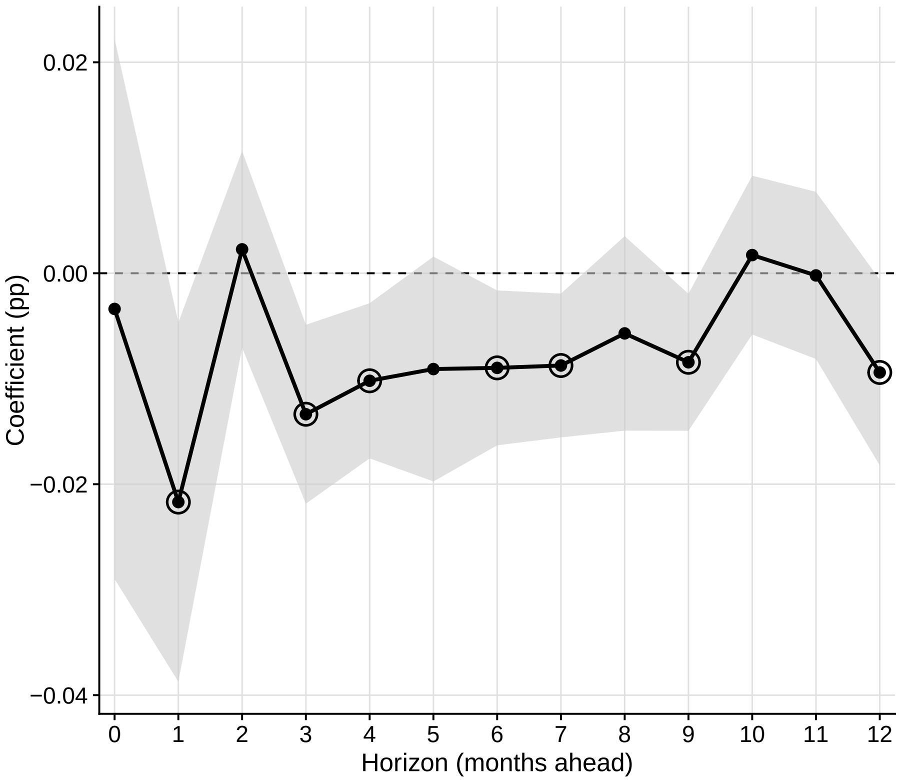


Figure 5.4.2: Local Projection: Differential M1 Response to Stablecoin-Market Expansion. The figure plots the estimated coefficients $\widehat{\beta}_h$ from the baseline local-projection specification for horizons $h = 0, 1, \ldots, 12$ months ahead. Each coefficient captures the differential response of monthly M1 growth in high-usage economies relative to low-usage economies following a unit shock to $\Delta \log StableCap_t$. The shaded area is the 95 percent confidence band based on cluster-robust standard errors at the country level. Open circles denote horizons at which the coefficient is statistically significant at the 10 percent level or better. All regressions include country and month-year fixed effects and domestic macroeconomic controls.

5.4.4 Robustness Checks

We assess whether the baseline result (a negative dynamic response of M1 growth in high-exposure economies following a stablecoin-market expansion) is sensitive to the choice of adoption measure or to the composition of the sample. Table 3 reports the main exercises.

A first check replaces the binary $HighStable_i$ dummy with a continuous adoption score derived from the normalised Chainalysis ranking, where India receives a score of 1.0 and Botswana a score of 0.0 (Table 3, column 2). This addresses the concern that a binary classification discards information about the intensity of adoption within each group: a country ranked first and one ranked fifteenth in the high-usage group are treated identically in the baseline, even though their effective exposure may differ substantially. The negative pattern is preserved across horizons and, if anything, strengthens at several points. At $h = 7$, for instance, the estimated coefficient is -0.0172 and significant at the one percent level, compared with -0.0088 in the baseline. This suggests that finer variation in adoption intensity reveals a stronger monetary substitution effect in the most exposed economies, and that the baseline estimates are conservative.

We then exclude the Covid-19 period, from March 2020 to December 2021, during which both global liquidity conditions and stablecoin capitalization expanded unusually rapidly (Table 3, column 3). Re-estimating the model on the restricted sample leaves the main pattern intact. The negative response persists across most horizons and significance is maintained at $h = 1$, $h = 3$, $h = 4$, $h = 6$, $h = 7$, and $h = 9$. Interestingly, excluding the Covid period strengthens the contemporaneous effect at $h = 0$, which becomes marginally significant at -0.0144, suggesting that the exceptional liquidity conditions of that episode introduced noise that partially masked the same-month response in the full sample. The baseline result is therefore not a Covid-era artifact.

To reduce sensitivity to a small number of particularly volatile monetary series, we drop the three most volatile countries in the sample (Viet Nam, Turkey, and Botswana) identified on the basis of the within-country standard deviation of $\Delta \log M1$ (Table 3, column 4). This is the most informative of the three checks. Removing these countries substantially strengthens the results: the negative coefficients become larger in absolute value and more precisely estimated across almost all horizons. Significance at the one percent level is obtained at $h = 1$, $h = 3$, and $h = 4$, and significance at the five percent level holds at $h = 5$, $h = 6$, $h = 7$, $h = 9$, and $h = 12$. This indicates that highly volatile monetary series attenuate the baseline estimates, and that the underlying monetary substitution signal is stronger and more persistent than the main specification suggests.

Across all three checks, the sign and broad pattern of the baseline results are preserved. The negative dynamic response of M1 growth in high-exposure economies following a stablecoin-market expansion is not sensitive to the choice of adoption measure or to the exclusion of the Covid period or the most volatile observations. If anything, the robustness checks point consistently in the same direction: the baseline is a lower bound on the true magnitude of the effect, rather than an upper bound. This reinforces the interpretation of Section 4.3: the monetary substitution channel identified in the model is already detectable in aggregate data at current adoption levels, and its quantitative importance is likely understated by the conservative baseline specification.

Table 3. Robustness Checks: Local Projection Results under Alternative Specifications.

	(1)		**(2)**		**(3)**		**(4)**	
	Baseline		**Continuous score**		**Excl. Covid**		**Excl. volatile**	
Horizon	**Coef.**	**SE**	**Coef.**	**SE**	**Coef.**	**SE**	**Coef.**	**SE**
0	-0.0034	(0.0127)	0.0111	(0.0218)	-0.0144*	(0.0071)	-0.0109**	(0.0041)
1	-0.0216**	(0.0084)	-0.0251*	(0.0144)	-0.0148**	(0.0071)	-0.0104***	(0.0031)
2	0.0023	(0.0046)	0.0108	(0.0076)	0.0070	(0.0046)	0.0015	(0.0045)
3	-0.0133***	(0.0042)	-0.0109	(0.0089)	-0.0119***	(0.0037)	-0.0156***	(0.0037)
4	-0.0102**	(0.0037)	-0.0139*	(0.0069)	-0.0094**	(0.0043)	-0.0121***	(0.0034)
5	-0.0091	(0.0053)	-0.0082	(0.0102)	-0.0074	(0.0055)	-0.0118**	(0.0054)
6	-0.0089**	(0.0036)	-0.0149**	(0.0062)	-0.0064*	(0.0033)	-0.0104**	(0.0039)
7	-0.0088**	(0.0034)	-0.0172***	(0.0054)	-0.0069*	(0.0033)	-0.0092**	(0.0037)
8	-0.0057	(0.0046)	-0.0082	(0.0074)	-0.0061	(0.0043)	-0.0041	(0.0046)
9	-0.0084**	(0.0032)	-0.0064	(0.0048)	-0.0112***	(0.0038)	-0.0087**	(0.0036)
10	0.0017	(0.0037)	0.0059	(0.0077)	0.0008	(0.0036)	-0.0009	(0.0027)
11	-0.0002	(0.0039)	-0.0006	(0.0055)	-0.0026	(0.0034)	-0.0012	(0.0040)
12	-0.0093**	(0.0044)	-0.0120*	(0.0061)	-0.0064	(0.0041)	-0.0108**	(0.0044)

Notes: Dependent variable is M1 growth at horizon h. Column (1) reports the baseline results with the binary $HighStable$ dummy interacted with $\Delta \log StableCap$. Column (2) replaces the binary dummy with a continuous adoption score based on the normalised Chainalysis ranking (0–1). Column (3) excludes the Covid-19 period (March 2020–December 2021). Column (4) excludes the three most volatile countries in the sample (Viet Nam, Turkey, Botswana). All regressions include country and month–year fixed effects, two lags of the dependent variable, and domestic macroeconomic controls. Cluster-robust standard errors at the country level are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

As a further diagnostic, we assess whether the two groups of economies displayed differential trends in M1 growth already before the period of significant stablecoin-market expansion. We re-estimate the baseline local-projection specification restricting the sample to the pre-expansion period from February 2018 to December 2019, when aggregate USD stablecoin capitalization remained below USD 5 billion and variation in $\Delta \log StableCap_t$ was limited. Given that this sub-sample spans approximately 22 months, we restrict the analysis to horizons $h = 0$ to $h = 6$, beyond which the forward M1 growth variable would require observations outside the pre-expansion window and the effective sample would become too small for reliable inference. If the negative pattern observed in the full-sample results reflected pre-existing differences in M1 dynamics between high- and low-exposure economies rather than a response to stablecoin-market growth, we would expect to find significant negative coefficients even in this early period. Figure 3 shows that this is not the case. The estimated coefficients in the pre-expansion period are small, mostly positive, and statistically indistinguishable from zero at all horizons except $h = 2$, where the coefficient is positive rather than negative. This pattern is consistent with the identifying assumption that the two groups of economies were on broadly similar M1 trajectories before stablecoin markets became quantitatively relevant, and that the negative differential response documented in the full sample emerges precisely in the period when stablecoin adoption expanded.

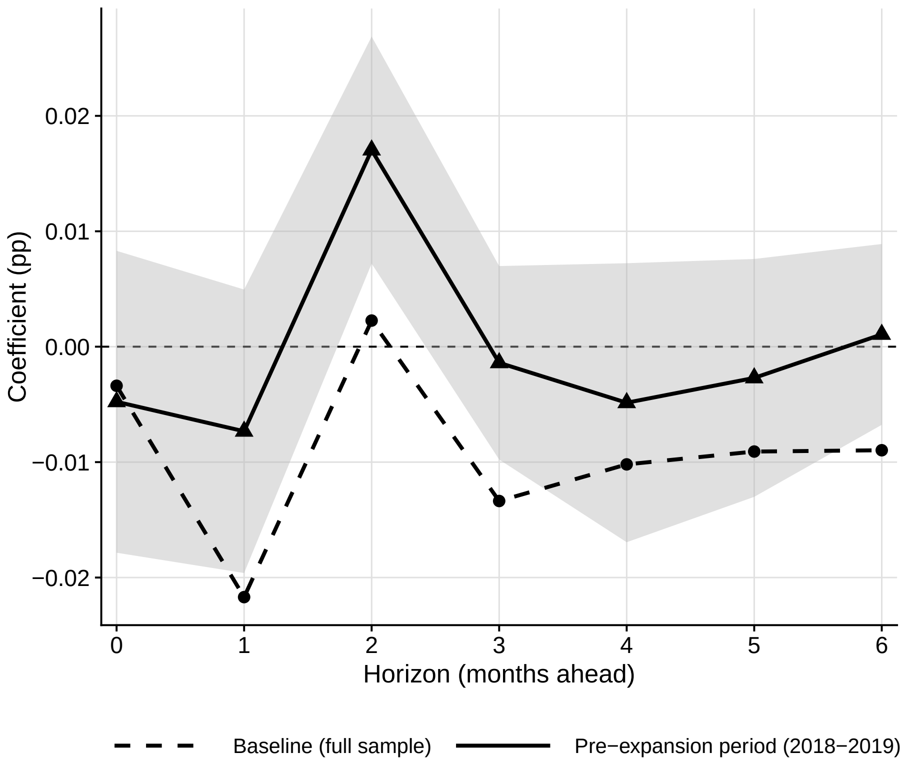


Figure 5.4.3: Pre-trend Test: Local Projection Coefficients in the Pre-Expansion Period. The figure plots the estimated coefficients $\widehat{\beta}_h$ from the baseline local-projection specification estimated on the sub-sample February 2018 to December 2019, before the period of significant USD stablecoin market expansion, alongside the full-sample baseline estimates for comparison. The analysis is restricted to horizons $h = 0, 1, \ldots, 6$ months ahead. The shaded area is the 95 percent confidence band for the pre-expansion period based on cluster-robust standard errors at the country level.

5.5 Policy Implications

The analysis in this paper points to a specific and actionable set of policy implications. The theoretical model shows that USD stablecoins can erode domestic money demand and attenuate monetary policy transmission in small open economies through monetary substitution and policy leakage. The empirical evidence suggests that these channels are already detectable at medium-run horizons, even if their aggregate magnitude remains modest at current adoption levels.

A prerequisite for any policy response is better measurement. The empirical results in Section 4 rely on a coarse proxy for stablecoin exposure because comprehensive, harmonised data on country-level stablecoin holdings and flows are not available. Central banks in high-exposure economies cannot assess how close they are to the threshold at which the theoretical channels become quantitatively important without better data on stablecoin adoption, on/off-ramp activity, and the composition of resident liquid balances. Concrete steps include requiring regulated intermediaries (exchanges, payment service providers, and on/off-ramp operators) to report stablecoin flows broken down by resident versus non-resident activity, extending household and firm portfolio surveys to cover digital dollar holdings, and integrating stablecoin activity into standard monetary statistics alongside currency in circulation and demand deposits. The robustness results in Section 4.4 suggest that the monetary substitution signal is stronger in economies with relatively stable monetary aggregates, which reinforces the case for improving measurement as a first priority.

The model's monetary-policy leakage channel implies that, as stablecoin adoption grows, the semi-elasticity of domestic money demand with respect to the domestic policy rate declines. Central banks in high-exposure economies may therefore need to recalibrate their policy frameworks to account for a gradually weaker link between policy rates and monetary aggregates. This does not necessarily require new instruments — existing interest rate corridors and reserve requirements can be adjusted — but it does require awareness that the transmission mechanism is being attenuated at the margin. A complementary response is to provide high-quality domestic digital payment alternatives that compete effectively with USD stablecoins on access, convenience, and safety. tokenized deposits issued by regulated banks, or a retail central bank digital currency denominated in domestic currency, can reduce the attractiveness of switching to tokenized dollars without requiring outright restrictions on stablecoin use. The objective is not to prohibit stablecoins but to ensure that residents have domestic options that are genuinely competitive, reducing the latent demand for substitution that the model identifies as the key driver of the monetary substitution channel. The empirical finding that the effect is stronger once the most volatile monetary series are removed suggests that domestic monetary credibility itself is a form of protection: economies with more stable monetary frameworks are less vulnerable to substitution even at comparable levels of stablecoin exposure.

Because USD stablecoins operate across borders outside the traditional banking perimeter, unilateral regulatory approaches are prone to gaps and arbitrage. A resident in a country that restricts stablecoin use can often access the same instruments through foreign platforms, as the model's capital control circumvention mechanism illustrates. Effective oversight therefore requires coordination between issuing jurisdictions (primarily the United States) and host countries where stablecoins are widely held. Practical steps include information-sharing agreements between supervisors, coordinated disclosure standards for stablecoin issuers operating cross-border, and explicit treatment of stablecoin flows in capital flow management frameworks and AML/CFT rules. The empirical results suggest that there is still a window of opportunity to put such frameworks in place before stablecoin usage becomes large enough to materially affect monetary transmission in a broad set of economies. Acting within this window, while the channels are detectable but still modest, is preferable to responding after the fact when substitution has already become entrenched.

5.6 Conclusion

USD-pegged stablecoins have moved beyond their origins as crypto-exchange settlement tools and are increasingly used as general-purpose dollar liquidity across borders. For residents of non-issuing economies, particularly those facing elevated inflation, exchange-rate instability, or restricted access to formal dollar intermediation, they provide frictionless access to tokenized dollars outside the domestic banking system. This paper has examined the macroeconomic implications of that shift, focusing on two mechanisms through which stablecoin adoption can affect monetary conditions in small open economies: monetary substitution and monetary-policy leakage.

On the theoretical side, we developed a minimal portfolio model in which households allocate real liquidity between domestic money and a USD-pegged stablecoin. The model shows that as stablecoins become more attractive through lower effective access costs, higher perceived safety, or improved platform integration, their share in liquid portfolios rises and domestic money demand falls relative to a given liquidity need. This monetary substitution channel directly attenuates the semi-elasticity of money demand with respect to the domestic policy rate, generating policy leakage: a fraction of any policy-induced change in the opportunity cost of liquidity is absorbed by reallocation between domestic money and stablecoins rather than by an adjustment in total liquidity. An extension of the model shows that stablecoins, by operating outside the banking perimeter, become a natural circumvention channel when capital controls or banking frictions restrict access to conventional dollar assets, a mechanism with no direct parallel in the traditional financial dollarization literature.

On the empirical side, we brought the model to cross-country data using a monthly panel of 24 countries over 2018–2025. Local projections of M1 growth on the interaction between changes in global USD stablecoin capitalization and a country-level indicator of retail crypto exposure reveal a negative and statistically significant differential response in high-exposure economies at multiple horizons between one and twelve months. This dynamic pattern is consistent with the monetary substitution channel of the model: residents in high-exposure economies gradually reduce their domestic money holdings following an expansion of global stablecoin markets, with the adjustment taking one to several months to materialize in aggregate data. The effect is robust to replacing the binary adoption indicator with a continuous adoption score, to excluding the Covid-19 period, and to dropping the most volatile countries in the sample. A pre-trend test further confirms the absence of differential M1 dynamics between the two groups before stablecoin markets became quantitatively relevant, supporting the identifying assumption underlying the main results. If anything, the robustness checks suggest that the baseline estimates are conservative, as the underlying monetary substitution signal is stronger and more persistent than the main specification indicates.

Viewed jointly, the theoretical and empirical results deliver a nuanced but clear message. The monetary substitution channel is already detectable in aggregate data at current adoption levels: residents in high-exposure economies demonstrably reduce their domestic money holdings following stablecoin-market expansions, with effects that are statistically robust across multiple specifications and horizons. At the same time, the estimated magnitudes remain modest in absolute terms, consistent with a situation in which tokenized dollars are still a marginal component of aggregate liquidity in most economies. The evidence is best read as an early signal. The footprint of stablecoin-market expansion on domestic monetary aggregates is visible but small today, and is likely to grow as adoption scales up and effective access costs continue to decline.

From a policy standpoint, this combination of forward-looking theoretical risk and early-stage empirical evidence argues for preparation rather than reaction. Central banks in high-exposure economies should invest in better measurement and monitoring of stablecoin flows, develop domestic digital payment alternatives that compete effectively on access and safety, and engage in international coordination to close regulatory gaps that unilateral approaches cannot address. The empirical results suggest that there is still a window of opportunity to put these frameworks in place before stablecoin usage becomes large enough to materially affect monetary transmission in a broad set of economies. The overarching message of the paper is therefore this: the channels through which tokenized dollars can reshape domestic monetary conditions are real and already operating at the margin. The question is not whether they matter, but how quickly they will become quantitatively important, and whether policy frameworks will be ready when they do.

5.7 Appendix A

Table A1. Universe of countries used for the high/low stablecoin-usage grouping (30 countries).

High-usage group (15 countries)	Low-usage group (15 countries)
India; Pakistan; Viet Nam; Ukraine; Brazil; Philippines; Nigeria; Russian Federation; Indonesia; Türkiye; Venezuela; Bangladesh; Argentina; Egypt; Morocco	Austria; Bahrain; Botswana; Denmark; Iceland; Ireland; Kuwait; Lithuania; Luxembourg; Malta; New Zealand; Norway; Slovenia; Uruguay; Costa Rica

Notes: The classification is based on the Chainalysis Global Crypto Adoption Index (retail centralized services sub-index). Country names follow the conventions used in the underlying data sources (e.g., "Viet Nam", "Türkiye").

Table A2. Monthly macro panel sample (countries with complete M1, CPI, policy interest rate, and USD FX series).

High-usage group (12 countries)	Low-usage group (12 countries)
India; Pakistan; Viet Nam; Ukraine; Brazil; Philippines; Nigeria; Russian Federation; Indonesia; Türkiye; Egypt; Morocco	Austria; Bahrain; Botswana; Denmark; Iceland; Ireland; Kuwait; Lithuania; Luxembourg; New Zealand; Norway; Slovenia

Table A3. Variables, transformations, and data sources.

Variable	Definition / transformation	Source
VIX_t	CBOE Volatility Index (daily)	CBOE
$M1_{i,t}$	Narrow money aggregate, monthly, country-level	Trading Economics / official sources
$\text{CPI}_{i,t}$	Consumer Price Index, monthly, country-level	Trading Economics / official sources
$\pi_{i,t}$	Monthly inflation: $\pi_{i,t} = \Delta\log(CPI_{i,t})$	Constructed
$i_{i,t}$	Main domestic policy interest rate (central bank policy interest rate), monthly level	Trading Economics / central bank
$\Delta\log(FX_{i,t})$ (monthly)	Monthly change in log USD exchange rate	Market data sources (primarily Investing.com)
Stablecap_t	Log of global USD stablecoin market capitalization (aggregate of major USD-pegged fiat-backed stablecoins, valued at par)	Issuer disclosures / market dataset

Notes: FX series are obtained from publicly available market-data sources (primarily Investing.com historical spot rates). The analysis uses log returns and rolling-window realized volatility, which are robust to small differences in end-of-day quotes across data vendors.

5.8 Appendix B

Proposition 4 (Stablecoins, bank USD and capital controls).
Suppose the interior solution $\omega_t^S \in (0,1)$ to

$$G(\omega_t^S; \varphi_t^S, \varphi_t^B, \kappa_S, \kappa_B, \tau_c, f_t) = 0$$

exists and is unique. Then:

1. The stablecoin share among USD assets is increasing in the intensity of capital controls on bank USD:

$$\frac{\partial \omega_t^S}{\partial \tau_c} > 0.$$

2. For given τ_c and f_t, the stablecoin share is higher when stablecoins enjoy a larger efficiency and access advantage over bank USD assets, in the sense that ω_t^S is increasing in φ_t^S and decreasing in φ_t^B, and it is decreasing in κ_S and increasing in κ_B.

   Sketch of proof. By the implicit function theorem,

$$\frac{\partial \omega_t^S}{\partial x} = -\frac{\partial G/\partial x}{\partial G/\partial \omega_t^S}, \qquad x \in \{\tau_c, \varphi_t^S, \varphi_t^B, \kappa_S, \kappa_B\}.$$

   Moreover,

$$\frac{\partial G}{\partial \omega_t^S} = -\frac{\psi_S \varphi_t^S}{f_t(\omega_t^S)^2} - \frac{\psi_B \varphi_t^B}{f_t(1-\omega_t^S)^2} < 0 \quad \text{for } \omega_t^S \in (0,1),$$

   and the relevant partial derivatives satisfy

$$\frac{\partial G}{\partial \tau_c} = 1 > 0, \quad \frac{\partial G}{\partial \varphi_t^S} = \frac{\psi_S}{\omega_t^S f_t} > 0, \quad \frac{\partial G}{\partial \varphi_t^B} = -\frac{\psi_B}{(1-\omega_t^S) f_t} < 0, \quad \frac{\partial G}{\partial \kappa_S} = -1 < 0, \quad \frac{\partial G}{\partial \kappa_B} = 1 > 0.$$

   Combining these signs with $\partial G/\partial \omega_t^S < 0$ yields the stated comparative statics.

Chapter 6

Conclusions

This dissertation studies blockchain-based infrastructures as institutional technologies that reshape cross-border exchange by changing how verification is produced, how intermediation is allocated, and how settlement assets and liquidity are organized. The central implication is conditionality: the reduction of coordination and reconciliation frictions is feasible, but it depends on governance arrangements, incentive compatibility, legal enforceability, and the credibility of the on-/off-chain boundary. The first essay, focused on international trade, indicates that distributed ledgers can strengthen transparency and auditability and reduce administrative delays in documentation and supply-chain coordination. However, persistent barriers, including limited multi-stakeholder participation, interoperability constraints, data governance challenges, and regulatory fragmentation, largely determine whether pilots scale beyond confined consortia. The second essay, centered on DeFi, shows that composability accelerates the diffusion of liquidity and innovation while creating a network structure in which spillovers intensify in stress states. In that setting, credit-related shocks explain a substantial share of short-horizon uncertainty, suggesting that risk assessment should prioritize ecosystem interdependencies rather than protocol-by-protocol metrics. The third essay frames USD-pegged stablecoins as tokenized private dollars that can compete with domestic money in residents' liquid portfolios. Its portfolio model identifies monetary substitution and monetary-policy leakage as the key mechanisms, and the local-projection evidence shows that expansions in global stablecoin capitalization are followed by weaker M1 growth in relatively high-exposure economies. The effect is detectable but still modest, reinforcing the need for better measurement of resident stablecoin exposure, credible domestic digital payment alternatives, and cross-border regulatory coordination before adoption becomes quantitatively larger. Overall, the dissertation points to a hybrid institutional shift. Efficiency gains from shared ledgers are feasible, but sustainable adoption ultimately hinges on verifiable real-world data and standards, system-level risk governance in composable financial architectures, and policy capacity to monitor and regulate tokenized private money, including reserve transparency, usage measurement, and cross-border coordination, as its scale grows.

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