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Time-varying Dependence between Bitcoin and Green Financial Assets: A Comparison between Pre- and Post-COVID-19 Periods

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Abstract

This paper studies the time-varying market linkages between Bitcoin and green assets before and during the COVID-19 pandemic through a TVP-VAR model with stochastic volatility. Both the roles of uncertainty and environmental attention related to cryptocurrency are considered when modeling market linkages, which underlying asymmetry is detected from three perspectives, i.e., bidirectionality of the impact direction, time points where the unit shock of the IRF analysis is imposed, and before and after the pandemic. We find that the investment sheltering role of Bitcoin for green assets is enhanced and expanded after the onset of the pandemic, while green assets in turn consistently act as an effective hedge for Bitcoin irrespective of the pandemic. Additional analyses confirm the robustness of our findings, which possess implications for not only hedging against green portfolios but also seeking green shelters.

Keywords: Bitcoin; Green financial assets; Time-varying dependence; Asymmetry; COVID-19

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1. INTRODUCTION

Over the past number of decades, climate change has become one of the most serious issues facing the world, calling for a global agenda for green and sustainable development in the future. However, over the last decade, cryptocurrencies have been developed and become more and more popular which are known to have high energy consumption with adverse environmental impacts¹ while attention on the future green development of the cryptocurrency market remains surprisingly scant (Corbet et al., 2021). As one of the leading cryptocurrencies, Bitcoin has soared in value in recent times but still faces concerns from academics and investors alike on whether to include this ‘dirty currency’ into the investment portfolio or not (Naeem and Karim, 2021). The recent headline pulled by the strategic withdrawal of Tesla’s acceptance of cryptocurrencies purchase due to environmental concerns has further drawn widespread attention of the power consumption and carbon emission issues of Bitcoin transactions. Accordingly, there exists an ongoing debate in academia and financial markets on whether to incorporate green assets into Bitcoin-related portfolios for dual goals of risk diversification and green investment commitment.

In parallel, the unprecedented COVID-19 pandemic has not only incurred vast changes to the everyday life to individuals but have had profound effects on operations of economic and financial systems (Huang et al., 2021). Since literature suggests that financial assets have become more correlated in the bust periods (Hartmann et al., 2004; Lee et al., 2011), acute economic losses incurred by the ongoing Covid019 pandemic therefore provides a critical test-bed for the dynamics of financial market co-movement and the potential investment shelters in the downturn (Goodell, 2020). Recently, Bitcoin, being recognized as ‘liquid gold’ due to its independence from political and economic tones of sovereign nations, has raised widespread discussion on its potential sheltering role during a market crash (Yarovaya et al., 2020). At the same time, it is pointed out that market dependence between Bitcoin

¹For instance, see <https://www.forbes.com/advisor/investing/bitcoins-energy-usage-explained/>.

46 and financial assets features a time-varying pattern, indicating that the degree of hedging and
47 safe-haven properties of Bitcoin, if any, tends to evolve over time instead of being constant
48 (Shahzad et al., 2019; Ren et al., 2022). Thus, the above entails careful reexamination of the
49 role of the pandemic in time-varying spillovers of financial markets, particularly the dynamic
50 dependence between Bitcoin and green assets in our case.

51 Against this background, this paper examines the time-varying market dependence be-
52 tween Bitcoin and green financial assets before and during the COVID-19 pandemic through
53 a time-varying parameter VAR (TVP-VAR) model with stochastic volatility. To study the
54 role of the pandemic on the market dependence, we have followed extant literature (see, e.g.,
55 Goodell and Goutte, 2021b; Huang et al., 2021) by considering two sub-samples before and
56 after the pandemic onset with the whole daily dataset spanning from September 2018 to
57 September 2021. The dynamics and asymmetry of the market dependence are studied from
58 three perspectives, i.e., various time horizons, before and during the pandemic, and bidi-
59 rectional market relations, respectively. The time-varying impulse response function (IRF)
60 analysis identified by our TVP-VAR model with stochastic volatility is conducted to study
61 the potentially dynamic market dependence over time. In addition, green financial assets
62 are represented by individual indices including the Dow Jones Sustainability World Index
63 (SWI), S&P ESG Leader Index (ESGLI), S&P Green Bond Index (GBI), and S&P Global
64 Clean Energy Index (GCEI).

65 Moreover, the uncertainty in social and economic conditions could alter investors' an-
66 ticipation, and the weakening of which further triggers the financial turmoil, leading to
67 fluctuations in the cryptocurrency market (Wu et al., 2022). At the same time, it is also
68 known that uncertainty from different perspectives could exert varying impacts and predic-
69 tive power on the cryptocurrency market (Lucey et al., 2021b). While rising uncertainty
70 plays a key role in the cryptocurrency market dynamics, the commonly-used index such as
71 economic policy uncertainty involves various sectors in the economy, which may not offer a
72 sufficiently-accurate measure for the uncertainty in the field of cryptocurrency. There has

73 long been a devoid of an uncertainty indicator that is specifically designed for the cryp-
74 tocurrency until the recently-developed cryptocurrency uncertainty indices by [Lucey et al.](#)
75 [\(2021b\)](#). We therefore employ the two indices by [Lucey et al. \(2021b\)](#) that capture the
76 sizes of unpredictable disturbances in price and policy of cryptocurrencies, respectively. The
77 two indices are Uncertainty of Cryptocurrency Policy (UCRY Policy) and Uncertainty of
78 Cryptocurrency Price (UCRY Price). Moreover, growing energy consumption caused by
79 cryptocurrency mining and its related emission issues have raised emerging environmental
80 concerns about the cryptocurrency. We therefore further incorporate the Cryptocurrency
81 Environmental Attention Index (ICEA) proposed by [Lucey et al. \(2021a\)](#) that measures
82 the extent of environmental sustainability concerns on the cryptocurrency trading by the
83 public. This enables us to determine how the linkages vary under different attention levels
84 for cryptocurrency environmental issues. Therefore, in our paper, the cross-market linkage
85 between Bitcoin and green assets will be investigated in a setting where the uncertainty and
86 environmental attention for the cryptocurrency are well considered.

87 Our paper is closely linked to the extant literature in the following three strands, market
88 dependence of Bitcoin with financial assets and commodities, investment sheltering role of
89 Bitcoin, and the role of COVID-19 pandemic in the market interaction, with a particular
90 focus on the time-varying market linkage between Bitcoin and green financial assets. Specif-
91 ically, existing studies has examined the market interaction between Bitcoin and general
92 financial markets of assets and commodities with some further discussion on the sheltering
93 role of Bitcoin for financial assets and the other way round (e.g., [Bouri et al., 2018](#); [Urquhart](#)
94 [and Zhang, 2019](#); [Conlon et al., 2020](#); [Corbet et al., 2021](#); [Wang et al., 2021](#); [Duan et al.,](#)
95 [2021a,b](#)). Amongst others, [Conlon et al. \(2020\)](#) and [Goodell and Goutte \(2021b\)](#) examine the
96 potential role of cryptocurrencies as a safe-haven or diversifier on equity indices during the
97 COVID-19 period. [Maghyereh and Abdoh \(2020\)](#) employ a quantile cross-spectral approach
98 to examine the tail dependence between prices of Bitcoin and financial indicators including
99 S&P 500 and exchange rate. Regarding the linkage between cryptocurrencies and commod-

100 ity markets, including gold and various commodities such as energy, metals, and agricultural
101 products, [Le et al. \(2021a\)](#) measure the spillover pattern between prices of Bitcoin and other
102 assets including stock and gold, and find the consistent safe-haven property of gold in the
103 post-COVID-19 period. [Rehman and Kang \(2021\)](#) point out a lead-lag connection between
104 Bitcoin and crude oil market.

105 Moreover, although being limited and ongoing, the market dependence between cryp-
106 tocurrencies notably including Bitcoin and green financial indices have been investigated
107 with studies determining whether the linkage is uni- or bi-directional, and whether it varies
108 over time remains unclear (e.g., [Okorie, 2021](#); [Symitsi and Chalvatzis, 2018](#)). For instance,
109 [Symitsi and Chalvatzis \(2018\)](#) show that there exists unidirectional return and volatility
110 interactions between Bitcoin and green financial assets represented by stock indices of en-
111 ergy and technology firms, while shock interactions are found to be bi-directional. As for
112 the potential investment shelter role for green financial assets against adverse market fluc-
113 tuations of cryptocurrencies, consensus has yet to be reached in existing empirical analyses
114 (e.g., [Naeem and Karim, 2021](#); [Lucey et al., 2021a](#)). For example, [Naeem and Karim \(2021\)](#)
115 point out that green financial assets such as clean energy indices act as hedges for Bitcoin.
116 [Ren and Lucey \(2021\)](#) show that stock prices of clean energy would not be a direct hedge
117 but safe-haven for both ‘dirty’ and ‘clean’ cryptocurrencies. Thus, the above demonstrates
118 that consensus of existing findings on the market interdependence between cryptocurrencies
119 and green energy indices has not yet been reached.

120 In addition, growing attention focuses on the role of COVID-19 pandemic in the financial
121 market linkage. Given that the later could become more connected during the economic
122 downturn ([Hartmann et al., 2004](#)), the market depression associated with onset of the ongoing
123 pandemic offers a critical testbed in this regard ([Huang et al., 2021](#)). Recent literature studies
124 the impact of the pandemic on the co-movement between markets of financial assets including
125 Bitcoin and commodities under uncertainty ([Aloui et al., 2020](#); [Sharif et al., 2020](#)), as well
126 as the sheltering role of Bitcoin against financial assets and commodities ([Conlon et al.,](#)

127 [2020; Conlon and McGee, 2020](#)). While it has been pointed out that the market dynamics
128 of financial assets including cryptocurrencies could be altered by the pandemic ([Goodell and](#)
129 [Goutte, 2021a](#)), research on the pandemic impact on the market nexus between Bitcoin and
130 green financial remains surprisingly scant by far.

131 Our paper contributes to the extant related literature in the following aspects. First,
132 rather than a conventional VAR model that only reports fixed coefficient estimates, we
133 employ a TVP-VAR model with stochastic volatility. Through this, the potential time-
134 varying property of variable relationships in both matrices of coefficient and covariance is
135 respectively identified. Moreover, our employed method offers a time-varying IRF analysis
136 that outperforms the conventional IRF by capturing the variable response in the face of a
137 unit structural shock being imposed at different time points, such as the first quarter, the half
138 year, and the third quarter, respectively, in our case. Overall, to the best of our knowledge,
139 our paper is among the first that investigates the possibly asymmetric and time-varying
140 market information spillovers between Bitcoin and green financial assets, while considering
141 related financial indicators notably including the cryptocurrency uncertainty index and the
142 index of cryptocurrency environmental attention.

143 We find that the market dependence between Bitcoin and the four considered green fi-
144 nancial assets is asymmetric from three perspectives, namely impact directions, time points
145 where the unit shock is being imposed in the IRF analysis, as well as before and during the
146 COVID-19 pandemic. As for the contemporaneous market relationship, Bitcoin is found to
147 act as an investment shelter of effective hedge for the specific green asset GCEI before the
148 pandemic, while its effective hedging role is further enhanced and extended to three green
149 financial assets, i.e., SWI, ESGLI, and GCEI, after the pandemic onset at different time hori-
150 zons. Conversely, the four green financial assets play an effective hedge for Bitcoin, and such
151 the role remains constant irrespective of the pandemic. The mutually reinforcing and en-
152 hanced investment sheltering ability between Bitcoin and green assets over time corroborates
153 with the extant literature, and is supported by no or even a negative relationship between

154 the two agents. The underlying reason has been discussed from two perspectives, i.e., green
155 economic transition and dynamics of production costs in terms of rising energy prices. In
156 addition, several additional analyses are conducted to demonstrate that our findings are ro-
157 bust to various changes in the research design. Our research is of important implications as
158 to whether there exists a green investment shelter against adverse fluctuations of Bitcoin,
159 and the sheltering role of Bitcoin for green portfolios.

160 The rest of this paper is structured as follows. Section 2 discusses our empirical data with
161 preliminary analysis. Section 3 introduces our employed methodology. Section 4 analyzes
162 empirical results. Section 5 discusses the analysis of robustness checks. The last section
163 concludes with a discussion on policy implications.

164 2. DATA AND PRELIMINARY ANALYSIS

165 Our research dataset includes Bitcoin price (BTC), four green financial assets (i.e., SWI, ES-
166 GLI, GBI, and GCEI), three indices describing the cryptocurrency market condition through
167 both perspectives of uncertainty (i.e., URCY policy and URCY price) and environmental
168 sustainability (ICEA), and the CBOE Volatility Index (VIX). In spirit of the extant litera-
169 ture (e.g., [Goodell and Goutte, 2021b](#); [Huang et al., 2021](#)), the research period spans from
170 01 September 2018 to 30 September 2021, and is divided into two sub-samples on 11 March
171 2020, which is the first day when the COVID-19 was announced as a pandemic by the WHO².
172 Accordingly, sub-samples of 01 September 2018 - 10 March 2020 and 11 March 2020 - 30
173 September 2021 are used to represent pre- and post-COVID-19 periods, respectively.

174 Regarding the Bitcoin price series, it is represented by the Coindesk Price Index from
175 www.coindesk.com, which represents an average of Bitcoin prices across leading Bitcoin
176 exchanges worldwide.³ The four green financial assets involve Dow Jones Sustainability

²See details about key dates of COVID-19 announced by the WHO at <https://www.who.int/emergencies/diseases/novel-coronavirus-2019/interactive-timeline>.

³The Coindesk Price Index is the data source commonly used in the literature (e.g. [Kwon, 2020](#); [Baur](#)

177 World Index (SWI), S&P ESG Leader Index (ESGLI), S&P Green Bond Index (GBI), and
178 S&P Global Clean Energy Index (GCEI), and are from S&P Dow Jones Indices database
179 (www.spglobal.com/spdji). The three cryptocurrency market related indices contain Uncer-
180 tainty of Cryptocurrency Policy Index (UCRY Policy), Uncertainty of Cryptocurrency Price
181 Index (UCRY Price), and Cryptocurrency Environmental Attention Index (ICEA). They are
182 sourced from [Lucey et al. \(2021a,b\)](#) that extracts news from the LexisNexis News & Business
183 database⁴. The VIX series is archived from COBE database (www.cboe.com).

184 [Figure 1 about here.]

185 Temporal dynamics of the price series of Bitcoin, green financial assets, indices of cryp-
186 tocurrency market condition, and VIX are drawn in Figure 1, respectively. Particularly, it
187 can be seen that all considered series except the VIX have witnessed a dramatic drop on
188 11 March 2020, i.e., the announcement date of COVID-19 as a pandemic. At the same
189 time, the VIX index peaked on the announcement date and then plunged, showing marked
190 volatility of financial markets induced by the pandemic. This also provides a visual demon-
191 stration regarding the separation of our whole data to investigate the pandemic impact on
192 the cross-market linkages. For each of the considered series, it is transformed in the return
193 format as the first-order log difference between the current day and the last day times 100 of
194 the original series, i.e., $R_t = (\log(P_t) - \log(P_{t-1}))$. Table 1 shows the descriptive statistics
195 for each transformed series in subsamples of pre- and post-COVID-19 periods, respectively.
196 Briefly, the return-transformed Bitcoin price index, green financial assets, and indices of
197 cryptocurrency market condition are found to possess larger mean values with higher stan-
198 dard deviations since the COVID-19 is announced as a pandemic. At the same time the mean
199 value of return-transform VIX index turned to be negative with relatively lower volatility in
200 the post-COVID-19 period compared to that in the pre-COVID-19 period, being consistent

et al., 2018; Bouri et al., 2019; Kapar and Olmo, 2019)

⁴See details about data of UCRY Policy, UCRY Price, ICEA at <https://lnkd.in/egtZzvS>.

201 with the existing findings (e.g., [Lucey et al., 2021a,b](#); [Naeem and Karim, 2021](#)).

202 [Table 1 about here.]

203 3. METHODOLOGY

204 3.1. Time-Varying Parameter VAR with Stochastic Volatility

205 The time-varying parameter VAR (TVP-VAR) model with stochastic volatility is known
206 to outperform the conventional VAR method and has been widely applied to modelling
207 the dynamic relationship between macroeconomic and financial indicators (e.g., [Chan and](#)
208 [Eisenstat, 2018](#); [Clark and Ravazzolo, 2015](#); [D’Agostino et al., 2013](#); [Nakajima et al., 2011](#)).
209 It not only considers the potential time-varying feature of the underlying structure, but also
210 accommodates the fluctuating disturbance, particularly in the financial turmoil. Therefore,
211 we employ the TVP-VAR model with stochastic volatility for clearer comprehension on
212 the relationship between price returns of Bitcoin and green financial assets by considering
213 the condition of the cryptocurrency market through aspects of uncertainty, environmental
214 sustainability, and financial volatility.

215 The model departs from a k -dimensional return vector R_t that involves Bitcoin prices
216 BTN_t , four green financial asset prices $GFA'_t = (SWI_t, ESGLI_t, GBI_t, GCEI_t)'$, three cryp-
217 tocurrency market related indices $CRI'_t = (UCRYPolicy_t, UCRYPrice_t, ICEA_t)'$, and the
218 financial market volatility VIX_t at period t ($t = 1, \dots, T$). The TVP-VAR model with
219 stochastic volatility is then formulated as: framework is formulated as

$$R_t = B_{1t}R_{t-1} + \dots + B_{pt}R_{t-p} + \varepsilon_t, \quad \varepsilon_t \sim N(0, A_t^{-1}\Sigma_t\varepsilon_t), \quad (1)$$

for $t = p + 1, \dots, n$, where B_{1t}, \dots, B_{pt} are $k \times k$ autoregressive coefficient matrices with the number of variables k and lags of p . ε_t refers to a $k \times 1$ structural shocks with A_t being identified as a lower triangular covariance matrix, Σ_t being as a diagonal matrix of stochastic

volatility, and $\epsilon_t \sim N(0, I)$. The structures of A_t and Σ_t are presented as follows:

$$A_t = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ a_{21,t} & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ a_{k1,t} & \cdots & a_{k,(k-1),t} & 1 \end{bmatrix} \quad \text{and} \quad \Sigma_t = \begin{bmatrix} \sigma_{1,t}^2 & 0 & \cdots & 0 \\ 0 & \sigma_{2,t}^2 & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & \sigma_{k,t}^2 \end{bmatrix}.$$

220 Let $X_t = (R'_{t-1}, \dots, R'_{t-p})'$ and $B'_t = (B_{1t}, \dots, B_{pt})$, the model can be rewritten in a
 221 more compact form:

$$R_t = B'_t X_t + \epsilon_t. \quad (2)$$

222 To better model the potentially time-varying relationship between macro-financial vari-
 223 ables in the TVP-VAR model, the coefficients of B_t , covariance matrix of A_t , and stochastic
 224 volatility of Σ_t are allowed to vary over time. To model the time-varying coefficients, we
 225 define $\beta_t = \text{vec}(B_t)$, by assuming that β_t follows a random walk process with $t = p+1, \dots, n$,

$$\beta_t = \beta_{t-1} + u_t, \quad u_t \sim N(0, \Sigma_\beta). \quad (3)$$

Similarly, we construct a_t as a row-wise stacked vector of the lower-triangular covariance elements of A_t , i.e., $a_t = (a_{21,t}, \dots, a_{k,k-1,t})'$ and σ_t^2 as a vector of the diagonal elements of Σ_t , i.e., $\sigma_t^2 = (\sigma_{1,t}^2, \dots, \sigma_{k,t}^2)'$, following [Primiceri \(2005\)](#). Both a_t and σ_t^2 are assumed to follow a random walk process, and we have

$$a_t = a_{t-1} + \vartheta_t, \quad \vartheta_t \sim N(0, \Sigma_a), \quad (4)$$

$$\log(\sigma_t) = \log(\sigma_{t-1}) + v_t, \quad v_t \sim N(0, \Sigma_\sigma), \quad (5)$$

226 Therefore, the vector involving the innovations to the structural shocks ϵ_t (ϵ_t), time-
 227 varying coefficients β_t (u_t), and stochastic volatilities of a_t (ϑ_t) and $\log(\sigma_t^2)$ (v_t) is known to

228 follow the below distribution

$$\begin{bmatrix} \epsilon_t \\ u_t \\ \vartheta_t \\ v_t \end{bmatrix} = \begin{bmatrix} I & 0 & 0 & 0 \\ 0 & \Sigma_\beta & 0 & 0 \\ 0 & 0 & \Sigma_a & 0 \\ 0 & 0 & 0 & \Sigma_\sigma \end{bmatrix}. \quad (6)$$

229 Given that our TVP-VAR model with stochastic volatility is featured by large time-
 230 varying parameters as specified in Equations (3) to (5), we will discuss in Section 3.3 re-
 231 garding how the Bayesian approach using a Markov chain Monte Carlo (MCMC) algorithm
 232 is employed to estimate the model.

233 3.2. Shock Identification

234 To identify the structural shock in our TVP-VAR model with stochastic volatility, we conduct
 235 a Cholesky decomposition for the covariance matrix of Σ_t , as shown in Section 3.2. We order
 236 the target series following the existing literature (e.g., [Lucey et al., 2021a,b](#); [Naeem and](#)
 237 [Karim, 2021](#)) as:

$$R_t = (UCRYPolicy_t, VIX_t, BTN_t, SWI_t, ESGLI_t, GBI_t, GCEI_t, UCRYPrice_t, ICEA_t). \quad (7)$$

238 Regarding the reason for the above ordering, in line with [Lucey et al. \(2021a,b\)](#), the
 239 series of the cryptocurrency policy uncertainty (UCRY policy) index is ordered first since
 240 that series such as VIX and Bitcoin can react instantaneously to uncertainty policy shocks.
 241 Given that other considered series are known to react faster than UCRY price index, the
 242 latter is accordingly ordered behind with the index of environmental sustainability of the
 243 cryptocurrency market (ICEA) being ordered last. Moreover, it is further worth noting that
 244 ordering Bitcoin before green financial assets is consistent with [Naeem and Karim \(2021\)](#).

245 3.3. Estimation Algorithm

246 The Bayesian method is applied to estimate our TVP-VAR model with stochastic volatil-
247 ity, wherein the MCMC algorithm is conducted using a simulation-based estimation that
248 generates a sequence of draws from the full conditional distributions of all parameters. The
249 time-varying parameters can be well estimated through a nested structure that computes
250 the likelihood function for each iteration process. To enforce the MCMC algorithm, the
251 following conditional distributions are formulated:

$$\begin{aligned} & \beta_t | a_t, \sigma_t^2, \Sigma_\beta, \\ & a_t | \beta_t, \sigma_t^2, \Sigma_a, \\ & \sigma_t^2 | \beta_t, a_t, \Sigma_\sigma, \\ & \Sigma_\beta | \beta_t, \\ & \Sigma_a | a_t, \\ & \Sigma_\sigma | \sigma_t^2. \end{aligned} \tag{8}$$

252 Detailed discussions of drawing samples from the above conditional posterior distributions
253 with priors follow the MCMC procedures of [Chen et al. \(2020\)](#) and [Nakajima et al. \(2011\)](#),
254 where σ_t^2 is illustrated as $\exp(h_t)$.

255 4. EMPIRICAL RESULTS

256 4.1. Parameter Estimates

257 To examine the spillover pattern between price returns of Bitcoin and green financial assets
258 while considering related financial indicators (i.e., cryptocurrency market related indices
259 and VIX), and investigate its potential dynamics over time before and during the COVID-
260 19 pandemic, we conduct the estimation by using the time-varying VAR (TVP-VAR) model
261 with stochastic volatility in the two subsamples, respectively. The lag order of the TVP-VAR

262 system is set to be 1,⁵ and jointly given that there are nine variables in total included in
263 the system, the estimated parameters therefore include 81 autoregressive coefficients (β_t), 36
264 covariance parameters (a_t), and 9 volatility parameters (σ_t^2) for the pre- and post-COVID-19
265 periods, respectively. Overall, with a particular focus on the time-varying relationships of
266 Bitcoin with green assets and related financial indicators, Figures 2 and 3 show dynamics
267 of the posterior draws of β_t over time before and during the COVID-19 pandemic; panels
268 (a) and (b) of 4 and 5 present dynamic plots of the posterior draws of a_t and σ_t^2 over time
269 before and after the announcement of the pandemic, respectively. The above time-varying
270 dynamics are depicted in the x-axis of the corresponding figures where the period of 01
271 September 2018 - 11 March 2020 denotes the period before the pandemic and 12 March 2020
272 - 30 September 2021 denotes the one during the pandemic.

273 [Figure 2 about here.]

274 [Figure 3 about here.]

275 With regard to the time-varying posterior estimates of β_t , the role of Bitcoin in driving
276 other series and the other way around exhibit distinct results over time, as shown in Figures
277 2 and 3. We find the potentially bi-directional relationships of Bitcoin prices with green
278 financial asset prices (i.e., SWI, ESGLI, GBI, and GCEI) and related financial indicators in-
279 cluding indices for the cryptocurrency market condition through perspectives of uncertainty
280 (URCY Policy and URCY Price) and environmental sustainability (ICEA), and VIX gener-
281 ally remain stable and unchanged overtime before and after the outbreak of the COVID-19.
282 Interestingly, it is worth noting that time-varying coefficients that show the relationship be-
283 tween Bitcoin prices and related financial indicators are found to be less significant at most
284 of the time.

⁵While there is no theoretical guidance for the lag order selection in the time-varying parameter (TVP) VAR system, in the empirical analysis, we have tried different order numbers, e.g., 2, 3, 4, or 5. The results are consistent with that of our benchmark estimation, and they are available from the authors upon request.

285 [Figure 4 about here.]

286 Moreover, the time-varying posterior estimates of a_t , and σ_t^2 experience a relatively
287 marked fluctuation before and after announcement of the COVID-19 pandemic. As shown in
288 Figures 3, it is clear that the systematic relationship (i.e., covariance shown by a_t) of Bitcoin
289 prices with price indices of green financial assets and related financial indicators could be
290 time-varying and sensitive to the COVID-19 pandemic, such as the relationship of Bitcoin
291 with SWI and UCRY price; at the same time, the estimates of a_t for the correlations of
292 Bitcoin with URCY Policy and VIX tend to be time-invariant. In addition, the dynamic
293 time-varying pattern of the covariance of Bitcoin prices with prices of green financial assets
294 is found to be different and even reserved in pre- and post-COVID-19 periods, while the
295 counterpart of that with financial related indicators is shown to be relatively constant in the
296 two sub-samples.

297 [Figure 5 about here.]

298 As for the estimates of σ_t^2 displayed in Figure 5, estimated variances of price indices
299 of green financial assets and related financial indicators are shown to be time-varying with
300 different patterns before and after the announcement of the pandemic. It is worth mentioning
301 that σ_t^2 of most of the green financial assets increases (except for that on ESGLI), while that
302 on indices related to the cryptocurrency market condition tend to decrease as time evolving
303 to the post-COVID-19 period.

304 4.2. Time-varying impacts of Bitcoin on green financial assets and related 305 financial indicators

306 Whether and how the impact of Bitcoin prices on green financial asset prices and related
307 financial indicators (i.e., indices of the cryptocurrency market condition from perspectives
308 of uncertainty and environmental sustainability and the VIX index) varies over time before

309 and after the announcement of the COVID-19 as a pandemic? To answer this question, we
310 conduct the time-varying impulse response function (IRF) analysis based on the parameter
311 estimates of the employed TVP-VAR model with stochastic volatility. Rather than the
312 conventional IRF that only observes variable response after receiving a unit shock to a
313 target variable at the initial time point (i.e., time 0), the IRF produced by the TVP-VAR
314 model with stochastic volatility captures potential variations of the variable response after
315 receiving a unit shock at different time points. That is, the variable response is allowed to
316 be time-varying once receiving a shock to a target variable at different time points, viz.,
317 the first quarter, the half year, and the third quarter, respectively, in our case. Since its
318 initial development by [Cogley and Sargent \(2001, 2005\)](#) and [Primiceri \(2005\)](#), it has been
319 raised an increasing attention by related literature (e.g., [Chan and Eisenstat, 2018](#); [Clark
320 and Ravazzolo, 2015](#); [D'Agostino et al., 2013](#)). Time variations of responses of green financial
321 asset prices and related financial indicators are plotted as shown in Figures 6 and 7 once
322 receiving a unit shock to Bitcoin prices in the first quarter, the half year, and the third
323 quarter, respectively. The potential different pattern of the time-variations in the pre- and
324 post-periods of the COVID-19 pandemic is compared and shown in Panels (a) and (b) of
325 the two figures, respectively. Overall, the variable responses are shown to have relatively
326 consistent tendency while having different magnitudes once receiving the Bitcoin price shock
327 on the three different time points. The variable responses during the COVID-19 period
328 demonstrate a different dynamic pattern compared to that before the COVID-19 period.

329 [Figure 6 about here.]

330 Specifically, once receiving a unit shock to Bitcoin prices before the COVID-19 pandemic,
331 as shown in Panel (a) of Figure 6, the contemporaneous responses of three of the four selected
332 green financial asset prices, i.e., prices of SWI, ESGLI, and GBI, are shown to be positive,
333 quickly turn to become negative after a short period, and eventually revert to zero after
334 around four horizons. At the same time, the response pattern of the specific green financial

335 asset (GCEI) price is shown to be reversed that it receives a negative and instant move, and
336 quickly reverts to zero within around four horizons. The above response pattern is found
337 to be consistent regardless of when the unit shock to Bitcoin prices is received, while the
338 response magnitude varies over horizons with different time points for the shock impulse.
339 Once receiving a unit shock to Bitcoin prices after the COVID-19 pandemic, as shown in
340 Panel (b) of Figure 6, the time-varying responses of both GBI and GCEI are shown to have
341 a broadly similar pattern as their counterparts shown before the COVID-19 pandemic; in
342 contrast, the responses of SWI and ESGLI reverse after the pandemic announcement. In
343 addition, the sizes of responses of each of the four green financial asset prices are found to
344 be relatively similar once the shock to Bitcoin prices is at different time points.

345 [Figure 7 about here.]

346 Regarding the time-varying responses of related financial indicators to a unit shock of
347 Bitcoin prices, both response path and magnitude are shown to be distinct before and after
348 the announcement of the COVID-19 pandemic. In Panel (a) of Figure 7, it can be seen that
349 cryptocurrency market related indices for policy and price uncertainty, i.e., URCY policy
350 and URCY price, depict a negative instant response although with different degrees and
351 then revert to zero after four horizons in the pre-COVID-19 period. At the same time, the
352 cryptocurrency market related index for environmental sustainability (ICEA) and the VIX
353 index broadly exhibit a positive response and then go back to zero with different response
354 sizes; this pattern for ICEA particularly applies only to short time points. In contrast,
355 after announcement of the COVID-19 pandemic, as shown in Panel (b) of Figure 7, time-
356 varying patterns of the responses of the four related financial indicators differ compared
357 with that before the pandemic. For example, the response of the VIX index totally turns
358 become negative against a positive response before the pandemic. Importantly, it is worth
359 mentioning that responses of each of the green financial asset prices and related financial
360 indicators are shown to be time-varying instead of being constant, depending on the time

361 points when a unit shock is imposed on the Bitcoin price, i.e., the first quarter, the half year,
362 and the third quarter, respectively, in our case.

363 Importantly, regarding the contemporaneous relationship, before the COVID-19 pan-
364 demic, Bitcoin prices exert positive impacts on prices of three out of the four target green
365 financial assets, i.e., SWI, ESGLI, and GBI, except for the price of GCEI , which is influenced
366 negatively, at various time horizons. Such positive impacts on prices of SWI and ESGLI turn
367 to become negative during the pandemic, while the respective positive and negative impacts
368 on GBI and GCEI are shown to be consistent in the face of the pandemic outbreak. It can
369 be therefore found that Bitcoin acts as an investment shelter on the specific green financial
370 asset GCEI before the pandemic, while its sheltering role is enhanced and further expanded
371 to three green financial assets, i.e., SWI, ESGLI, and GCEI, during the pandemic. As for
372 indices related to the cryptocurrency market condition, Bitcoin is found to perform a con-
373 sistent zero contemporaneous impact on URCY policy and VIX in both subsamples before
374 and after the pandemic onset, while its sheltering role for UCRY price is only effective before
375 the pandemic. Our results of the investment sheltering property of Bitcoin against various
376 financial indicators corroborate with existing literature ([Huang et al., 2021](#); [Le et al., 2021a](#)).
377 The hedging role of Bitcoin against green assets is found to be further enhanced after the
378 pandemic onset over time as supported by the weakened relation between Bitcoin and green
379 assets. The corresponding reason can be attributed to both aspects of green transition and
380 dynamics of production costs, and will be further discussed in the next section.

381 4.3. Time varying impacts of green financial assets and related financial 382 indicators on Bitcoin

383 Having studied the spillover of Bitcoin price fluctuations on prices of green financial assets
384 and related financial indicators, we investigate the spillover impact from the other direction
385 by using the time-varying IRF produced by the TVP-VAR model with stochastic volatility.
386 Through this, the potentially bi-directional relationship of Bitcoin prices with green financial

387 asset prices and related financial indices is identified. The corresponding results regarding
388 the time-varying Bitcoin price response at different time points in pre- and post-COVID-
389 19 periods are respectively reported in Figures 8 and 9. Specifically, once receiving a unit
390 price shock to green financial assets before the pandemic, as shown in Panel (a) of Figure
391 8, Bitcoin prices respond positively from zero at the initial stage to shocks from SWI and
392 GCEI, while the impacts of ESGLI and GBI on Bitcoin prices turn negative from zero. The
393 response of Bitcoin prices to the shocks from green financial assets at different time points
394 (i.e., the first-quarter, the half year, and the third-quarter periods) depicts a consistent
395 and overlapping pattern. Moreover, as depicted in Panel (b) of Figure 8, Bitcoin prices
396 demonstrate a consistent response to shocks from all green financial assets before and after
397 the pandemic onset except for GBI. For the latter, it experienced a reversed pattern when
398 facing Bitcoin price shocks before and after the pandemic.

399 [Figure 8 about here.]

400 In terms of the Bitcoin price response to a unit shock from related financial indicators,
401 as shown in Figure 9, the responses to shocks from indices of the cryptocurrency market
402 condition from perspectives of price uncertainty (UCRY Price) and environmental sustain-
403 ability (ICEA) tend to have a similar pattern that evolves from zero at the initial time point,
404 peaks at the short horizons, and then revert to zero within around four horizons. The above
405 responses are highly consistent not only in the face of shocks from different time points (i.e.,
406 the first-quarter, the half year, and the third-quarter periods), but also in pre- and post-
407 COVID-19 periods. Moreover, the responses of Bitcoin prices to shocks from both indices of
408 the cryptocurrency market condition from perspectives of policy uncertainty (URCY Policy)
409 and VIX are shown to have different dynamic patterns in the face of shocks from different
410 points. At the same time, the announcement of the pandemic tends to reverse the Bitcoin
411 price response to shocks from URCY Policy and VIX at various time points.

412 [Figure 9 about here.]

413 Importantly, as for the contemporaneous price impacts of the four-target green financial
414 assets on Bitcoin, they are shown to be zero and remain consistent before and during the
415 COVID-19 pandemic at different time points (i.e., the first quarter, the half year, and the
416 third quarter) as depicted in Figure 8. The above demonstrates the effective hedging role
417 of green financial assets for Bitcoin. Regarding that of the financial indicators related to
418 the cryptocurrency market condition, indices of VIX, UCRY price, and ICEA consistently
419 depict negative or no significant relationship with Bitcoin before and during the pandemic
420 at different time points, showing as an investment hedge. At the same time, compared to
421 the pre-pandemic period, the impacts of UCRY policy on Bitcoin reverses to be negative
422 after the pandemic onset with relatively large magnitudes. Furthermore, it is worth noting
423 that although being within the same and broad category, different types of green assets
424 could impact Bitcoin differently, and vice versa. This is consistent with the viewpoint that
425 various green assets could result in distinct environmental benefits from green transition,
426 further leading to their different relations with Bitcoin (Naeem and Karim, 2021; Symitsi and
427 Chalvatzis, 2018). In addition, since financialization of green-related projects/investments
428 features different degrees, this might also lead to different relation patterns of various green
429 assets with Bitcoin (Naeem et al., 2021).

430 Overall, our results are in line with existing findings that green markets provide effective
431 diversification and hedging potential for other financial assets notably including Bitcoin
432 (Naeem et al., 2021; Nguyen et al., 2021; Lucey et al., 2021b). In the light of the extant
433 literature (Chan et al., 2019; Cheah et al., 2022; Dyhrberg, 2016; Grobys, 2021; Liu et al.,
434 2022; Pal and Mitra, 2019), such the sheltering role of green assets can be explained by two
435 underlying mechanisms, i.e., the process of green economic transition, and the dynamics of
436 production costs. In the context of a globally rising energy consumption with large CO2
437 emissions, the environmental threats have encouraged the finance of cleaner energy, while
438 also calling for green transition of the energy-intensive development mode including Bitcoin
439 trading and mining. Accordingly, although the presence of active Bitcoin trading pursuing

440 for economic profits, green investors would instead adhere to cleaner investments, leading to
441 negligible or even reverse relationship between dynamics of the two types of assets (Naeem
442 and Karim, 2021). At the same time, from the perspective of production costs, it has to be
443 acknowledged that fossil energy is still the major source that drives the economic operation,
444 and the its price along with the electricity price have recently experienced a marked rising
445 due to various reasons such as pandemic recovery, political conflicts, and energy structure
446 adjustment, etc. This would further encourage the usage of renewable and clean energy
447 financed by green projects, while Bitcoin activities would instead encounter higher costs
448 due to the high electricity usage (Le et al., 2021b). Thus, our findings demonstrate the
449 effectiveness of the investment sheltering role of green assets for Bitcoin-related portfolios
450 that inclusion of the former would hedge against the financial risk associated with the latter.

451 5. ROBUSTNESS CHECKS

452 How robust are our findings to changes in the research design? In this section, we conduct
453 additional analyses to reassure the robustness of our findings in the face of inclusion of the
454 price series of another important cryptocurrency, i.e., Ethereum, replacement of the green
455 asset indices with alternative ones, and changes in the sample period, respectively.

456 5.1. Inclusion of the Ethereum price series

457 How sensitive are our obtained results regarding the market interaction between Bitcoin and
458 green assets when considering market dynamics of other leading cryptocurrencies? Our ro-
459 bustness check starts by including the Ethereum price in the empirical estimation. Ethereum
460 is known as the cryptocurrency Ether issued in a decentralized computing platform to reward
461 mining nodes, which is another widely-traded cryptocurrency in addition to Bitcoin (Conlon
462 et al., 2020). Specifically, we re-estimate the market interaction between Bitcoin and green
463 asset by using the TVP-VAR model with the stochastic volatility, while considering the role
464 of Ethereum price.

Overall, as an intuitive illustration through the time-varying impulse response function (IRF) analysis, it is clear that the results are broadly consistent in the estimations with and without considering the Ethereum price.⁶ In particular, the IRF plot regarding the Bitcoin – green asset market interaction when considering the Ethereum price before and during the COVID-19 pandemic is exhibited in Figure 10, which results are similar to the corresponding counterparts in the main analysis shown in Figure 5. In terms of the contemporaneous relationship, the response of green financial assets after receiving a unit shock to Bitcoin prices before the pandemic is presented in Panel (a) of Figure 10 where Bitcoin acts as an investment shelter on the specific green financial asset GCEI. During the pandemic, its sheltering role is further enhanced and extended to three green assets, i.e., SWI, ESGLI, and GCEI, as shown in Panel (b) of Figure 10. The dynamic and potentially sheltering role of the Bitcoin price tends to be consistent when the unit shock is impulse in different time points, i.e., the first quarter, the half year, and the third quarter, further demonstrating that our results are not sensitive to inclusion of additional cryptocurrency prices.

[Figure 10 about here.]

5.2. Replacement of green asset indices with alternative ones

To further examine the robustness of our main results regarding the time-varying market dependence of Bitcoin with green financial assets, we follow [Ren and Lucey \(2021\)](#) by considering the WilderHill Clean Energy Index (CEI) to measure the overall performance of clean energy sector. CEI is then used to replace the S&P Global Clean Energy Index (GCEI) in the re-estimation of our TVP-VAR model with stochastic volatility. Our obtained results after the replacement of GCEI by CEI have been visually presented by the time-varying IRF

⁶For each of the following three robustness checks, the IRF results about all the time-varying interactions of Bitcoin prices with green financial asset prices and related financial indices before and during the COVID-19 pandemic are shown to be broadly consistent with our main findings. While the full version of the IRF plots is compressed due to limited space and is available from the authors upon request, we provide some typical illustrations that show the particular market interactions under focus.

487 plot with the impact of the market dynamics of green assets on that of Bitcoin particularly
488 shown in Figure 11. Overall, the response patterns of the Bitcoin price when receiving a
489 unit shock to each of the four green financial assets shown in Figure 11 generally mimic that
490 of the counterparts in our main findings reported in Figure 8 both before and during the
491 COVID-19 periods. This further supports our argument that the green financial assets are
492 typically regarded as the investment shelter as a (weak) hedge for Bitcoin. Therefore, our
493 results are not sensitive to the variable replacement of the employed green financial assets.

494 [Figure 11 about here.]

495 5.3. Changes in the sample period

496 As an additional robustness check, we conduct a re-estimation by changing the sample period.
497 Following the extant literature (e.g., [Conlon et al., 2020](#); [Conlon and McGee, 2020](#)), updated
498 sub-samples before and after the announcement date of the COVID-19 pandemic with the
499 length for each sub-sample being as a whole year, i.e., from 01 March 2019 to 11 March 2020,
500 and from 12 March 2020 to 30 March 2021. It has been checked that the market relationship
501 of Bitcoin with green assets and related financial indicators using the updated subsamples
502 is consistent with that of our main findings. Particularly, the time-varying IRF results for
503 the response of Bitcoin prices in the face of a unit shock to related financial indicators
504 using the updated sub-samples of before and during the pandemic are respectively depicted
505 in Figure 12, being broadly in line with the corresponding counterparts obtained in our
506 main results shown in Figure 9. Importantly, the contemporaneous price impacts of related
507 financial indices on Bitcoin are found to be zero except the positive impact of URCY policy
508 on Bitcoin before the pandemic although its contemporaneous impact turns to be zero during
509 the pandemic. The above speaks in favor of the weak sheltering role of typical and related
510 financial indicators such as VIX, UCRY price, and ICEA for Bitcoin in both the sub-samples
511 of before and during the COVID-19, further reassuring the robustness of our main findings.

512 [Figure 12 about here.]

6. CONCLUSIONS

513

514 In the face of rapid climate warming worldwide, the pursuit of future dynamics of the Bitcoin
515 market within a green and sustainable environment has become increasingly important,
516 driving ongoing but still limited attention on whether to add green assets to the Bitcoin-
517 related portfolio for risk diversification while contributing to the green commitment. At the
518 same time, the onset of the COVID-19 pandemic and its associated financial turmoil call for
519 a reinvestigation of the cross-sectional dynamics of the financial markets, among which the
520 connectedness tends to become more correlated during the downturn.

521 Our paper, therefore, examines the dynamics of the market dependence between Bitcoin
522 and green financial assets over time by applying a recently-developed time-varying param-
523 eter VAR (TVP-VAR) model with stochastic volatility. Four indices such as Dow Jones
524 Sustainability World Index (SWI), S&P ESG Leader Index (ESGLI), S&P Green Bond In-
525 dex (GBI), and S&P Global Clean Energy Index (GCEI) are considered to represent the
526 dynamics of the green assets through four perspectives in a comprehensive manner. The
527 role of two uncertainty indices specifically designed for the cryptocurrency market by [Lucey](#)
528 [et al. \(2021b\)](#), along with an index of cryptocurrency environmental attention developed by
529 [Lucey et al. \(2021a\)](#), are particularly considered for accurate interpretation of the Bitcoin
530 market interaction with green asset markets.

531 Consistent with our expectations, the potential asymmetry of the market dependence is
532 found through three perspectives, i.e., impact directions, time points where the unit shock
533 is being imposed in the IRF (i.e., short-, medium-, and long-runs), as well as before and
534 during the pandemic. The investment sheltering role of Bitcoin/green assets against adverse
535 fluctuations in one another is shown by the contemporaneous market linkage. Specifically,
536 before the pandemic, Bitcoin is found to consistently play a sheltering role of effective hedge
537 on the specific green financial asset GBI at various time horizons as indicated by its negative
538 price impact on GBI. The sheltering role of Bitcoin is further enhanced after the pandemic

539 outbreak that the price of Bitcoin negatively affects that of three out of four green assets
540 under research, i.e., SWI, ESGLI, and GBI, during the pandemic. On the other hand, the
541 four green assets are shown to consistently exhibit an investment shelter as a weak hedge for
542 Bitcoin at different time horizons before and during the pandemic. The robustness of our
543 findings is further reassured by a series of additional analysis.

544 While it is known that assets tend to become increasingly co-moved during economic
545 downturns (e.g., [Bekaert et al., 2009](#); [Goodell and Goutte, 2021b](#)), in the financial turmoil
546 related to the COVID-19 bear market, Bitcoin has depicted its independence with other
547 assets, showing effective investment sheltering role especially against green assets. These
548 findings contribute to the currently-ongoing debate as to whether green assets could act
549 as an investment shelter for the Bitcoin-related portfolio, and offer Bitcoin investors with
550 clear insights for both risk mitigation and green commitment in their portfolios. In turn,
551 comprehension on the underlying investment sheltering role of Bitcoin for green portfolios
552 is also gained. Therefore, our findings are important for not only hedging against green
553 portfolios but also seeking green shelter. The findings also help policymakers promote the
554 green and sustainable development of the financial market, notably the Bitcoin market,
555 effectively combating global climate change

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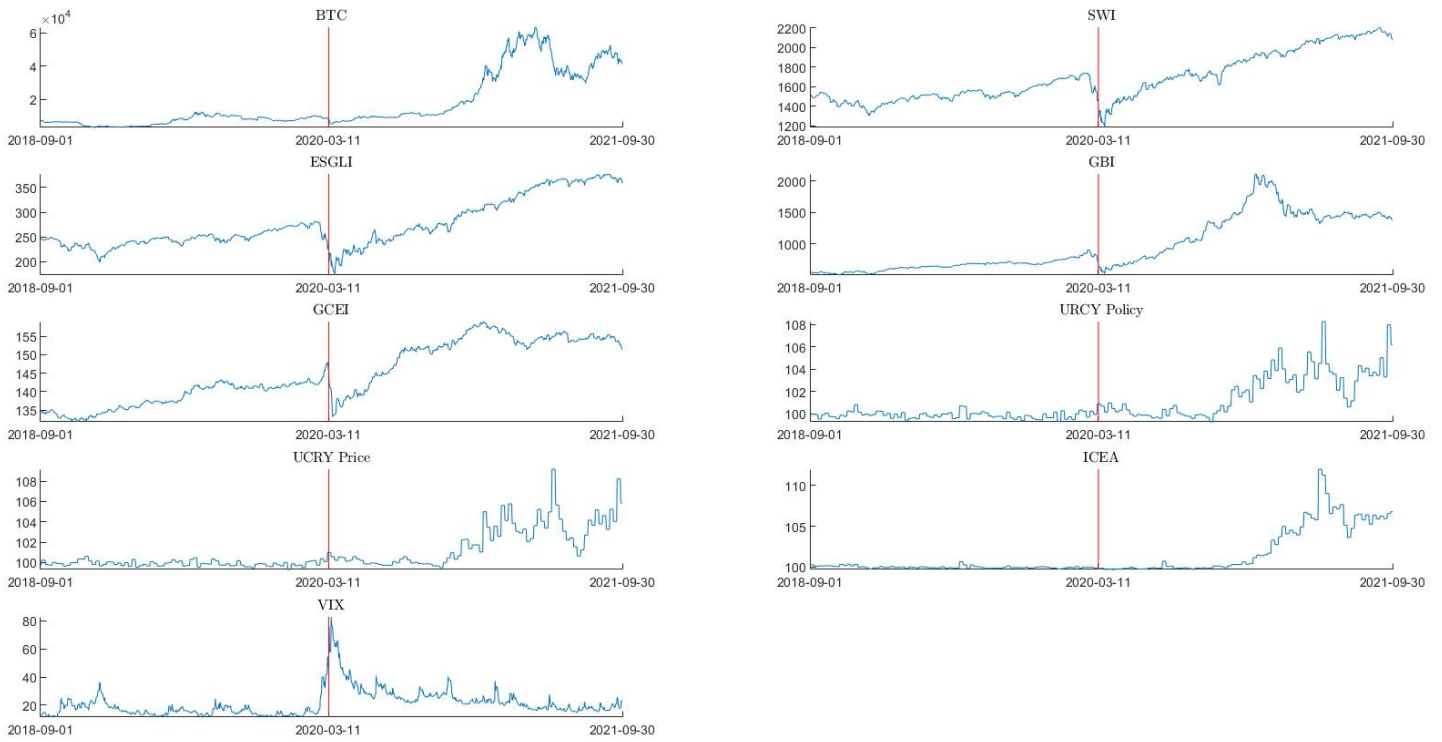


Figure 1: *Dynamics of target factors over time*

Note: This figure plots the time-varying dynamics of nine target series under research including the Bitcoin price (BTC), four green financial assets (i.e., SWI, ESGLI, GBI, and GCEI), three indices describing the cryptocurrency market condition through both perspectives of uncertainty (i.e., URCY policy and URCY price) and environmental sustainability (ICEA), and the CBOE Volatility Index (VIX).



Figure 2: Time-varying posterior estimates for autoregressive coefficients β_t before the COVID-19 pandemic

Note: This figure reports the time-varying dynamics of the posterior estimates of β_t defined in Equation (3) before the pandemic. Sub-figures on left two columns show the dynamic impacts of Bitcoin prices on prices of green assets (i.e., SWI, ESGLI, GBI, and GCEI) and related financial indicators (i.e., UCRY policy, UCRY price, ICEA, and VIX) over time. Conversely, the ones on right two columns show the response of Bitcoin when facing impacts from green assets and related financial indicators over time. In each sub-figure, the blue solid line stands for the time-varying dynamics of the posterior mean of β_t , and the red dotted lines denote dynamics of the corresponding 95% intervals. The x-axis denotes time periods, and the y-axis denotes the impact magnitude.

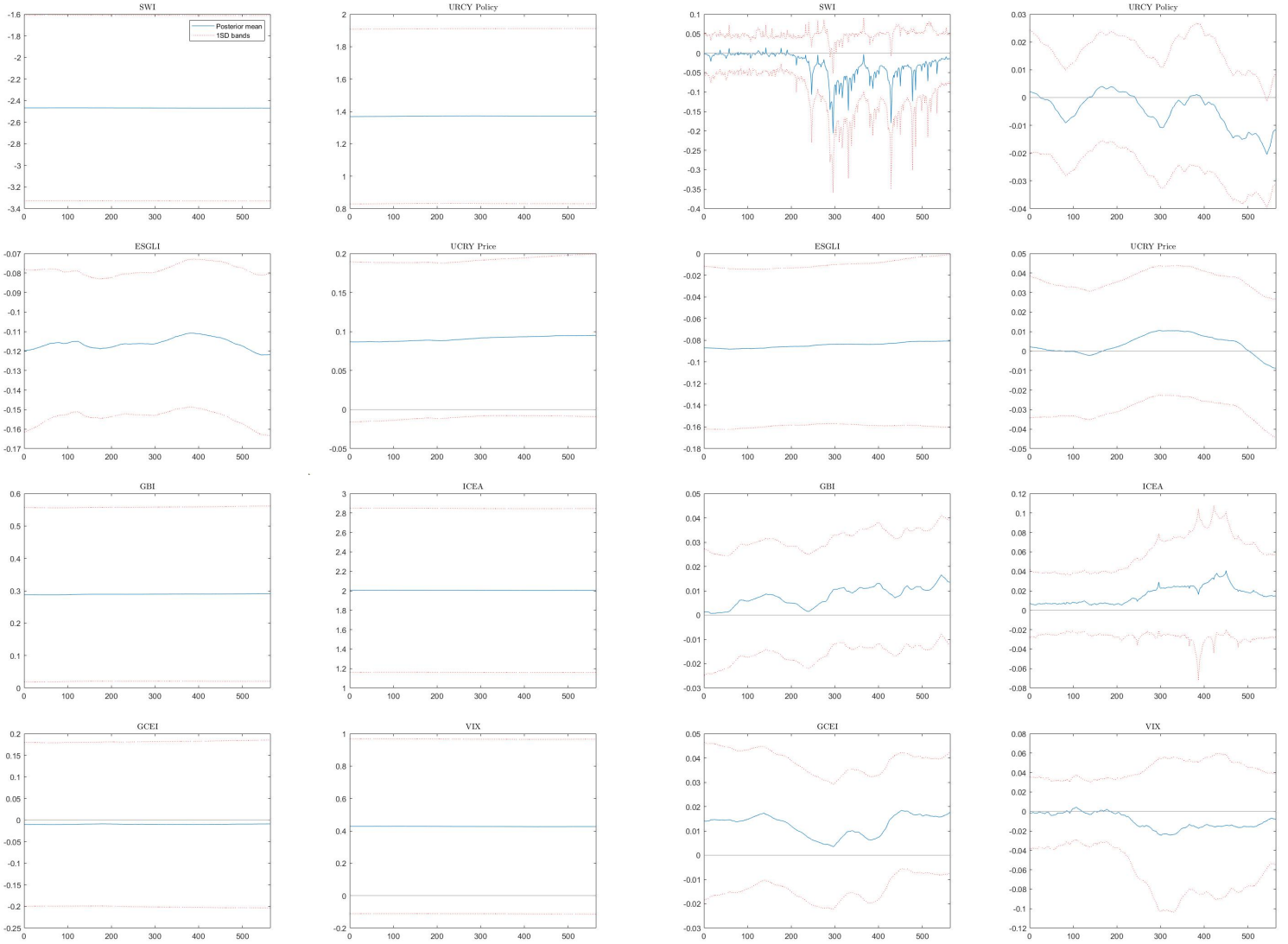


Figure 3: Time-varying posterior estimates for autoregressive coefficients β_t in during the COVID-19 pandemic

Note: This figure reports the time-varying dynamics of the posterior estimates of β_t defined in Equation (3) during the pandemic. Sub-figures on left two columns show the dynamic impacts of Bitcoin prices on prices of green assets (i.e., SWI, ESGLI, GBI, and GCEI) and related financial indicators (i.e., UCRY policy, UCRY price, ICEA, and VIX) over time. Conversely, the ones on right two columns show the response of Bitcoin when facing impacts from green assets and related financial indicators over time. In each sub-figure, the blue solid line stands for the time-varying dynamics of the posterior mean of β_t , and the red dotted lines denote dynamics of the corresponding 95% intervals. The x-axis denotes time periods, and the y-axis denotes the impact magnitude.

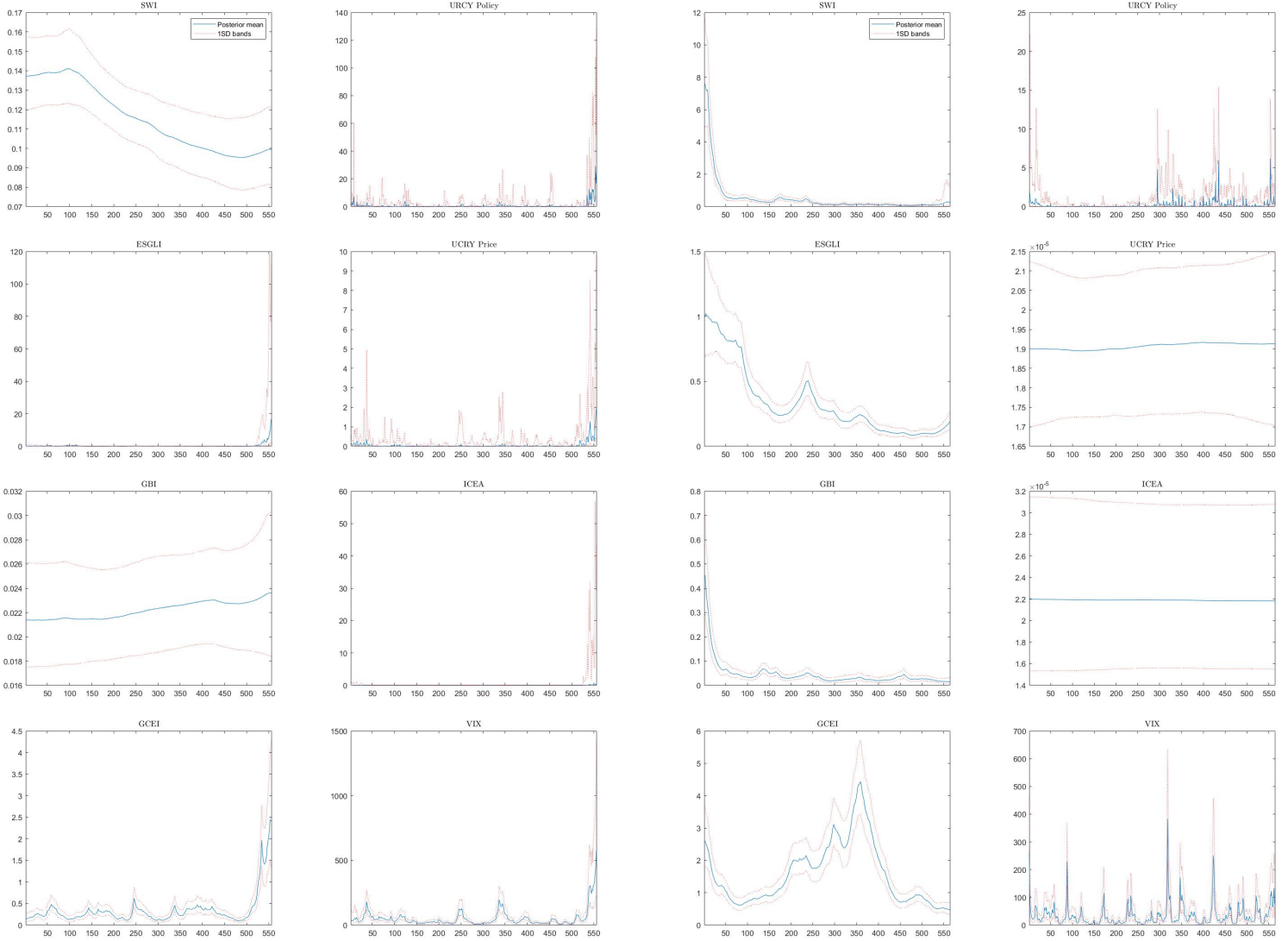


(a) *Pre-COVID-19 period*

(b) *Post-COVID-19 period*

Figure 4: Time-varying posterior estimates for covariance parameters a_t before and during the COVID-19 pandemic

Note: This figure reports the time-varying dynamics of the posterior estimates of t defined in Equation (4). The estimated covariance parameters (i.e., t) of Bitcoin prices with green asset prices and related financial indicators before and during the pandemic are shown in panels (a) and (b), respectively. In each sub-figure, the blue solid line stands for the time-varying dynamics of the posterior mean of β_t , and the red dotted lines denote dynamics of the corresponding 95% intervals. The x-axis denotes time periods, and the y-axis denotes the impact magnitude.



(a) *Pre-COVID-19 period*

(b) *Post-COVID-19 period*

Figure 5: Time-varying posterior estimates for volatility parameters σ_t^2 in the pre- and post-COVID-19 periods

Note: This figure reports the time-varying dynamics of the posterior estimates of σ_t^2 defined in Equation (5). The estimated volatility parameters (i.e., σ_t^2) of each of the considered series before and during the pandemic are shown in panels (a) and (b), respectively. In each sub-figure, the blue solid line stands for the time-varying dynamics of the posterior mean of β_t , and the red dotted lines denote dynamics of the corresponding 95% intervals. The x-axis denotes time periods, and the y-axis denotes the impact magnitude.

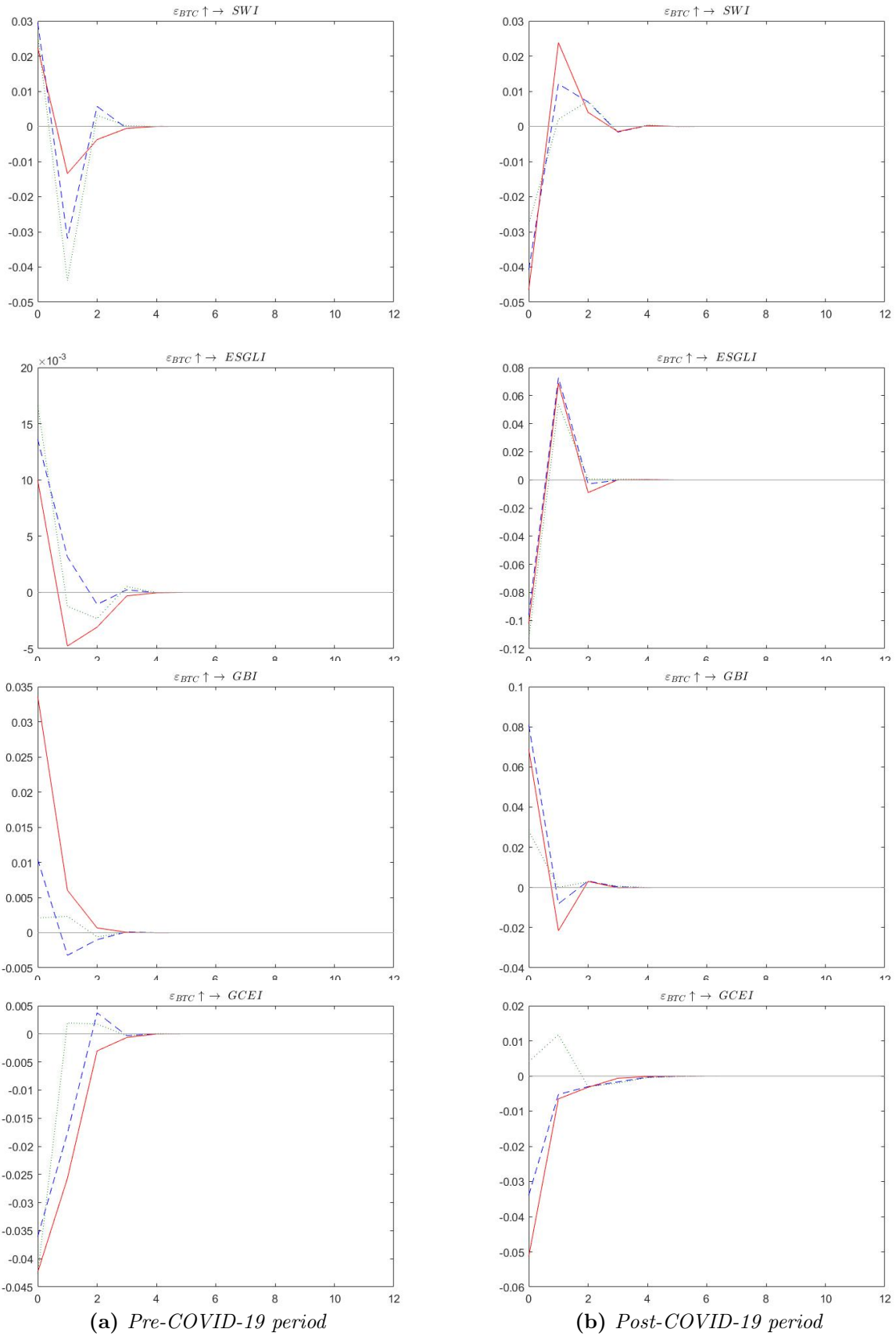


Figure 6: The time-varying impulse response of green financial asset prices to a unit shock of Bitcoin prices in the pre- and post-COVID-19 periods

Note: This figure shows the IRF plots before and during the pandemic as shown in panels (a) and (b), respectively. The gray dotted line, blue dashed line, and red solid line refer to the response of the specific green asset when facing a unit shock to Bitcoin prices at different time points, i.e., the first quarter, the half year, and the third quarter, respectively.

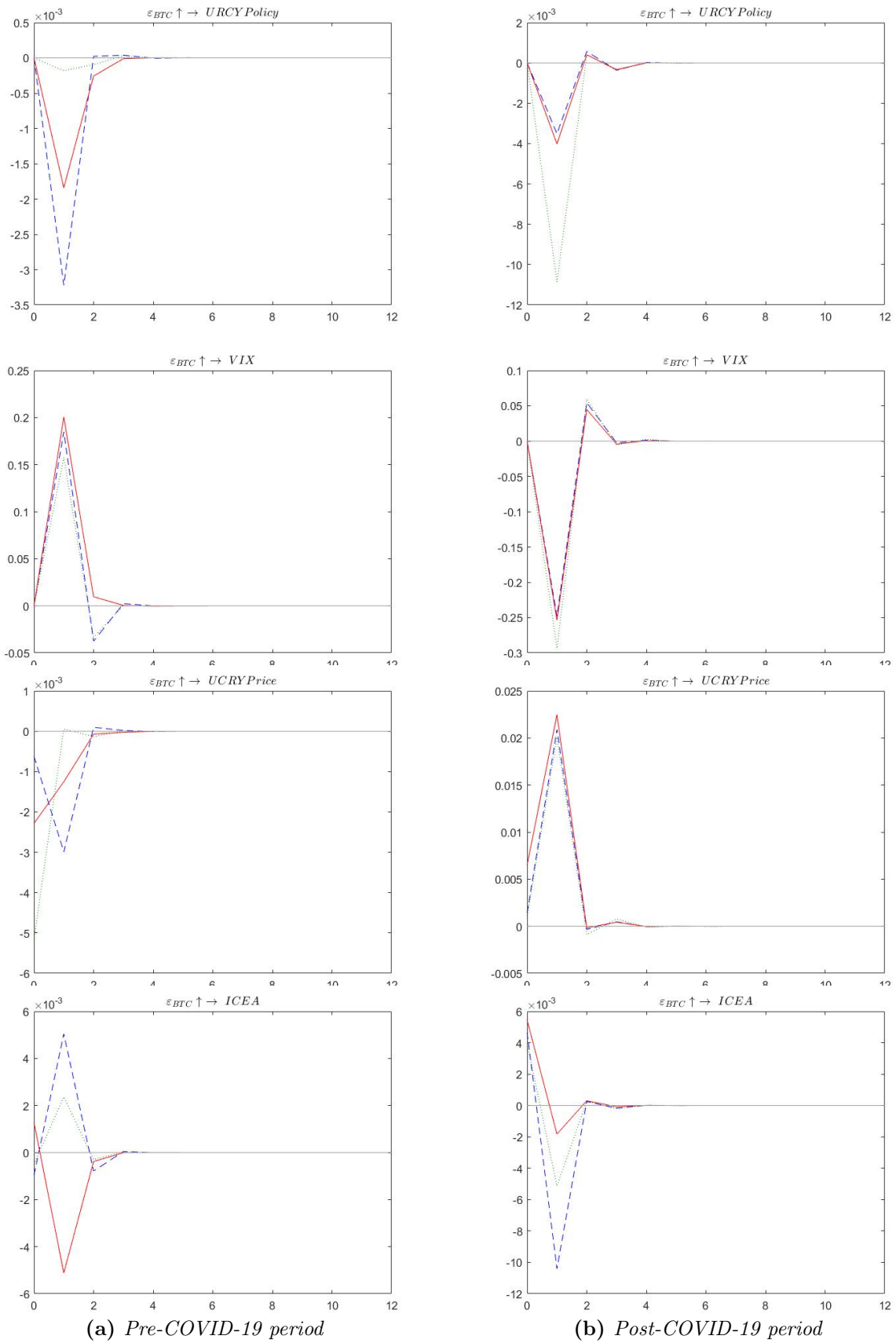


Figure 7: The time-varying impulse response of related financial indicators to a unit shock of Bitcoin prices in the pre- and post-COVID-19 periods

Note: This figure shows the IRF plots before and during the pandemic as shown in panels (a) and (b), respectively. The gray dotted line, blue dashed line, and red solid line refer to the response of the specific related financial indicator when facing a unit shock to Bitcoin prices at different time points, i.e., the first quarter, the half year, and the third quarter, respectively.

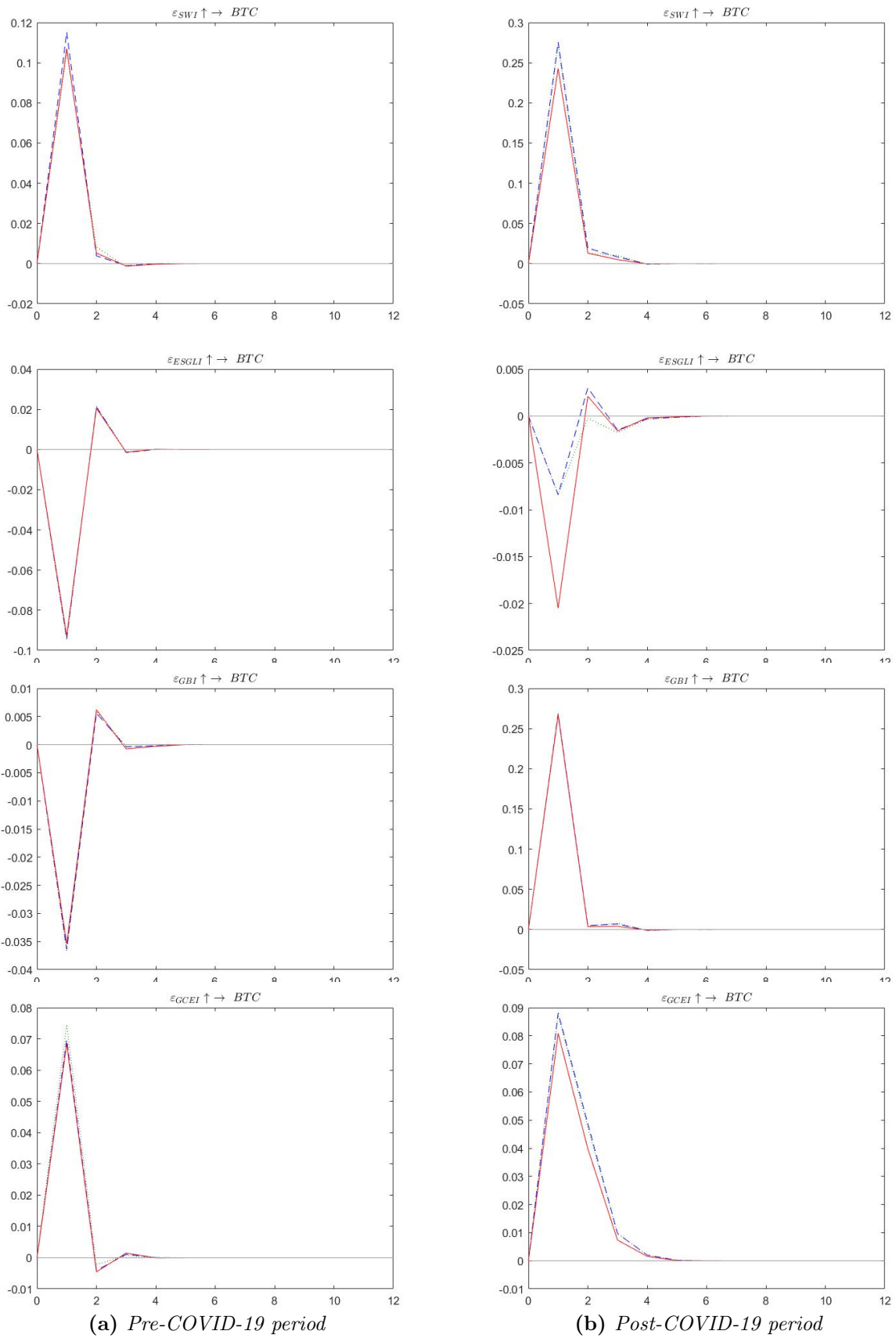


Figure 8: The time-varying impulse response of Bitcoin prices to unit shocks of green financial asset prices in the pre- and post-COVID-19 periods

Note: This figure shows the IRF plots before and during the pandemic as shown in panels (a) and (b), respectively. The gray dotted line, blue dashed line, and red solid line refer to the response of the Bitcoin price when facing a unit shock to the price of the specific green asset at different time points, i.e., the first quarter, the half year, and the third quarter, respectively.

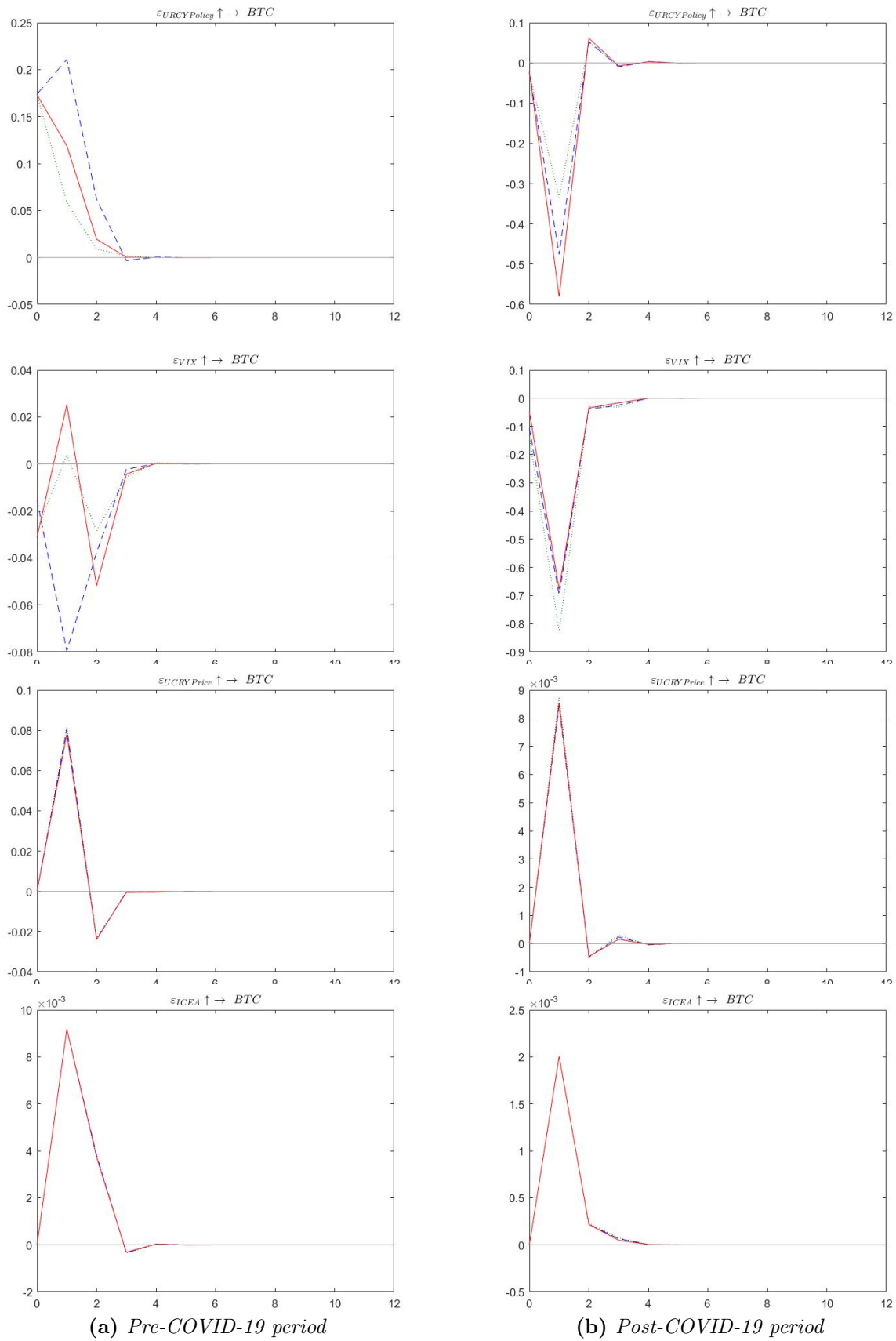


Figure 9: The time-varying impulse response of Bitcoin prices to unit shocks of related financial indicators in the pre- and post-COVID-19 periods

Note: This figure shows the IRF plots before and during the pandemic as shown in panels (a) and (b), respectively. The gray dotted line, blue dashed line, and red solid line refer to the response of the Bitcoin price when facing a unit shock to the related financial indicator at different time points, i.e., the first quarter, the half year, and the third quarter, respectively. 38

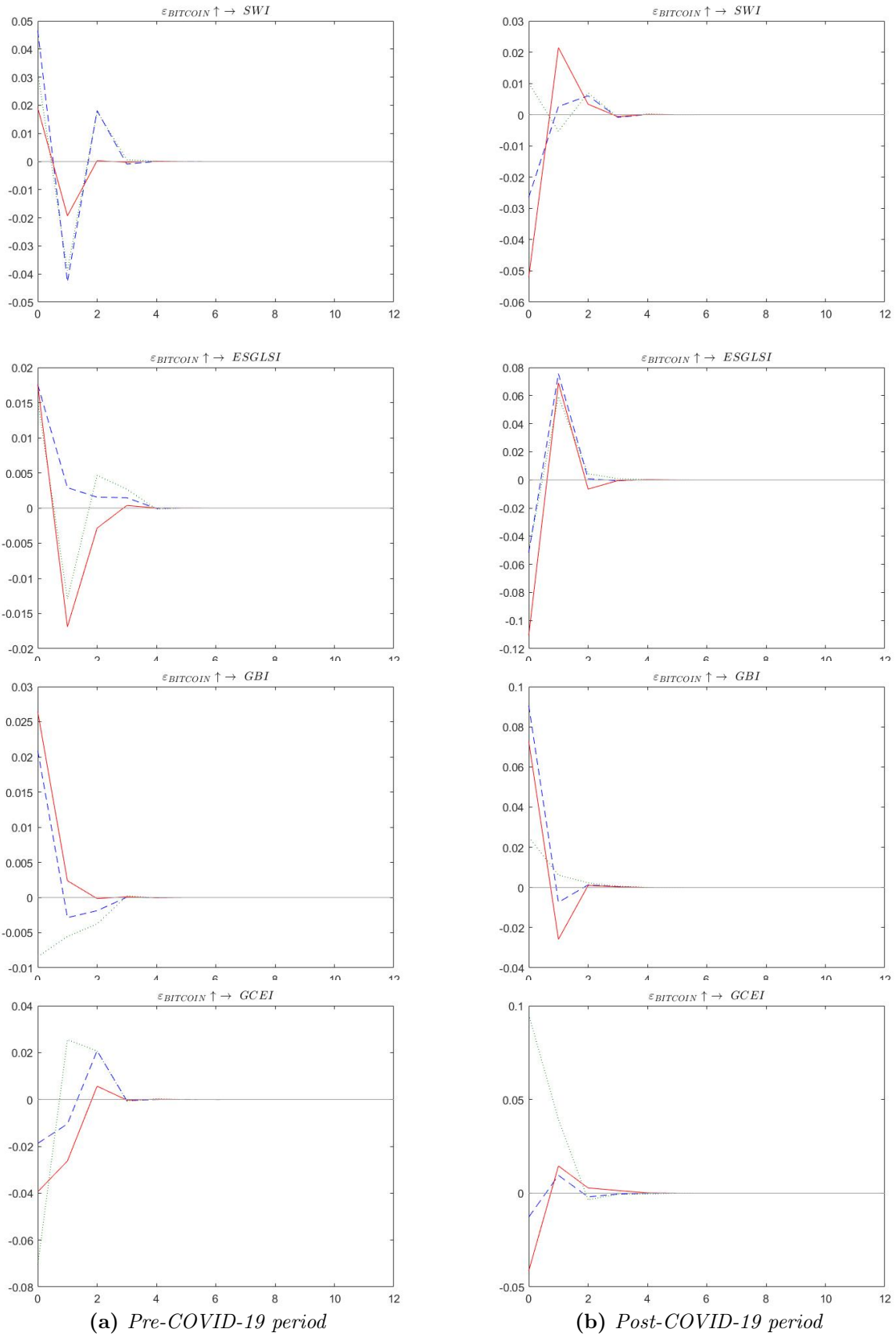


Figure 10: Robustness 1: IRF plots of green asset prices to a unit shock of Bitcoin prices in the pre- and post-COVID-19 when including the Ethereum prices

Note: This figure shows the IRF plots before and during the pandemic as shown in panels (a) and (b), respectively. The gray dotted line, blue dashed line, and red solid line refer to the response of the specific variable when facing a unit shock to Bitcoin prices at different time points, i.e., the first quarter, the half year, and the third quarter, respectively.

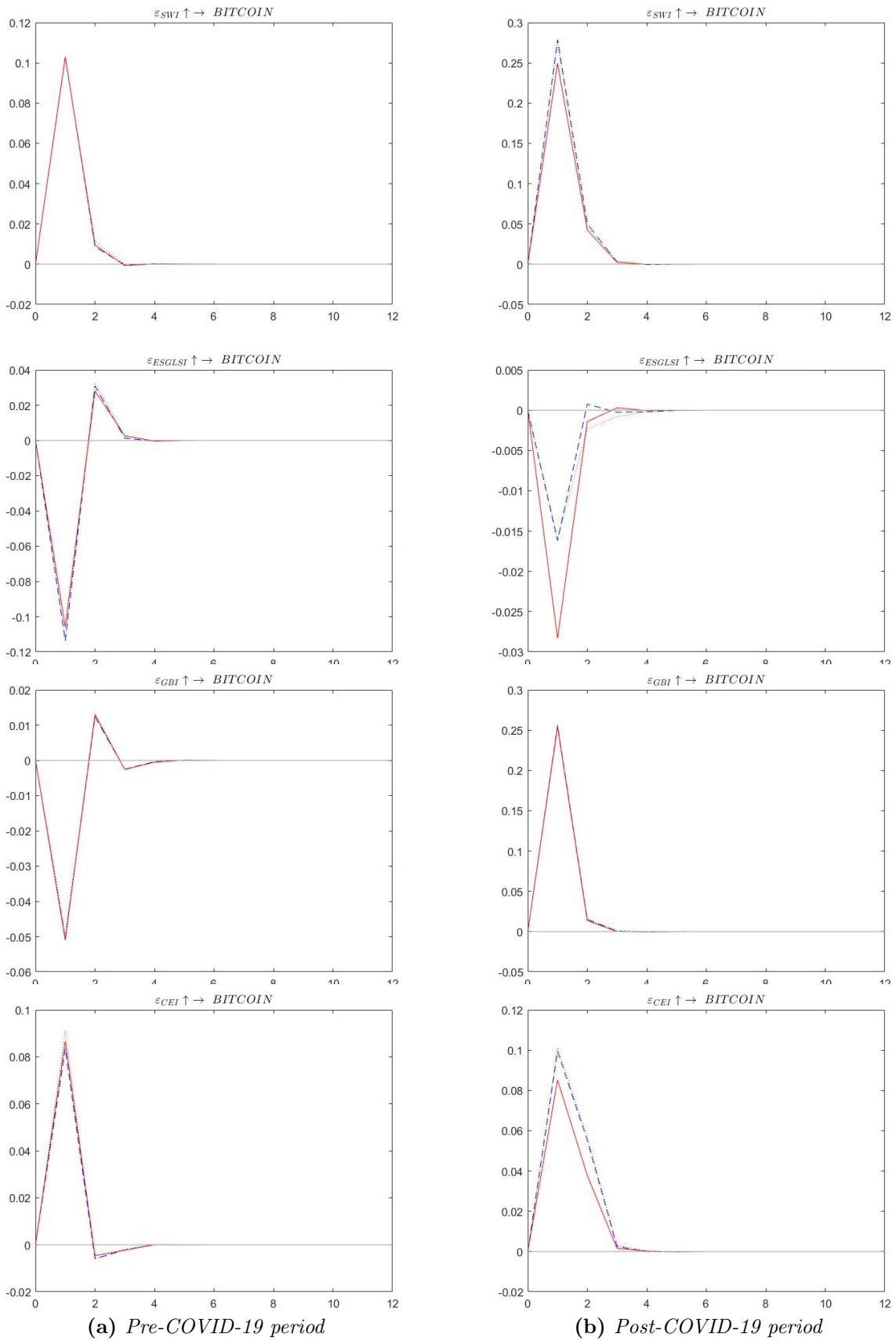


Figure 11: Robustness 2: IRF plots of Bitcoin prices to a unit shock of green asset prices in the pre- and post-COVID-19 with alternative green asset prices

Note: This figure shows the IRF plots before and during the pandemic as shown in panels (a) and (b), respectively. The gray dotted line, blue dashed line, and red solid line refer to the response of the specific variable when facing a unit shock to a target green asset at different time points, i.e., the first quarter, the half year, and the third quarter, respectively.

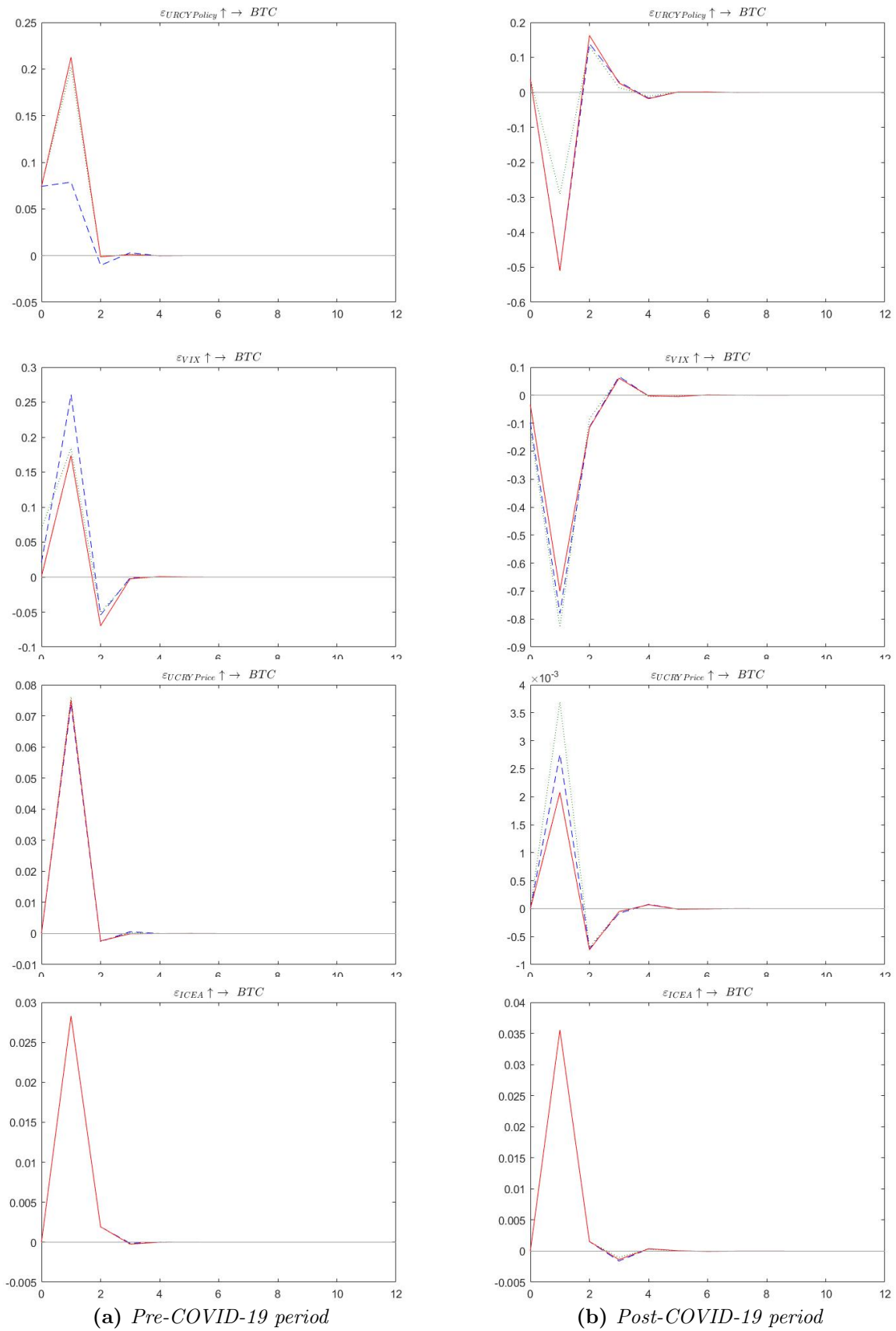


Figure 12: Robustness 3: IRF plots of Bitcoin prices to a unit shock of related financial indicators in the pre- and post-COVID-19 with changes in the sample period

Note: This figure shows the IRF plots before and during the pandemic as shown in panels (a) and (b), respectively. The gray dotted line, blue dashed line, and red solid line refer to the response of the specific variable when facing a unit shock to a target related financial indicator at different time points, i.e., the first quarter, the half year, and the third quarter, respectively.

Table 1: Descriptive statistics

	Mean	Std. Dev.	Minimum	Maximum	Skewness	Kurtosis
<i>Panel A: Pre-Covid-19</i>						
BTC	0.0222	3.5610	-14.9442	15.2987	-0.1216	3.6718
SWI	-0.0295	0.8499	-10.6051	2.8620	-4.5717	49.5546
ESGLSI	-0.0368	1.0774	-10.8401	4.4731	-2.8730	26.4139
GBI	0.0098	0.2101	-2.3671	0.8167	-2.3432	30.2399
GCEI	0.0177	1.1340	-12.4971	5.5528	-4.1089	43.9267
UCRY Policy	0.0022	0.1295	-0.9091	0.9041	0.2036	18.3164
UCRY Price	0.0021	0.1519	-1.1347	1.0598	0.3207	21.1604
ICEA	-0.0006	0.0611	-0.4383	0.7623	2.7226	57.5845
VIX	0.3171	7.2506	-19.8144	38.2167	1.3691	5.5387
<i>Panel B: Post-Covid-19</i>						
BTC	0.3473	3.7728	-13.4276	16.1041	0.1385	1.8977
SWI	0.0754	0.9812	-8.7034	7.6939	-0.5779	21.2194
ESGLSI	0.0883	1.4428	-12.9915	11.2908	-0.5905	21.8781
GBI	0.0124	0.2861	-2.4099	2.0127	-0.8740	15.6212
GCEI	0.1366	1.8595	-10.5579	11.0330	-0.2783	6.9841
UCRY Policy	0.0091	0.4410	-3.5751	4.4182	2.0752	37.0057
UCRY Price	0.0083	0.4646	-3.2736	3.9308	2.7952	35.0517
ICEA	0.0120	0.3533	-2.3672	5.6834	6.4870	127.4807
VIX	-0.1618	6.7453	-20.8405	48.0214	1.6034	9.2081

Note: This table provides descriptive statistics of the variables used in this study, including the price series of Bitcoin (BTC), the four green financial assets, i.e., SWI, ESGLSI, GBI, GCEI, the two uncertainty index of the cryptocurrency market through aspects of policy and price, i.e., UCRY policy and UCRY price, the index of Cryptocurrency Environmental Attention (ICEA), and the CBOE Volatility Index (VIX).