Effects of the Covid-19 pandemic on derivatives markets: Evidence from global futures and options exchanges

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Abstract
We examine key developments in trade-related activity on global derivatives markets during the Covid-19 pandemic. We first document significant increases in volumes and open interest. Drawing upon techniques from network theory, we next find greater market interconnectedness and notable changes in market centrality. For US exchanges, we examine their response to the increased market uncertainty and find large and more frequent changes to margin requirements. We also find a considerable drop in trader participation driven mainly by noncommercial traders along with an increase in the percent of open interest held by commercial shorts and noncommercial longs.

KEYWORDS
Covid-19, derivatives, financial crisis, futures, networks, open interest, options, volume

JEL CLASSIFICATION
G12, G13, G14, G15, G23, L14

1 INTRODUCTION

The outbreak of coronavirus disease (Covid-19) and the subsequent spread of the pandemic have had tremendous spillover effects on the macroeconomy and global gross domestic product (GDP) as governments, firms and individuals dealt with the effects of lockdowns, social distancing, disruptions to supply chains, unemployment, and general overall economic upheaval. As discussed in Baker et al. (2020), unlike other pandemics during the past hundred years, the Covid pandemic led to unprecedented effects on the US stock market.1 In this paper we study various economic effects of the pandemic in the context of an important component of the global financial system—derivatives markets for exchange-listed futures and options—for managing market risks and facilitating price discovery.

Our paper also seeks to provide a unique and natural extension of studies on the behavior and connectedness of global financial markets during times of financial crises. The existing literature on market integration and contagion has for the most part focused on equity markets and to a lesser extent on bonds and currencies, and on how shocks to financial markets affect the valuations and returns of these financial assets. Our study focuses on derivatives markets and sheds new light on how participants respond during times of heightened market

1Consistent with this, we find the increase in market volatility to be comparable to or exceed, in terms of its magnitude and speed of onset, that observed during the Great Recession wherein the volatility index (VIX) experienced more than a 400% increase (from 18.5% to 80.1%) during the eight and half-week period of August 22–October 27, 2008. In comparison, the VIX index during the onset of the Covid pandemic increased more than 500% (from 14.5% to 80.6%) during the much shorter 4-week period of February 20–March 19, 2020.
uncertainty in terms of their trading activities and the role of exchanges in the process. In addition, we provide new evidence on how levels of connectedness and financial integration of global derivatives markets are affected during such times. Further, we focus on changes in trade activity rather than valuations or rates of returns as examined in the existing literature on equities for two reasons: first, derivative instruments are not part of the market portfolio as they are in net-zero supply (i.e., the number of long positions equals that of shorts), and the initial value of a derivatives contract is typically zero for linear derivatives, such as futures and swaps, or is small for nonlinear derivatives, such as options. Additionally, to establish a rationale for studying volumes, we expect at least three potential channels through which a volatility shock can induce trade activity in derivatives markets. First, an increase in volatility could alter the demand for hedging and the need to manage the higher risks and hence lead to greater trade volume. Second, an increase in market volatility could increase incentives and rewards for speculators to gather private information to exploit and profit from trade and hence again lead to higher volume. Third, if asset correlations increase during a market crisis, the presence of natural hedges can decline leading to a greater demand for real hedging as a substitution effect and hence greater volume.

Our analysis is facilitated in part by a unique and comprehensive database containing trade volume and open interest information for nearly all futures and options contracts listed on derivatives exchanges across the globe. The data include information from 113 different exchanges in 40 countries spanning multiple geographic regions, including North America, Europe, Asia, and Latin America. Further, the contracts cover those based on (1) financial instruments, including bonds and interest rates, equities, and currencies; and (2) commodity products, including agriculture, energy, precious and nonprecious metals, and other related items (e.g., weather, housing, and inflation). To explore more microlevel effects of the pandemic, for a number of US-based futures exchanges for which data are available, we also obtain information on daily margin requirements (performance bonds) for a broad set of futures spanning multiple asset classes; regulatory-reported position information of commercial and noncommercial large traders; and amounts of traders’ funds held in accounts at all US futures commission merchants (FCMs) to support margin requirements for their trading activities.

To help motivate our research questions as well as to place into historical perspective derivatives trading during the pandemic in relation to that during prior financial crises, we present three related illustrations. Figure 1a shows the time-series of global monthly volume of futures and options traded over the period 2002–2021. On the basis of casual observation, one can see large changes in early 2020 coinciding with the timing of the outbreak, and whose magnitudes appear to exceed those during earlier notable periods of economic unrest, including the Great Recession (2007–2009), the European debt crisis (2010–2012), and the Brexit referendum (2016–2017). These observations raise questions as to whether they extend similarly across various geographic regions, derivatives product groups and asset classes as well as, more broadly, to how financial market connectedness changed during the pandemic in the context of derivatives activity.

Second, in consideration of the vital role of margins in protecting the financial integrity and solvency of FCMs, exchanges and clearing houses, especially during periods of market crises, we similarly present in Figure 1b for the period 2002–2021 the monthly time-series of the total amounts of funds of institutional, corporate, and retail traders held in accounts at FCMs to support the margin requirements for their trading positions. Of note, we observe a historically large jump in such funds in March 2020 far exceeding that in any prior month.

Third, we present in Figure 1c the number of traders holding reportable positions in a large cross-section of contracts listed on US futures exchanges as indicated in weekly commodity futures trading commission (CFTC) Commitments of Traders (COT) reports over the 2019–2021 period. Coinciding with the above-noted record increase in funds held in margin accounts in March 2020, there is a large decline in trader numbers followed by an upward trend, thus raising questions about potential changes in the composition of market participants.

To investigate these observations in greater depth, we explore the following research questions that focus on four primary areas of inquiry:

(1) What effects has the Covid-19 pandemic had on derivatives trading activity on exchanges across major geographic regions, including North America, Asia, Europe, and Latin America? Similarly, how have these effects varied across different asset classes and derivatives instruments?

(2) How did the onset of the pandemic affect levels of connectivity in derivatives trading activity between countries and geographic regions?

(3) In light of changes in market volatility, how did US futures exchanges respond in terms of adjusting margin requirements to maintain financial integrity and protect against customer default? Further, what was the effect on
the demand for futures trading in terms of the amounts of funds that traders deposited with FCMs to support margin requirements?

(4) Finally, what effect did the pandemic have on trader composition of open interest in terms of breakdowns between long and short commercial and noncommercial large traders?

Our main findings to these inquiries are as follows. We first find a strong increase in trading activity at the onset of the pandemic. Using event study methodology based on measures of trading activity, we find a significant cumulative jump of 60.7% in global futures and options trade volume for the 3-month January–March 2020 period, and a 65.4% increase for the year. For open interest, we find smaller but significant changes of 13.2% and 14.3% increases for the same 3-month and 1-year periods, respectively. These findings for volume and open interest were also generally
observed at the region level for North America, Asia, and Europe, but activity in Latin American markets showed the largest increases. For the various asset classes, increases in trading activity were substantially larger for financial than for commodity derivatives.2

By examining changes in derivatives trading activity following the outbreak of the pandemic, we find that the mean (median) cross-correlation in country-level volume increased from 0.290 (0.278) to 0.381 (0.440), with 67% of the pairwise correlations increasing. Further, using concepts and metrics taken from network theory, we create and inspect properties of minimum spanning trees (MSTs) to identify changes in interconnectedness among countries and geographic regions. Pre-Covid, we observe a trade network with several primary hubs of countries of influence, including Japan, Germany, the United States, and Singapore. Post-Covid, we find an overall increase in global trade connectedness along with the United States assuming the dominant role of centrality in the transmission and flow of information between countries.

Next, in our investigation of margin setting by US futures exchanges, we analyze daily front-month margin requirements for 35 futures spanning multiple asset classes and find large, significant increases in margin requirements during the Covid period of approximately 43.5% as compared with the prior-year levels. In addition, exchanges became more active in their frequency of making margin adjustments as they responded to market volatility. Further, we observe a dramatic increase in trader funds held in accounts at FCMs to support margin requirements with the total amount increasing from $172.9 billion in February 2020 to $264.6 billion in March 2020. This 1-month increase of 53.0% far exceeds any monthly change observed since 2002 including those during the earlier periods of the Great Recession and European debt crisis.

Finally, we find a large drop in market participants during the February–April 2020 period with noncommercial large traders comprising the largest component. Interestingly, this large drop in the noncommercial traders, who are often associated with speculative trading, coincides with the observed large increases in margin requirements. We further find, in subsequent months beginning in early June, a trend in the divergence of commercial positions with the percentage of their short positions increasing while that of their long positions declining and reverting towards pre-Covid levels. In contrast, the percentage of noncommercial long positions increases while that of noncommercial short positions declines. These findings were most pronounced for the agriculture, metals, and currency assets classes, but less so for equity and interest-rate futures.

The remainder of the paper is organized as follows. In Section 2, we provide a review of a number of related studies on the effects of the pandemic on financial markets. (We also provide in Appendix A a timeline summary of key developments in the Covid-19 pandemic). In Section 3, we present our empirical analysis of global futures and options trading activity conducted at the exchange, region, and asset class levels. In addition, we explore how correlation structures and network connectedness changed during the pandemic. In Section 4, we analyze how US futures exchanges adjusted margin requirements in view of the increased market volatility and the response of traders. In Section 5, we investigate how the composition of the various participants in futures markets changed during the pandemic Section 6 concludes.

2 | STUDIES OF ECONOMIC EFFECTS OF COVID-19 ON FINANCIAL MARKETS

The pandemic has prompted a growing literature to examine its economic impact on various financial markets. For instance, Baker et al. (2020) show that the Covid-19 outbreak had an unprecedented negative impact on the US stock market performance and volatility not seen in previous pandemics over the last century. They attribute it in large part to social distancing practices and lockdowns given the importance of the service sector in the modern economy. In line with this explanation, Carter et al. (2021) document significant negative returns for US firms in travel-related industries. When examining the firm characteristics that market participants use when factoring Covid-related news into stock prices, they find that higher cash reserves and lower levels of debt mitigated the negative effects of Covid. Consistent with these findings, Ramelli and Wagner (2020) show that a firm’s strong financial health in terms of its

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2 Our findings of higher regional and global trading volume and open interest during the Covid period are not intended to necessarily suggest that derivatives markets developed greater market liquidity nor do they universally extend to all contract markets. To illustrate an exception, Peng et al. (2021), using intraday data, find large drops in various market microstructure liquidity measures for contracts in the soybean complex in February 2020.
liquidity and leverage was especially important in industries that are affected the most by the pandemic. Albulescu (2021) also finds that announcements of Covid-19 case and death figures increased US stock market volatility. Interestingly, he further finds that data reported at the global level had a stronger impact on the US stock market volatility than those data reported at the US level.

Other studies having a broader prospective examine the impact of the health crisis on financial markets around the world. Ashraf (2020) finds that the growth in Covid-19 reported cases had a significant negative impact on both US and foreign stock returns. Zhang et al. (2020) show that stock market volatility increased considerably in all countries in their sample, except China, between February and March 2020. The highest level of stock market volatility in March 2020 was observed in the United States, in line with the highest number of confirmed US Covid-19 cases during the same time. Consistent with the other studies, Ali et al. (2020) report that after the epidemic turned into a pandemic (i.e., post-March 10, 2020, as classified by the WHO), global equity as well as commodity markets exhibited a considerable decline and increased volatility. Furthermore, they find that the European regional index experienced increased volatility during the phase when the US became an epicenter of the pandemic.

Another strand of literature has focused on the effect of Covid-19 on financial and commodity market liquidity. This study has documented deteriorated liquidity conditions in the US fixed-income market, including US Government bonds (Ermolov, 2020) and corporate bonds (Kargar et al., 2020; O’Hara & Zhou, 2021). Focusing on agricultural futures markets, Peng et al. (2021) find a substantial decrease in soybean futures liquidity several weeks before US equity, bond as well as other agricultural markets were impacted.

The emerging literature has also attempted to address the effects of the Covid-19 pandemic on the systemic risk in financial markets. For example, Akhtaruzzaman et al. (2021) report increased dynamic conditional correlations between stock returns of Chinese and G7 firms and generally higher optimal hedge ratios during the Covid-19 period, suggesting increased financial contagion as well as hedging costs following the start of the pandemic. Similarly, Zhang et al. (2020) observe an increase in systemic risks in response to the pandemic, reporting a rise in weekly return correlations among twelve countries in the first week of March of 2020.

Finally, several studies have investigated structural changes in global financial markets due to the Covid-19 crisis using network analysis methods. For example, Aslam et al. (2020) examine the properties of the global stock market network represented by 56 stock market indices and conclude that market risk increased following the Covid-19 outbreak. Pang et al. (2021) focus on the yields of European sovereign bonds and, using alternative network filtering methods, find a decrease in the average correlation during the Covid-19 pandemic. We add to this literature by focusing on how derivatives markets changed during a financial crisis.

3 | GLOBAL DERIVATIVES TRADE ANALYSIS

3.1 | Data description

To facilitate our analysis of derivatives trading during periods preceding and following the outbreak of the pandemic, we utilize a database created for us by programmers at the Futures Industry Association (FIA), which is the leading global trade organization for futures, options, and centrally cleared derivatives. While our study focuses on those periods immediate to the pandemic, the entire database covers the period 2002–2021 and includes information on monthly futures and options trading activity on 113 different exchanges in 40 countries spanning multiple geographic regions (North America, Europe, Asia, Latin America, and Other [Greece, Israel, Turkey, and South Africa]). The futures and options include contracts on (1) commodity instruments and indices including those on agriculture, precious and nonprecious metals, and other related products (e.g., weather, housing, and inflation), and (2) financial instruments including those based on interest rates, equity, and currency.

3See https://www.who.int/director-general/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19—11-march-2020
4The effects of earlier financial crises including the Great Recession on systemic risk have been widely examined, see, for example, Yang and Zhou (2017) and Kotkatvuori-Ornberg et al. (2013).
5Following the preparation of this database, we learned that beginning in July 2021 the FIA will retrospectively cover the US Nodal Exchange, which trades energy-related derivatives.
3.2 Volume and open interest effects

3.2.1 Pre- and post-Covid univariate comparisons

We first compare levels of volume and open interest for futures and options trading during the pre- and post-Covid periods, and subsequently analyze the monthly changes in trading activity following the outbreak of the pandemic using event study methods. As discussed in greater detail in Appendix A, for purposes of our analysis we treat January 2020 as the initial event month for the outbreak of the pandemic, but recognize its economic spread throughout subsequent months. To provide perspective on the relative sizes of the various markets that we analyze, we first present breakdowns on trading activity by contract type (futures vs. options), geographic region (North America, Europe, Asia, and Latin America), product grouping (Financial vs. Commodity) and asset class (e.g., agriculture, currency, interest rate, etc.). For the global totals and each breakdown, we compute the average monthly volume and open interest (and global market share percentage of each) during each of the two 12-month periods of January–December 2019 and January–December 2020 surrounding the January 2020 outbreak of the pandemic. In addition, we compute t statistics for the mean differences between the two periods. Results based on volumes are presented in panel A of Table 1, while those based on open interest are presented in panel B.

In panel A of Table 1, we see in the prior 12-month period immediately preceding the outbreak of the pandemic that global futures volume averaged 1605 mm contracts a month, while post-Covid the volume increased to an average 2129 mm contracts a month or a 33% increase. Options volume grew similarly increasing from 1270 mm contracts a month to 1772 mm contracts or by 40%. In section (i) for the various regions, Asia had the largest average futures volume of 640 mm contacts a month (or a 40% global share) before the pandemic, followed by North America at 355 mm contracts a month (22%), Europe at 331 mm contracts (21%) and Latin American at 238 mm contracts (15%). In the post-Covid period, each region grew in futures volume with Latin America growing the most rapid to 366 mm contracts or a 54% increase. For options volume, Asia again had the largest regional market shares pre- and post-Covid at 45% and 46%, respectively. Following Asia again, North America had 39% markets shares in both of the two periods. Also, Latin America had the largest options growth rate with average volume rising from 104 to 173 mm contracts a month, or a 66% increase.

In section (ii), the Financial sector represented 64% of both the pre- and post-Covid global futures volume. Pre-Covid, equity futures were the largest component of the Financials at 31% followed by interest rates at 19% and currency at 13%. Post-Covid, equity futures volume grew the most in absolute and percentagewise amounts, increasing from an average of 503 mm contracts to 811 mm contracts a month or 66%. For the Commodity sector (36% of global futures volume both pre- and post-Covid), energy futures were the largest segment pre- and post-Covid at 13% and 12%, respectively, followed by metal (10% and 9%) and agriculture (9% and 10%). Interestingly, in both periods Commodity options captured a relatively minor 2% share of total options volume.

For the results based on open interest in panel B of Table 1, we see that changes in global futures and options open interest were more modest across the two periods. For futures, in contrast to a 33% increase in volume, open interest declined 4% from an average of 255 mm contracts a month to 244 mm contracts. Regionally, North America had the largest market share of futures open interest both pre- and post-Covid at 32% and 30%, respectively. Interestingly, despite North America, Europe, and Latin America all having increases in futures volume, their open interest declined in the post-Covid period. For options, open interest grew by 15% across the two periods though also at a lower rate than of options volume (40%). North America had the highest market share pre- and post-Covid at 57% and 54%, respectively. Latin America had the highest growth rate in options open interest at 109%.

In section (ii) of panel B, futures open interest in the Financial sector fell from an average of 177 mm contracts per month (70% of total) to 163 mm contracts (67% of total) or by 8%. Futures open interest fell the most for interest-rate futures from 86 mm contracts to 75 mm contracts or by 13%. Commodity futures open interest grew modestly by 4%. Finally, for the Financials and Commodities groups, options open interest grew at 15% and 13%, respectively.

3.2.2 Global, regional, and product grouping growth figures

We next compute and present log monthly changes in volume and open interest for each month t relative to month-end December 2019 (for purposes of consistency with our subsequent event study analysis) for the various futures and options groupings over the 2019–2020 period. We present these changes for the global, region, and asset class
## TABLE 1  Breakdowns of global futures and options trading pre- and post-Covid periods

|                  | Futures |             | Options |             |
|------------------|---------|-------------|---------|-------------|
|                  | Mean-pre| % Of total | Mean-post| % Of total |
|                  |         |            | Mean change|            |
| **Panel A: Trade volume** |         |            | Mean-pre | % Of total | Mean-post | % Of total | Mean change |
| Global           | 1,605,339,081 | 100 | 2,128,713,624 | 100 | 33*** | 1,269,534,317 | 100 | 1,772,166,191 | 100 | 40*** |
| (i) Region       |         |            |         |            |         |            |         |            |
| Asia             | 639,773,461 | 40 | 872,424,213 | 41 | 36*** | 568,824,128 | 45 | 806,508,318 | 46 | 42*** |
| Europe           | 330,926,420 | 21 | 379,827,657 | 18 | 15* | 89,093,662 | 7 | 87,565,421 | 5 | −2 |
| Latin America    | 237,503,288 | 15 | 366,337,076 | 17 | 54*** | 104,064,278 | 8 | 172,655,651 | 10 | 66*** |
| North America    | 354,937,104 | 22 | 373,182,071 | 18 | 5 | 500,520,453 | 39 | 697,413,838 | 39 | 39*** |
| Other            | 42,198,809 | 3 | 136,942,607 | 6 | 225*** | 7,031,796 | 1 | 8,022,964 | 0 | 14 |
| (ii) Asset group |         |            |         |            |         |            |         |            |
| Financial        | 1,027,338,643 | 64 | 1,361,010,312 | 64 | 32*** | 1,245,218,324 | 98.1 | 1,740,445,461 | 98 | 40*** |
| Interest rates   | 308,377,985 | 19 | 274,035,028 | 13 | −11 | 89,287,500 | 7 | 68,995,510 | 4 | −0.7** |
| Equity           | 502,529,595 | 31 | 810,873,715 | 38 | 61*** | 1,044,145,494 | 82 | 1,570,924,893 | 89 | 65*** |
| Currency         | 216,431,063 | 13 | 276,101,569 | 13 | 28*** | 111,785,329 | 9 | 100,525,058 | 6 | −10** |
| Commodity        | 578,000,438 | 36 | 767,703,312 | 36 | 33*** | 24,315,994 | 2 | 31,720,730 | 2 | 30*** |
| Agriculture      | 137,545,463 | 9 | 202,568,546 | 10 | 47*** | 9,761,677 | 1 | 11,552,578 | 1 | 19** |
| Energy           | 200,871,456 | 13 | 249,435,261 | 12 | 24** | 11,525,321 | 1 | 13,837,152 | 1 | 20** |
| Metals           | 165,530,553 | 10 | 197,223,817 | 9 | 19** | 2,971,367 | 0 | 4,146,314 | 0 | 40*** |
| Other            | 74,052,967 | 5 | 118,492,852 | 6 | 60*** | 57,628 | 0 | 2,184,686 | 0 | 3691*** |
| **Panel B: Open interest** |         |            | Mean-pre | % Of total | Mean-post | % Of total | Mean change |
| Global           | 254,909,831 | 100 | 244,094,167 | 100 | −4*** | 665,301,945 | 100 | 763,113,288 | 100 | 15*** |
| (i) Region       |         |            |         |            |         |            |         |            |
| Asia             | 46,823,913 | 18 | 50,729,220 | 21 | 8*** | 34,694,303 | 5 | 34,530,678 | 5 | −1 |
| Europe           | 79,517,771 | 31 | 69,688,702 | 29 | −12*** | 182,643,368 | 27 | 185,714,839 | 24 | 2 |
| Latin America    | 36,322,288 | 14 | 34,930,970 | 14 | −4 | 60,285,970 | 9 | 125,838,668 | 16 | 109*** |
| North America    | 80,811,362 | 32 | 73,167,234 | 30 | −10*** | 380,810,106 | 57 | 412,620,868 | 54 | 8*** |
| Other            | 11,434,497 | 4 | 15,578,040 | 6 | 36*** | 6,868,198 | 1 | 4,408,236 | 1 | −36** |
| (ii) Asset group |         |            |         |            |         |            |         |            |
| Financial        | 177,476,633 | 70 | 163,271,035 | 67 | −8*** | 641,309,212 | 96 | 736,088,470 | 96 | 15*** |
| Interest rates   | 85,776,998 | 34 | 74,588,785 | 31 | −13*** | 118,451,129 | 18 | 102,127,807 | 13 | −14*** |
| Equity           | 71,357,543 | 28 | 68,004,846 | 28 | −5* | 512,775,130 | 27 | 625,471,561 | 82 | 22*** |
| Currency         | 20,342,092 | 8 | 20,677,404 | 8 | 2 | 10,082,952 | 1 | 8,489,102 | 1 | −16** |
| Commodity        | 77,433,198 | 30 | 80,823,132 | 33 | 4*** | 23,992,734 | 4 | 27,024,819 | 3 | 13*** |
| Agriculture      | 14,709,362 | 6 | 16,555,064 | 7 | 13*** | 5,839,142 | 1 | 6,122,249 | 1 | 5 |
| Energy           | 47,825,709 | 19 | 46,257,074 | 19 | −3*** | 14,872,688 | 2 | 17,319,481 | 2 | 17*** |
| Metals           | 10,957,892 | 4 | 12,166,527 | 5 | 11*** | 3,054,336 | 0 | 2,955,714 | 0 | −3 |
| Other            | 3,940,236 | 2 | 5,844,466 | 2 | 48*** | 226,568 | 0 | 627,375 | 0 | 177*** |

Note: This table presents summary statistics for futures and options trading activity by regions and asset classes in the 12-month pre- and post-Covid periods. The pre-Covid period is January 2019–December 2019 and the post-Covid period is January 2020–December 2020. Panel A reports mean trade volumes, market shares of each region, and asset group, and the percentage difference in mean levels between the two periods along with indicators of statistical significance. Panel B reports the same statistics for open interest. *, **, and *** indicate significance at 10%, 5%, and 1% levels, respectively.
breakdowns in Figures 2–4, respectively. In Figure 2a, during the first 3 months of the pandemic (January–March 2020) we observe very large log increases in both global futures and options volume of approximately 59% and 31%, respectively. These increases were then followed by a large decline over the next couple of months, and a subsequent similar, continued upward growth in each month for the remainder of 2020. In Figure 2b based on open interest, we observe a general increase for options experienced about an 18% increase during early 2020, while that for futures was relatively flat before declining by about 6%.

In Figure 3a,b we present growth rates in volume and open interest for futures and options combined, respectively, for each geographic region. In Figure 3a, for the three larger regions (North America, Asia, and Europe), we observe somewhat similar comovements during the pandemic period. The other region, Latin America, differed somewhat with a small initial spike in volume in 2020 followed by a pattern of continued growth through most of the remainder of 2020. In Figure 3b based on open interest, again with the exception of Latin America, the growth during 2020 is fairly flat to modestly positive and again similar across regions.

In Figure 4a,b we similarly present breakdowns for volume and open interest, respectively, according to the two asset groups Financial (interest rates, equities, and currencies) and Commodity (agriculture, energy, and metals). The patterns of the combined futures and options volume growth for both financial and commodity derivatives are somewhat similar as shown in Figure 4a. For open interest (Figure 4b), both sectors showed initial spikes during the early months of the pandemic following which Financials continued to grow while Commodities tended to revert to pre-Covid levels.6

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6While the focus of our study is on exchange-traded derivatives, we can offer comment on the growth of over-the-counter (OTC) derivatives during 2020. On the basis of Bank of International Settlements (BIS) survey statistics compiled and reported semiannually, total global notional amounts of OTC derivatives grew 9% from $558.3 trillion to $606.8 trillion from year-end 2019 to June 2020. This was followed by a 4% decline to $582.1 trillion in December 2020. These changes were largely driven by interest rate derivatives, which grew from $449.0 to $495.1 trillion from December 2019 to June 2020, before receding to $466.5 trillion in December 2020. Similar to exchange-traded commodity derivatives, OTC commodity derivatives remained flat for the year at $2.1 trillion at each of the three dates. For more information, see http://stats.bis.org/statx/.
FIGURE 3  Changes in region-level derivatives trading activity: January 2019–December 2020. The figures plot the relative change in log region volume and open interest of futures and options contracts. The log volume/open interest at relative month-1 (December 2019) is normalized to zero.

FIGURE 4  Changes in Financial and Commodity derivatives trading activity: January 2019–December 2020. The figures plot the relative change in log volume and open interest of futures and options contracts for Financial and Commodity groups. The log volume/open interest at relative month-1 (December 2019) is normalized to zero.
3.2.3 Event study tests

To determine whether the changes in volume and open interest through the onset of the pandemic presented in the above figures are statistically significant, we conduct a trading activity-based event study using various event windows. The length of these windows varies from 1 to 4 months and 12 months (i.e., [0, 0], [0, 1], [0, 2], [0, 3], and [0, 11]) based on using January 2020 as the event month \( t = 0 \). To perform these tests, for each exchange \( i \) in month \( t \), we calculate the monthly percentage change in trading activity, and then compute the weighted mean change and standard error using global trading activity weights. Results for trade volume are presented in panel A of Table 2, while those based on open interest are presented in panel B.

In panel A, we report a cumulative change in global volume of futures and options combined in the 3-month January–March 2020 window \([0, 2]\) of 60.7%, which is statistically significant at the 1% level. For the entire 2020 year window \([0, 11]\), cumulative growth was a significant 65.4%. Similar levels of statistical significance for the 3-month window \([0, 2]\) were observed in each region and for both the Financial and Commodity asset groups. Europe had the largest initial 3-month growth in the volume of 107.7% but was an insignificant 13.8% for all of

| TABLE 2 Event study tests of cumulative trading activity in pandemic period |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Event window                | [0, 0]                      | [0, 1]                      | [0, 2]                      | [0, 3]                      | [0, 11]                     |
| **Panel A: Trading volume** |                             |                             |                             |                             |                             |
| Global                      | 0.151***                    | 0.285***                    | 0.607***                    | 0.179***                    | 0.654***                    |
| (i) Region                  |                             |                             |                             |                             |                             |
| Asia                        | 0.037                       | 0.084                       | 0.363***                    | 0.071                       | 0.758***                    |
| Europe                      | 0.129*                      | 0.383***                    | 1.077***                    | 0.250                       | 0.138                       |
| Latin America               | 0.397***                    | 0.352***                    | 0.400***                    | 0.337***                    | 0.871***                    |
| North America               | 0.229***                    | 0.515***                    | 0.840***                    | 0.238***                    | 0.419***                    |
| CME Group                   | 0.222***                    | 0.762***                    | 1.173***                    | 0.151                       | 0.123***                    |
| (ii) Asset group            |                             |                             |                             |                             |                             |
| Financial                   | 0.213***                    | 0.350***                    | 0.622***                    | 0.093**                     | 0.584***                    |
| Commodity                   | −0.085                      | 0.031                       | 0.534***                    | 0.464***                    | 0.604***                    |
| **Panel B: Open interest**  |                             |                             |                             |                             |                             |
| Global                      | −0.007                      | 0.113***                    | 0.132***                    | 0.070***                    | 0.143***                    |
| (i) Region                  |                             |                             |                             |                             |                             |
| Asia                        | 0.011                       | 0.142***                    | 0.071                       | 0.009                       | 0.083                       |
| Europe                      | 0.149***                    | 0.273***                    | 0.149***                    | 0.164***                    | −0.046**                    |
| Latin America               | −0.203***                   | −0.025                      | 0.462***                    | −0.026                      | 0.517***                    |
| North America               | −0.033                      | 0.068***                    | 0.036**                     | 0.061***                    | 0.148*                      |
| CME Group                   | 0.087***                    | 0.163***                    | 0.086***                    | 0.056                       | −0.161***                   |
| (ii) Asset group            |                             |                             |                             |                             |                             |
| Financial                   | −0.013                      | 0.117***                    | 0.134***                    | 0.067***                    | 0.162***                    |
| Commodity                   | 0.027*                      | 0.071***                    | 0.114***                    | 0.087***                    | 0.041                       |

**Note:** This table reports results of tests of significance of cumulative mean changes in trading activity in futures and options markets over various monthly event windows. Trading activity measures include volume and open interest. Month 0 is January 2020. The results are presented for trading on all exchanges (Global), various geographic regions, the CME Group of exchanges (CME, CBOT, NYMEX, and COMEX), and the Financial and Commodity asset groups. *, **, and *** indicate significance at 10%, 5%, and 1% levels, respectively.

**Abbreviations:** CBOT, Chicago Board of Trade; CME, Chicago Mercantile Exchange; COMEX, Commodity Exchange; NYMEX, New York Mercantile Exchange.
2020. For the CME Group, cumulative volume growth for the first 3 months was 117.3%, but reverted to 12.3% for all of 2020.\footnote{For additional reader interest, we also include in the region category statistics report in Table 2 those for the US-based holding company CME Group, which consists of the four exchanges: the Chicago Mercantile Exchange (CME), the Chicago Board of Trade (CBOT), the New York Mercantile Exchange (NYMEX), and the Commodity Exchange (COMEX).}  

In panel B of Table 2, growth in futures and options open interest is generally of a much smaller magnitude than that of volumes across both regions and asset groups, and in a number of subsamples was insignificant. Globally, the changes in open interest in the first 3 months and all of 2020 were a statistically significant 13.2% and 14.3%, respectively. However, growth in Asia though positive, was insignificant after 3 months. Further, growth in open interest in both Europe and the CME Group while positive for early 2020 became statistically negative by year-end. For the two asset groups, the change in open interest in Financials was larger with a change in the first 3 months of 13.4%, and 16.2% for the year. In contrast, Commodity open interest grew 11.4% in the first 3 months of 2020 and an insignificant 4.1% for the year.

### 3.3 Correlation analysis

As financial markets and derivatives markets in particular have grown and expanded throughout the world, it is important to understand how levels of trade interconnectedness are affected during periods of market crises. Prior research, primarily focusing on the behavior of asset returns, finds increases in market volatility during crises and the tendency for volatilities and correlations to move more strongly together (see, e.g., Bookstaber, 1997; Marti et al., 2021; Sandoval & Franca, 2012). As a dimension of financial market integration, it is important to understand whether these findings extend similarly to the behavior of derivatives trading activity.

To investigate this, we first compute correlation matrices at the country and region levels based on changes in monthly derivatives trade volume during both the pre- and post-Covid periods. For the pre-Covid period, we use the 5-year 2015–2019 period, and for the post-Covid period we use the remaining months in our data of January 2020–March 2021. In Figure 5 we present heat maps based on the country-level cross-correlations of monthly volume changes for the 30 countries represented in the pre- and post-Covid periods. In the heat maps, darker red colors represent higher positive correlations while darker blue colors represent more negative correlations. When comparing the pre- and post-Covid heat maps, we observe generally speaking, a pattern of increasing correlations between countries during the post-Covid period.

To investigate this further, given the size of the matrices and to assist in our comparison, we first report in Table 3 various summary statistics based on the 435 $\frac{[1]}{2}$ pairwise correlations in each period. In the pre-Covid period, the mean correlation was 0.290 as compared with 0.381 in the post-Covid period, or a near 10% statistically significant increase. On the basis of median values, the difference was more pronounced based on pre- and post-Covid values of 0.278 and 0.440, respectively, or a significant increase of 62.2%. Further, of the 435 pairwise correlations, there were 292 (67%) increases and 143 (33%) decreases in the post-Covid period.

We also report in Figure 6 the distribution of the pairwise correlations in each period. Comparing the two distributions, in the pre-Covid period we observe the correlations to have somewhat of a normal distribution shape. In the post-Covid period, there is a notable skew-shaped shift to the right, positive side due to the increased magnitude of the correlations. There is also an increase in the number of negative correlations between the two periods from 37 to 75. Of these 75 negative pairwise correlations, 35 involved at least one country in Latin America. This observed shift to a skew-shaped distribution is a finding similarly reported for stocks returns in Onnela et al. (2003) and Sensoy and Tabak (2014) during periods of the Black Monday stock market crisis of 1987, the 1997 Asian crisis and the 2007–2009 Great Recession, and which the authors suggest is evidence of contagion.

In Figure 7 we present region-level heat maps and means of cross-correlations of the monthly derivatives trade volume changes. During the pre-Covid period, the four regions generally exhibited strong positive correlations. To illustrate, North America had correlations of 0.614, 0.565, and 0.449 with Europe, Latin America, and Asia, respectively. Even the lowest correlation in the matrix of 0.351 between Europe and Latin America was relatively strong. Post-Covid, we observe several notable changes. These include a strong strengthening of the correlations among North America, Europe, and Asia. To illustrate, the correlations between North America with Europe and Asia increase to 0.854 and 0.585, respectively (from 0.614 and 0.449). In contrast, there is a weakening of the correlations between Latin America and each of the other three major regions. Most notably, the correlation between Latin America and North America fell from 0.565 to 0.339.
This behavior of the Latin American region (which is largely influenced by the large Brazilian B3 exchange) along with the earlier reported findings regarding Latin America are interesting. We conjecture that these were influenced by at least three factors. First, trade activity on the B3 exchange is less diversified across the various asset classes than that on exchanges in other regions and is dominated by equity derivatives. To illustrate, during the 12-month pre-Covid period, trade volume growth was more concentrated in equity derivatives compared to other asset classes.

**FIGURE 5**  Heat maps of country-level correlation matrices of derivatives trade volume growth. The figures plot the heat maps of pairwise correlations of country-level monthly derivatives trade volume growth for pre- and post-Covid periods. (a) The heat map for the pre-Covid period (2015–2019) and (b) the heat map for the post-Covid period (2020–March 2021).

**TABLE 3** Summary statistics of trade volume correlations

| Panel A: Correlations | Mean   | Median | Min   | Max   |
|-----------------------|--------|--------|-------|-------|
| Pre-Covid             | 0.290  | 0.278  | −0.315| 0.896 |
| Post-Covid            | 0.381  | 0.440  | −0.600| 0.959 |
| Difference (post-pre) | 0.091  | 0.162  | −0.285| 0.063 |
| p value               | 0.000  | 0.000  |       |       |

| Panel B: Changes in correlations | Number | Percentage |
|----------------------------------|--------|------------|
| Increases                        | 292    | 67         |
| Decreases                        | 143    | 33         |
| Total                            | 435    | 100        |

Note: This table reports summary statistics for country-level pairwise correlations of changes in monthly derivatives trade volume in the pre- and post-Covid periods. The pre-Covid period is from 2015 to 2019 and the post-Covid period is from 2020 to March 2021. Panel A shows the mean, median, minimum, and maximum values of the pairwise correlations of 30 represented countries as well as the p value of tests for differences in means and medians. Panel B shows the number and percentage of correlations that increase/decrease following the pandemic outbreak.
period the volume of index futures and individual equity options comprised 42% and 23%, respectively, of all exchange
volume. This 65% total is significantly large compared with that in other regions where the mean share of equity
derivatives trading was about 54%. Second, during 2019 and early 2020, Brazil equity markets underwent a resurgence
due to market reforms.8 Third, the public health effects of the Covid-pandemic in Brazil were experienced somewhat
later than in major countries of other regions. To illustrate, by the end of March 2020, new daily cases surged to 100 or

8See, for example, “Why Brazil Is The Best Stock Market In The World Right Now” at https://www.forbes.com/sites/kenrapoza/2019/01/08/brazil-is-the-best-stock-market-in-the-world-right-now/?sh=202a2acc71d5

FIGURE 6 Correlation histograms: pre- and post-Covid. This figure provides histograms of country-level correlations of
percentage volume changes during the pre- and post-Covid periods.

FIGURE 7 Heat maps of region-level correlation matrices of derivatives trade volume growth. The figures plot and report the
heat maps and means of pairwise correlations of region-level monthly volume growth for pre- and post-Covid periods. (a) The
heat map for the pre-Covid period (2015–2019) and (b) the heat map for the post-Covid period (2020–March 2021).
more per million population in the United States as well as major European countries, including Italy, Spain, and France. On the other hand, Brazil did not reach this threshold until late May.9

3.4 | MST analysis and network metrics

We further analyze the changes in the country-level cross-correlations wherein we employ MST technology based on network theory. In the literature analyzing interconnectedness of financial markets and financial institutions, network analysis has been commonly applied (e.g., see Aslam et al., 2020; Raddant & Kenett, 2021; Summer, 2013). A major benefit of using MST technology in network analysis is that it can help describe and facilitate the interpretation of large correlation systems by allowing for a significant reduction in the information space within large matrices without arguably a loss in essential information. Further, given that all markets are connected to some extent, the MST methodology helps identify the set of nodes within a matrix that has the most and strongest connections and provides a topological view of the structure of the system. The resulting MST diagram is thus an appropriate tool for identifying those countries playing central roles in the global derivatives market as well as the peripheral countries with limited power to influence the market. Another benefit of using the MST technology is that it produces various diagnostic metrics, including an assortment of centrality statistics, to assist in the analysis of the topological properties of the network.10 We use this technique to investigate how the Covid pandemic affected connections between countries and derivatives exchanges.

Following procedures introduced in Mantegna (1999), to construct an MST we first make a nonlinear transformation of our correlation matrices into distance matrices using the distance metric \( d_{ij} = \sqrt{2(1 - \rho_{ij})} \) where \( \rho_{ij} \) is the correlation of derivatives trade volume changes between countries \( i \) and \( j \). This procedure thus converts correlations ranging from +1 to −1 to Euclidean distances ranging from 0 to 2. Hence, higher correlations are associated with shorter or closer distances. Using the distance matrix, we then consider an undirected graph \( G \) of the network of distances having vertices (or nodes) \( V \) and edges (or links) \( E \), that is, \( G = (V, E) \).

A spanning tree is an acyclic subset of the graph \( G \) in which (1) all vertices (in our case countries) are represented and are connected to at least one other vertex via an edge of a given length or distance; and (2) none of the vertices have a cycle or a loop back to itself (i.e., the tree is acyclic). While there can be several spanning trees in a network, the MST is defined as the one having the smallest sum of distances of its edges that keeps the tree in one connected component. To build the MST we utilize the Kruskal (1956) algorithm whereby we first connect the two vertices having the shortest edge or lowest connecting distance. The next shortest edge is then identified and added to the tree. This procedure is repeated until each remaining unconnected vertex has been added to the tree with the requirement that no closed loops are created. We present the resulting MSTs for the pre- and post-Covid periods in Figure 8a,b.

Comparing the two trees, we make a number of observations. First, the length of the two trees (the sum of the distances of all edges in the MST scaled by the number of edges) shrank from 0.821 to 0.649, thus indicating an increased level of connectedness. Second, in the pre-Covid period we also observe a number of “hubs” with the predominant ones, including Japan, Germany, the United States, and Singapore. Further, there is a tendency for the Latin American countries to lie towards the outer edges of the MST reflecting their lower connectedness to other countries. The Asian countries tend to show a large degree of clustering especially in consideration that two of the exceptions (Australia and New Zealand) are geographically closer to each other than to the other Asian countries. Several of the European countries are connected with the exception of the United Kingdom and France who appear to be more of a part of the North America (the United States and Canada) orbit. Post-Covid, the major hubs clearly include the United States and to a lesser extent Japan and Sweden. The Asian and European countries now appear to be more widely dispersed throughout the tree. Again, the Latin American countries remain on the outer edges of the tree.

To further investigate the nature of the connectedness and relative importance of the various countries for facilitating the flow of information, for each node (country) we compute three topological statistics based on measures of centrality, including degree, betweenness, and closeness centrality. While the three measures are typically empirically highly correlated, there are differences in their economic interpretation. In simple terms, the degree centrality of a given node is the number of other nodes that it is in immediate, direct contact with and is an indicator of the breadth of

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9For additional details, see https://ourworldindata.org/covid-cases
10For further discussion and application of MSTs in financial market settings, see, for example, Onnela et al. (2003), Aswani (2017), Aslam et al. (2020), and Zhang et al. (2020).
its relations with other nodes. Betweenness centrality is the importance of a node as an intermediate part between other nodes, in other words, it can be thought of as a measure of the extent to which the node serves as a bridge for the flow of information between other nodes. Closeness centrality is a measure of a given node's average closeness to all other nodes, which reflects its relative importance to all other nodes and ability to spread information more rapidly. As discussed in Sensoy & Tabak (2014), markets having greater centrality are thought to have a greater influence and a greater ability to transmit information to other markets especially during global crises. On the other hand, markets having low centrality are more resilient to economic shocks of a global nature and are more dependent on their own domestic and regional conditions.

We provide in Appendix B expressions and more detailed information for the calculation of each of the three centrality measures along with an overall network centralization statistic for each measure. Using these expressions, we compute the various measures for each country based on the MSTs presented earlier in Figure 8a,b for the pre- and post-Covid periods. We present a summary of these findings in Table 4 wherein for each measure we report the five countries having the highest global rankings along with their individual metrics. To facilitate comparison across MSTs, the measures are normalized to produce values between 0 and 1 with higher values denoting greater centrality.

11 Individual measures for each centrality measure and associated global ranking for all 30 countries are available upon request.
In panel A of Table 4 for the pre-Covid period, we observe that Japan appears to be the country with the highest overall centrality as it ranks first in both betweenness (0.697) and closeness (0.345) and tied for second on degree centrality (0.138). The United States ranked highest on degree centrality (0.207) and third and fourth, respectively, on closeness (0.302) and betweenness (0.473). Other countries exhibiting high centrality include Sweden and Germany.

In the post-Covid period, the United States holds the top position of centrality based on each of the three measures with values of 0.172, 0.724, and 0.319 for degree, betweenness, and closeness centrality, respectively. Japan ranked second on each measure, while Sweden ranked third on each measure. These findings are consistent with those we observed earlier in Figure 8 wherein the United States appears to become the primary hub in the post-Covid period and Japan a second major hub. Finally, we observe little change between periods in the overall network centralization statistic for each measure.

### Table 4  Network centrality measures by leading countries

| Degree centrality | Betweenness centrality | Closeness centrality |
|-------------------|------------------------|----------------------|
| **Panel A: Pre-Covid period** | | |
| Rank | Country | Centrality | Rank | Country | Centrality | Rank | Country | Centrality |
|-------|---------|------------|-------|---------|------------|-------|---------|------------|
| 1 | The United States | 0.207 | 1 | Japan | 0.697 | 1 | Japan | 0.345 |
| 2 | Australia | 0.138 | 2 | Germany | 0.507 | 2 | Sweden | 0.322 |
| 2 | Japan | 0.138 | 3 | Sweden | 0.488 | 3 | The United States | 0.302 |
| 2 | Singapore | 0.138 | 4 | The United States | 0.473 | 4 | Germany | 0.296 |
| 2 | Poland | 0.138 | 5 | Poland | 0.406 | 5 | Singapore | 0.290 |
| Overall mean | 0.067 | 0.127 | | | | 0.228 |
| Centralization | 0.150 | 0.590 | | | | 0.247 |

| **Panel B: Post-Covid period** | | |
| Rank | Country | Centrality | Rank | Country | Centrality | Rank | Country | Centrality |
|-------|---------|------------|-------|---------|------------|-------|---------|------------|
| 1 | The United States | 0.172 | 1 | The United States | 0.724 | 1 | The United States | 0.319 |
| 2 | Japan | 0.138 | 2 | Japan | 0.525 | 2 | Japan | 0.293 |
| 3 | Sweden | 0.103 | 3 | Sweden | 0.431 | 3 | Sweden | 0.282 |
| 3 | Germany | 0.103 | 4 | Germany | 0.362 | 4 | France | 0.271 |
| 3 | Singapore | 0.103 | 5 | Italy | 0.352 | 5 | Germany | 0.252 |
| Overall mean | 0.067 | 0.147 | | | | 0.206 |
| Centralization | 0.113 | 0.598 | | | | 0.240 |

*Note:* In this table, we report the degree, closeness, and betweenness centrality measures for the five leading countries for each measure during the pre- and post-Covid periods. We also report for all countries the overall mean value and the network centralization statistic for each measure.

4 | **Margin and Customer Segregated Fund Analysis**

We next investigate the management and setting of margin requirements by US futures exchanges in response to changes in the levels of market uncertainty that developed during the Covid-19 pandemic. We focus on US markets due to the availability of margin data. Also, in conjunction, we inspect the response of traders in terms of their demand for futures as measured by the amounts of customer funds required of them to be held in accounts at FCMs to support the margin requirements of their positions.

The management of counterparty credit risk in futures markets to prevent and mitigate losses associated with default differs from that in OTC derivatives markets. For OTC derivatives transactions, counterparty credit risk has traditionally been managed through stipulations set forth in master agreements in regard to collateral requirements, the maintenance of protective covenants, and the use of mark-to-market margining. In contrast, for exchange-traded derivatives, such as futures,
counterparty default risk is managed through the use of clearing houses affiliated with the exchanges who assume the role of counterparty to both sides of a transaction. In turn, to ensure the financial integrity of the exchange and its clearinghouse and to protect these entities from customer default, traders are subject to initial and maintenance margin requirements along with the daily resettlement of gains and losses on the value of their open positions. To assist in the setting of these margin requirements, US futures exchanges make use of standard portfolio analysis of risk (SPAN) margining systems, which in large part are based on value at risk (VaR) methodologies that typically set margin levels at sufficient levels to cover potential 1-day market movements with a high probability (e.g., 99%).

4.1 Customer funds during the pandemic

To help motivate our analysis of margin changes and to place into historic context the effect of the Covid-19 pandemic on margin requirements, we first inspect levels of customer funds held at FCMs during the period 2002–2021. FCMs are the entities through which all futures customers (e.g., institutional, corporate, and retail traders) will conduct and clear their trading. As discussed in Emm et al. (2020), the primary functions of FCMs are (1) to solicit and accept customer orders for futures trading, and (2) to accept and ensure that sufficient levels of customer funds are in place to support the initial and variation margin requirements for their trades.

The Commodity Exchange Act, the governing law over futures trading, requires an FCM to protect and separate their customer funds from the FCM’s own proprietary funds and trading activities. Hence, customer funds are referred to as either segregated or secured funds, but have a technical distinction. Funds intended to support trading and margin requirements on US futures exchanges are referred to as segregated or “seg” funds, while funds of US customers wishing to trade on foreign futures exchanges are held in different accounts and are referred to as secured funds. FCMs are also required to file monthly reports (Form 1-FR-FCM) to the CFTC in which they must disclose the total amounts of segregated and secured funds held on behalf of customers. The CFTC then compiles information from these filings and publishes a monthly “Financial Data for FCMs” report that provides totals of each type of fund held at each FCM.

We obtain all monthly CFTC reports over the period 2002–2021 from which we record total amounts of segregated and secured funds held at FCMs. We present monthly totals for both types of funds and their associated percentage changes in Figure 9a,b, respectively. In Figure 9a we see sizeable changes in levels of customer funds, especially segregated funds, during crisis periods associated with the Great Recession (2007–2009), the European debt crisis (2010–2012), and to a lesser extent the Brexit referendum (2016–2017). Still, these changes pale in comparison with the jump observed in March 2020 when segregated funds reached $264.6 billion, compared with $172.9 billion in the month prior. As indicated in Figure 9b, this represented a monthly increase of 53.0%, while the next largest increases in segregated funds were 9.8% in April 2006 and 9.1% in both February 2008 and September 2008. Further, the March 2020 increase exceeded the 24-month accumulated growth of 43.4% from all of January 2007 to December 2008 portion spanning much of the Great Recession. Similarly, secured funds rose to $53.7 billion in March 2020 from $41.2 billion in February, or an increase of 30.3%. Given our earlier finding of much lower levels of growth in open interest in North America during the Covid-19 period, this large increase in customer segregated funds can be largely attributable to a general overall large increase in margin requirements, which we next explore in greater depth.

4.2 Analysis of margin levels and changes

To investigate margin levels, we utilize data published by the CME Group on daily futures margin requirements for a large sample of 35 futures contracts spanning six asset classes and that trade on the four futures exchanges (CBOT, CME, NYMEX, and COMEX) comprising the CME Group. The margins we investigate are for outright positions in the front-month contract of each futures (in which trade volume and open interest are typically the highest). These margin amounts serve as both the initial and maintenance margin requirements for commercial traders and as the maintenance margin requirement for noncommercial traders.

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12Research (see, e.g., Park & Abruzzo, 2016) also suggests that competitive pressures with competing contracts on other exchanges may influence an exchange’s margin setting.

13As of March 2020, there were 53 FCMs in the United States who carried customer funds.
In Figure 10a–f, we present plots of the daily margin levels covering the 1-year periods before and following the Covid-19 outbreak for futures contracts in each asset class. While there is cross-sectional variation in the patterns among futures within and across asset classes, generally speaking, during the pre-Covid period we observe relatively stable margin levels. In contrast, in the post-Covid period, we observe large significant jumps in daily margin levels, especially beginning in March 2020, followed by a general leveling off or downward tapering.

To further quantify these observations, we compute and report in Table 5 various summary statistics for each futures and asset class for the 12-month pre- and post-Covid periods. In panel A of the table, these statistics include the mean daily margin levels per contract in the pre- and post-Covid periods, the dollar and percentage differences in mean levels between the two periods along with Newey–West corrected p values for the differences. Correspondingly, in panel B, for each futures and asset class we report the number of increases and decreases in margins in each period to proxy for the rates of information arrival affecting prices and volatilities that would typically prompt the exchange to adjust margins.

Generally speaking, in the post-Covid period we find in panel A statistically significant increases in daily margin levels across nearly all futures and asset classes. We also observe in panel B a greater number of margin changes, most of which are increases, in the post-Covid period. To illustrate, in panel A for energy futures, we find significant increases in margin levels between the two periods for crude oil, gasoline, and heating oil futures (for natural gas futures the difference was statistically insignificant). More specifically, for crude oil there was a statistically significant increase on average daily margin levels of $2167 or 56.9%. In addition, in the pre-Covid period in panel B, we report 4 increases and 7 declines in crude oil margins followed by 9 increases and 8 declines in the subsequent period. Across all 4 energy futures, there was an average percentage increase in margin levels of 30.1%. Further, there were 18 overall increases and 22 decreases in energy futures margins during the pre-Covid period compared with 30 increases and 24 decreases during the post-Covid period.

For interest-rate futures, there were statistically significant increases in margin requirements between the two periods in six of the eight futures. Treasury bond (T-bond) futures, one of the more actively traded interest-rate futures,
shows a 78.1% margin increase. For 2- and 5-year T-note futures, there were insignificant changes on average margin levels. Across all interest-rate futures there was a total of 55 margin changes in the 1-year pre-Covid period followed by 85 changes in the subsequent 1-year period. Although in the post-Covid period we observe more decreases in interest-rate futures margins compared with increases, the average increase was considerably more sizable than the average decrease.

Of the various asset classes, the changes between the two periods appear to be the most pronounced for metal futures. To illustrate, average silver and gold futures margins increased by $6378 (157.9%) and $4665 (119.5%),

FIGURE 10  Daily futures margin requirements: January 2019–February 2021. These figures present levels of daily margin requirements for front-month futures contracts in various asset classes.
|                          | Pre  | Post | Diff (post-pre) | p value | % Diff |
|--------------------------|------|------|----------------|---------|--------|
| **Energy**               |      |      |                |         |        |
| Crude oil                | 3807 | 5974 | 2167           | 0.001   | 56.9   |
| RBOB gasoline            | 4406 | 6130 | 1724           | 0.002   | 39.1   |
| Heating oil              | 4092 | 4945 | 853            | 0.014   | 20.8   |
| Natural gas              | 2152 | 2228 | 76             | 0.812   | 3.5    |
| **Mean**                 |      |      |                |         | 30.1   |
| **Interest rates**       |      |      |                |         |        |
| Ultra T-bond             | 3944 | 9580 | 5636           | 0.000   | 142.9  |
| T-bond                   | 2634 | 4691 | 2057           | 0.000   | 78.1   |
| Ultra 10-year T-note     | 1518 | 2635 | 1117           | 0.000   | 73.6   |
| 30-day fed funds         | 274  | 382  | 108            | 0.074   | 39.4   |
| 10-year T-note           | 1168 | 1568 | 400            | 0.000   | 34.2   |
| Eurodollar               | 242  | 316  | 74             | 0.029   | 30.6   |
| 5-year T-note            | 720  | 722  | 2              | 0.953   | 0.3    |
| 2-year T-note            | 532  | 462  | −70            | 0.154   | −13.2  |
| **Mean**                 |      |      |                |         | 48.2   |
| **Currency**             |      |      |                |         |        |
| Japanese yen             | 1933 | 3380 | 1447           | 0.000   | 74.8   |
| Swiss franc              | 2732 | 3989 | 1257           | 0.000   | 46.0   |
| Australian dollar        | 1299 | 1680 | 381            | 0.000   | 29.3   |
| Canadian dollar          | 1057 | 1343 | 286            | 0.000   | 27.1   |
| British pound            | 2290 | 2690 | 400            | 0.000   | 17.5   |
| New Zealand              | 1282 | 1477 | 195            | 0.005   | 15.2   |
| Euro currency            | 2065 | 2267 | 201            | 0.064   | 9.8    |
| **Mean**                 |      |      |                |         | 31.4   |
| **Metals**               |      |      |                |         |        |
| Silver                   | 4038 | 10416| 6378           | 0.000   | 157.9  |
| Gold                     | 3905 | 8570 | 4665           | 0.000   | 119.5  |
| Platinum                 | 1902 | 3684 | 1782           | 0.000   | 93.7   |
| Copper                   | 2616 | 3378 | 762            | 0.000   | 29.1   |
| **Mean**                 |      |      |                |         | 100.1  |
| **Agriculture**          |      |      |                |         |        |
| Soybean oil              | 516  | 752  | 236            | 0.000   | 45.7   |
| Lean hogs                | 2006 | 2684 | 678            | 0.000   | 33.8   |
| Feeder cattle            | 2984 | 3973 | 989            | 0.000   | 33.2   |
| Live cattle              | 1596 | 2058 | 462            | 0.000   | 29.0   |
| Corn                     | 901  | 917  | 16             | 0.771   | 1.8    |
| Wheat                    | 1362 | 1308 | −54            | 0.150   | −4.0   |
| Soybean meal             | 1214 | 1159 | −55            | 0.356   | −4.5   |
TABLE 5 (Continued)

|                                | Pre | Post | Diff (post − pre) | p value | % Diff |
|--------------------------------|-----|------|-------------------|---------|--------|
| Soybeans                       | 1821| 1618 | −203              | 0.001   | −11.1  |
| Mean                           |     |      |                   |         | 15.5   |
| **Equity**                     |     |      |                   |         |        |
| NASDAQ 100                     | 7534| 14,030| 6496             | 0.000   | 86.2   |
| S&P500                         | 31,010| 54,440| 23,430          | 0.000   | 75.6   |
| Dow Jones                      | 5573| 9427 | 3854             | 0.000   | 69.2   |
| Nikkei 225                     | 5237| 7456 | 2219             | 0.000   | 42.4   |
| Mean                           |     |      |                   |         | 68.3   |

Panel B: Summary statistics for margin increases and decreases

|                                | Pre No. of increases | Pre No. of decreases | Pre Mean increase (%) | Pre Mean decrease (%) | Post No. of increases | Post No. of decreases | Post Mean increase (%) | Post Mean decrease (%) |
|--------------------------------|----------------------|----------------------|-----------------------|-----------------------|-----------------------|-----------------------|------------------------|------------------------|
| **Energy**                     |                      |                      |                       |                       |                       |                       |                        |                        |
| Crude oil                      | 4                    | 7                    | 9.5                   | −6.7                  | 9                     | 8                     | 14.8                   | −11.5                  |
| RBOB gasoline                  | 2                    | 3                    | 12.2                  | −8.7                  | 7                     | 6                     | 12.9                   | −12.7                  |
| Heating oil                    | 4                    | 5                    | 8.1                   | −7.7                  | 4                     | 5                     | 15.5                   | −11.3                  |
| Natural gas                    | 8                    | 7                    | 10.6                  | −20.7                 | 10                    | 5                     | 9.3                    | −11.8                  |
| Total                          | 18                   | 22                   | 10.1                  | −10.9                 | 30                    | 24                    | 13.1                   | −11.8                  |
| Mean                           |                      |                      |                       |                       |                       |                       |                        |                        |
| **Interest rates**             |                      |                      |                       |                       |                       |                       |                        |                        |
| Ultra T-bond                   | 3                    | 2                    | 11.7                  | −7.9                  | 7                     | 5                     | 18.8                   | −9.0                   |
| T-bond                         | 3                    | 2                    | 7.7                   | −7.9                  | 6                     | 5                     | 16.2                   | −8.4                   |
| Ultra 10-year T-note           | 3                    | 3                    | 10.4                  | −7.5                  | 6                     | 5                     | 13.7                   | −8.3                   |
| 30-day Fed Funds               | 8                    | 1                    | 14.3                  | −20.4                 | 3                     | 9                     | 29.0                   | −14.1                  |
| 10-year T-note                 | 4                    | 2                    | 7.9                   | −10.1                 | 6                     | 4                     | 9.7                    | −8.5                   |
| Eurodollar                     | 7                    | 2                    | 13.9                  | −10.1                 | 2                     | 6                     | 25.8                   | −11.6                  |
| 5-year T-note                  | 4                    | 3                    | 8.9                   | −9.8                  | 3                     | 5                     | 9.7                    | −9.0                   |
| 2-year T-note                  | 5                    | 3                    | 11.3                  | −13.4                 | 4                     | 9                     | 10.9                   | −10.5                  |
| Total                          | 37                   | 18                   | 10.8                  | −10.9                 | 37                    | 48                    | 16.7                   | −9.9                   |
| Mean                           |                      |                      |                       |                       |                       |                       |                        |                        |
| **Currency**                   |                      |                      |                       |                       |                       |                       |                        |                        |
| Japanese yen                   | 1                    | 0                    | 19.4                  | 2                     | 5                     | 3                     | 15.7                   | −12.2                  |
| Swiss franc                    | 2                    | 1                    | 14.9                  | −9.6                  | 3                     | 3                     | 17.8                   | −9.9                   |
| Australian dollar              | 1                    | 1                    | 8.0                   | −11.1                 | 5                     | 3                     | 13.9                   | −11.2                  |
| Canadian dollar                | 0                    | 2                    | −11.5                 | 6                     | 3                     | 12.7                  | −12.0                  |
| British pound                  | 1                    | 1                    | 14.3                  | −12.5                 | 2                     | 1                     | 11.8                   | −10.0                  |
| New Zealand                    | 0                    | 1                    | −14.3                 | 4                     | 3                     | 14.7                  | −11.2                  |

(Continues)
### TABLE 5 (Continued)

#### Panel B: Summary statistics for margin increases and decreases

|                | Pre          | Post          |                |                |                |                |
|----------------|--------------|--------------|----------------|----------------|----------------|----------------|
|                | No. of        | No. of        | Mean           | Mean           | Mean           | Mean           |
|                | increases     | decreases     | increase (%)   | decrease (%)   | increase (%)   | decrease (%)   |
| Euro currency  | 0            | 2            | −11.5          |                | 6              | 3              | 9.4            | −9.1          |
| Total          | 5            | 8            |                |                | 31             | 19             |                |              |
| Mean           | 14.2         | −11.8        |                |                | 13.7           | −10.8          |                |              |

**Metals**

|                | Pre          | Post          |                |                |                |                |
|----------------|--------------|--------------|----------------|----------------|----------------|----------------|
|                | No. of        | No. of        | Mean           | Mean           | Mean           | Mean           |
|                | increases     | decreases     | increase (%)   | decrease (%)   | increase (%)   | decrease (%)   |
| Silver         | 4            | 1            | 12.2           | −8.3           | 11             | 3              | 12.6           | −9.8          |
| Gold           | 3            | 0            | 9.8            |                | 10             | 2              | 11.1           | −11.7         |
| Platinum       | 4            | 2            | 13.7           | −11.9          | 5              | 3              | 15.4           | −9.8          |
| Copper         | 1            | 3            | 12.5           | −11.7          | 6              | 2              | 14.6           | −12.1         |
| Total          | 12           | 6            |                |                | 32             | 10             |                |              |
| Mean           | 12.0         | −10.6        |                |                | 13.4           | −10.8          |                |              |

**Agriculture**

|                | Pre          | Post          |                |                |                |                |
|----------------|--------------|--------------|----------------|----------------|----------------|----------------|
|                | No. of        | No. of        | Mean           | Mean           | Mean           | Mean           |
|                | increases     | decreases     | increase (%)   | decrease (%)   | increase (%)   | decrease (%)   |
| Soybean oil    | 3            | 1            | 11.0           | −10.0          | 6              | 2              | 13.1           | −9.3          |
| Lean hogs      | 4            | 0            | 13.0           |                | 2              | 0              | 13.8           |              |
| Feeder cattle  | 1            | 0            | 20.5           |                | 2              | 2              | 20.0           | −16.6         |
| Live cattle    | 1            | 0            | 20.0           |                | 3              | 2              | 11.7           | −15.0         |
| Corn           | 4            | 2            | 13.2           | −12.8          | 0              | 2              | −7.8           |              |
| Wheat          | 2            | 1            | 7.7            | −13.8          | 3              | 3              | 10.9           | −6.9          |
| Soybean meal   | 1            | 3            | 10.0           | −13.8          | 7              | 2              | 10.6           | −10.5         |
| Soybeans       | 2            | 3            | 6.6            | −13.7          | 5              | 1              | 10.1           | −9.1          |
| Total          | 18           | 10           |                |                | 28             | 14             |                |              |
| Mean           | 12.8         | −12.8        |                |                | 12.9           | −10.7          |                |              |

**Equity**

|                | Pre          | Post          |                |                |                |                |
|----------------|--------------|--------------|----------------|----------------|----------------|----------------|
|                | No. of        | No. of        | Mean           | Mean           | Mean           | Mean           |
|                | increases     | decreases     | increase (%)   | decrease (%)   | increase (%)   | decrease (%)   |
| NASDAQ 100     | 0            | 1            | −5.3           |                | 9              | 1              | 10.2           | −5.9          |
| S&P500         | 2            | 1            | 5.0            | −4.8           | 7              | 1              | 9.7            | −8.3          |
| Dow Jones      | 0            | 2            | −7.9           |                | 7              | 3              | 13.4           | −9.1          |
| Nikkei 225     | 0            | 1            | −14.3          |                | 6              | 2              | 11.1           | −8.7          |
| Total          | 2            | 5            |                |                | 29             | 7              |                |              |
| Mean           | 5.0          | −8.1         |                |                | 11.1           | −8.0           |                |              |

**Note:** This table presents summary statistics for various futures contracts grouped by asset classes in the 12-month pre- and post-Covid periods. The pre-Covid period is from January 2019 to December 2019 and the post-Covid period is from January 2020 to December 2020. Panel A reports mean daily margin levels in dollars per contract in each of the two periods, the dollar and percentage difference in mean levels between the two periods along with Newey–West corrected $p$ values for the differences in margin levels. Panel B reports the number of increases and decreases in margins for both periods. Abbreviations: RBOB, Reformulated Gasoline Blendstock for Oxygenate Blending; T-bond, Treasury bond.
respectively. For all four metal futures contracts, the average increase between the two periods was 100.1%. In addition, the total number of increases and decreases in the pre-Covid period were 12 and 6, respectively, while the total number of increases and decreases in the post-Covid period rose to 32 and 10, respectively.

The above findings similarly extend to the futures contracts in the currency and equity futures asset classes that had average increases in margin levels of 31.4% and 68.3%, respectively. However, the findings for the agriculture futures were more mixed with only four of the eight futures showing a statistically significant increase in margins. Overall, agriculture futures had an average margin change of 15.5%, which was the smallest increase among all asset groups.

Finally, to summarize the frequency and magnitude of margin changes between the two periods, in Figure 11 we present histograms of the percentage margin changes across all contracts for each period. For the taller post-Covid histogram, one can observe a greater frequency of both margin increases and decreases. In addition, the largest positive changes are also observed in the post-Covid period histogram.

5 | COMMERCIAL/NONCOMMERCIAL TRADER ANALYSIS

We next explore whether the Covid-19 pandemic had an effect on the trader composition of futures markets. For transactions on US futures exchanges, the CFTC requires clearing members, FCMs, and foreign brokers (collectively called “reporting firms”) to file daily reports with the CFTC that provide position information on their customers who hold open positions above specified reporting thresholds. The CFTC then publishes a summary of this information in a weekly COT report that contains breakdowns of each Tuesday’s open interest. The reports separate these larger, reportable traders into “commercial” and “noncommercial” categories. A trader is generally classified as commercial if engaged in business activities hedged with the use of futures or option markets. Thus, the commercial category will typically include producers, merchants, processors, and users of the physical commodity who manage their business risks by hedging. The noncommercial category will include professional money managers (commodity trading advisors [CTAs], commodity pool operators [CPOs], and hedge funds) as well as a wide array of other noncommercial (speculative) traders. These classifications have also been used in the literature wherein the open interest for commercial traders is used to proxy for hedging activity and that for noncommercial traders to proxy for speculative activity (e.g., see Boyd et al., 2015; Chatrath et al., 1997; Kang et al., 2020). In addition, the COT report provides breakdowns of the long and short open interest of “nonreportable positions,” which are derived by subtracting the total of long and short “reportable positions” from the total open interest. The reports also provide information on the number of traders in each reportable group. Using these data, we explore the effects the pandemic has had on the trader composition of the various futures contracts.

We obtain all weekly futures and options combined COT reports published by the CFTC for the period January 2019–March 2021. The individual contracts we select parallel the CME Group futures and options contracts in the various asset classes analyzed in the prior section. For each week, we aggregate the open interest and number of traders across individual contracts and by trader categories. In Figure 12a we plot the total open interest as well as the amounts of open interest held by each trader category (commercial long and short, noncommercial long and short, and nonreportable long and short), while in Figure 12b we plot the time-series of the total number of traders
and those in the commercial and noncommercial categories. We observe a sharp increase in the total open interest from January 7 to March 10 of 2020 followed by a general downward tapering. The increase in open interest during this period is driven by the increased positions of commercial traders. In contrast, there is a slight drop in open interest for noncommercial traders. Turning to Figure 12b, we observe a sharp decrease in the number of traders from February 25 to April 7 of 2020 with the drop appearing to be mainly driven by a decline in the number of noncommercial traders. Taken together with our earlier findings of large increases in margin requirements during the overlapping February to March 2020 period, this observation of a decline in the number of noncommercial traders is consistent with the higher margins driving out some of the speculative trading as proxied by non-commercial traders.14

To further explore changes in the relative composition of commercial and noncommercial positions, in Figure 13a, we plot the time-series percentages of open interest held by each trader category (for both the long and short sides) for all asset classes combined. We observe that commercial traders increased both their long and short positions from January to March of 2020, while noncommercial traders decreased both their long and short positions. Subsequent to this period beginning in early June, we also observe a divergence in commercial positions as the percentage of their short positions increases while that of the long positions declines and reverts to pre-Covid levels. In contrast, the percentage of noncommercial long positions increases while that of noncommercial short positions declines.

In Figure 13b–g, we similarly report breakdowns for each of the asset categories. The patterns, in general, are consistent with the overall picture but there do appear to be some cross-sectional differences. For instance, for

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14 Along these lines, Hardouvelis & Kim (1995) find evidence of market participants leaving the metals market following margin increases. While margin requirements can be satisfied with interest-bearing instruments, such as Treasuries, Hartzmark (1986) contends that the opportunity cost of higher margins is not zero as investors may have limited access to liquid assets thus leaving fewer available funds after satisfying margin requirements to invest elsewhere.
agricultural futures, from January to March 2020 we observe a general increase in the percentage of open interest held by commercial traders and a decrease by noncommercial traders. Subsequently, we again see a strong divergence that develops as the percentage of commercial short positions increases while commercial long positions decline. For noncommercial traders, the percentage of long positions increases while that of their short positions declines. Similar patterns are also observed for currencies, energy and, to a lesser extent, metals. However, for equity index and interest-rate futures, we observe little if any divergence in long and short positions for either commercial or noncommercial traders.

6 | CONCLUSION

As Covid-19 spread throughout the world in early 2020, financial markets reacted to unprecedented challenges and uncertainty. Using an extensive database containing information on futures and options trading activity on derivatives exchanges across the globe, we examine the effects of the pandemic on derivatives markets. Further, this paper attempts to shed additional light on the interconnectedness of derivatives markets especially in the context of market crisis.

At the onset of the pandemic, we find a surge in futures and options volume and a smaller increase in corresponding open interest. We observe similar patterns of growth in trade volume and open interest across different geographic regions and derivatives asset classes, albeit of varying magnitudes. Our analysis of correlations in monthly derivatives trade volume between countries and geographic regions in pre- and post-Covid periods suggests increased connectivity in derivatives trading activity during the pandemic, in line with previously documented findings of greater asset return correlations during periods of financial crises. Additionally, in response to the added uncertainty and volatility in markets, we analyze the behavior of US futures exchanges to ensure their financial integrity through the margin setting process and document historic large increases in customer funds held to meet margin requirements. Finally, we document changes in the composition of open interest on US exchanges in the post-Covid period, including, among others, a sharp decrease in the number of noncommercial traders in early 2020.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the authors upon reasonable request. Restrictions apply to the availability of data obtained from the Futures Industry Association, which were acquired with a fee.

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FIGURE 13 Percentage of open interest by trader type and asset class: January 2019–March 2021. These figures report the percentages of open interest held by each trader category (for both the long and short sides) for various asset classes. The statistics are based on data from CFTC Commitments of Traders reports covering futures and options contracts traded on the CME Group exchanges and spanning six asset classes, including agriculture, energy, metals, interest rates, equity, and currency. Trader categories include commercial long (Comm_long), commercial short (Comm_short), noncommercial long (Ncomm_long), noncommercial short (Ncomm_short), nonreportable long (Nrept_long), and nonreportable short (Nrept_short). CFTC, Commodity Futures Trading Commission; CME, Chicago Mercantile Exchange.
APPENDIX A: A TIMELINE SUMMARY OF KEY COVID-19 DEVELOPMENTS

According to the World Health Organization (WHO), the first warning sign came on December 31, 2019, when the Wuhan Municipal Health Commission reported 27 cases of pneumonia of unknown cause in Wuhan City, China. On January 5, 2020, WHO issued its first public Disease Outbreak News report detailing the information about the cases; on January 9, Chinese authorities reported that a novel coronavirus was determined to be a possible cause of the outbreak; and after the first death reported on January 11 and the first recorded case outside of China (in Thailand) reported on January 13, the Pan American Health Organization/WHO issued its epidemiological alert on Covid-19 on January 16. The Center for Disease Control and Prevention (CDC) confirmed the first case of Covid-19 in the United States on January 21. On January 23, it was announced that the entire city of Wuhan was under lockdown. Soon thereafter, on January 31, the United States declared Covid-19 a public health emergency.

Subsequently, and considering the severity of the coronavirus outbreak with over 100,000 cases of Covid-19 in more than 114 countries, on March 11, 2020, WHO declared Covid-19 a global pandemic. In the United States, on March 13, President Trump declared a national emergency, freeing federal funds for emergency response, and imposed travel restrictions for non-US citizens. The first statewide stay-at-home order was issued by California on March 19. According to WHO’s April 4 report, the number of worldwide cases at the time stood at over 1 million with over 50,000 deaths. Subsequently, on December 8, 2020, the first Covid-19 vaccine in the world outside clinical trials was administered in the UK. Vaccination of US public began on December 14, 2020. Thus, based on the above developments, for purposes of our analysis we treat January 2020 as the initial event month for the outbreak of the pandemic, but recognize its economic spread throughout subsequent months.

APPENDIX B: NETWORK CENTRALITY MEASURES

To determine the importance of a node in a network for facilitating the flow of information, we compute a number of related topological metrics based on concepts of centrality. These include degree, betweenness, and closeness centrality. Following the notations and methods presented in Sensoy & Tabak (2014), Zhukov (2015), and McCulloch (2017), we present expressions for node-level values of centrality based on each of the three centrality measures (i) degree, (ii) betweenness, and (iii) closeness centrality, or $C_D(i)$, $C_B(i)$, and $C_C(i)$, respectively. Further, each of the
measures is normalized to produce values between 0 and 1 (with higher values denoting greater centrality), and to facilitate comparison across networks.

(i) Degree centrality for a node $i$ is given by

$$C_D(i) = \frac{\sum_{j=1}^{N} A_{ij}}{(N - 1)},$$

(B.1)

where $A_{ij}$ is equal to 1 if nodes $i$ and $j$ are directly adjacent, and 0 otherwise, $N$ is the number of nodes in the network, and $(N - 1)$ is a scaling factor.

(ii) Betweenness centrality for node $i$ is given by

$$C_B(i) = \frac{2 \times \sum_{a \neq b \neq i} \lambda(a, b | i)}{(N - 1) \times (N - 2)},$$

(B.2)

where $\lambda(a, b | i)$ is the number of shortest paths between nodes $a$ and $b$ that pass through node $i$, $\lambda(a, b)$ is the total number of shortest paths through $a$ and $b$, and the numerator $(N - 1) \times (N - 2)/2$ is the normalization factor.

(iii) Closeness centrality for a given node $i$ is given by

$$C_C(i) = \frac{(N - 1)}{\sum_{j=1}^{N} sd(i, j)},$$

(B.3)

where $sd(i, j)$ is the shortest distance between nodes $i$ and $j$ and is equal to the minimum number of edges to reach node $j$ from node $i$. The term $(N - 1)$ in the numerator serves as a normalization factor.

Finally, based on the individual node values for a given metric, one can compute an overall degree of centralization statistic for the entire network that assists in understanding the extent to which a network is dominated by one or a few central nodes. A general expression for each network statistic based on a given centrality measure $X$ (i.e., degree, betweenness, or closeness centrality) is given by

$$NC_X = \frac{\sum_{i=1}^{N} (C_{X \text{max}} - C_X(i))}{\max \sum_{i=1}^{N} (C_{X \text{max}} - C_X(i))},$$

(B.4)

where $NC_X$ is the overall network centralization statistic based on centrality measure $X$, $C_{X \text{max}}$ is the maximum of the $N$ individual node values based on measure $X$, and $C_X(i)$ is the centrality measure value of node $i$ based on measure $X$. The numerator is thus the sum of the deviations (i.e., distances) of the individual node values from the maximum node value while the denominator is a normalization factor. It can be shown that the values of these normalization factors for the degree, betweenness, and closeness measures are equal to $(N - 2) \times (N - 1)$, $(N - 1)$, and $[(N - 2) \times (N - 1)/(2N - 3)]$, respectively. As is the case for the individual node measures, the overall network centralization statistic for each measure also has a value between 0 and 1 with higher values denoting greater network centralization.