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COVID-19’s effect on the spatial integration of fish markets: Evidence from carp price in China

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ABSTRACT

While curbing the spread of Coronavirus Disease 2019 (COVID-19), lockdown policies and “stay-at-home” restrictions caused massive supply chain disruptions worldwide. This led to breaks in spatial market integration, which could further lead to market inefficiency and resource misallocation. Taking daily price data from 2016 to 2021, this study investigates COVID-19’s effect on the spatial market integration of fish in China using cointegration tests. We find a high degree of spatial market integration for fish in China before the COVID-19 pandemic. Further, our results show that COVID-19’s effect on the spatial market integration of fish varies spatially in China. Specifically, COVID-19 reduces the degree of spatial market integration in most provinces, especially those with high infection rates. Meanwhile, the degree of spatial market integration in provinces with low infection rates remains high. Therefore, the government should be regionally specific when formulating market recovery policies.

1. Introduction

The Coronavirus Disease 2019 (COVID-19) pandemic has been the worst public health disaster in recent years, characterized by rapid transmissions, widespread infections, and slow recovery. As of September 1st, 2022, there had been more than 600 million confirmed cases and over 6.4 million deaths worldwide. Many countries took control measures to curb the spread of COVID-19, among which China and Japan were the first to implement control policies, on January 22nd, 2020. After that, a great number of other countries adopted similar policies, including “lockdowns” and “stay-at-home” mandates (Akter, Fang et al., 2020; Nafees and Khan, 2020).

Such measures had profound effects on agricultural product markets in terms of the supply, demand, transportation, and price volatility. They caused production reductions (Soto et al., 2021), supply chain disruptions (Mahajan and Tomar, 2021), trade flow restrictions (Kerr, 2020), reduced dietary options (Devereux et al., 2020), short-term stockouts (Hobbs, 2020), and rising prices (Rude, 2020; Ruan et al., 2020). Fish is highly perishable and thus highly vulnerable to supply chain disruptions (Mahajan and Tomar, 2021). As a result, fish was most affected by COVID-19 among agricultural products (Zhang et al., 2020).

This paper, therefore, aims to study COVID-19’s economic effect on fish markets. In particular, we focus on the spatial market integration of fish. Spatial market integration, as an important part of market analysis, has significant implications for market operation, market efficiency, and price discovery (Barrett, 1996; Goodwin and Piggott, 2001). The lockdown policies caused massive supply chain disruptions (Mahajan and Tomar, 2021) and trade flow restrictions (Kerr, 2020), which may have resulted in barriers between spatial markets. It is worthwhile, therefore, to explore how COVID-19 affects the spatial market integration of fish.

China is an ideal subject for this research. First, China is a top-ranked country in aquaculture. Specifically, it is the largest producer, top exporter, and second-largest importer of aquaculture food (Food and Agriculture Organization (FAO), 2021). China also has the highest aquaculture consumption, as many as 19.6 million tons annually (CSY, 2021). As the official website of the World Health Organization: emerging confirmed cases, total confirmed cases, and deaths of COVID-19 globally. https://covid19.who.int/

China is one of the first countries to implement a national lockdown policy, and its quarantine policies are among the strictest in the world. How such a stringent regulation policy affected the spatial integration of fish market recovery policies.
aquaculture markets is still generally unknown.

Furthermore, we focus on carp due to its importance in China. On the one hand, carp has the top output among all fish species in China. The harvest of carp is more than 11.17 million tons annually, accounting for 80% of the total inland aquaculture yield (Yin et al., 2017). On the other hand, carp is the most popular fish among Chinese consumers (Newton et al., 2021). In China, carp has been consumed for thousands of years (Li et al., 2021), and its consumption volume is ranked 1st among all fish species. In addition, carp is a major domestic-oriented produced and consumed species (Asche et al., 2022). Since China imported only 59.5 tons and exported only 44 tons of carp on average every year, 99.99% of carp in Chinese markets are either domestically produced or domestically consumed. Therefore, COVID-19’s effect on the spatial market integration of carp is worth investigating as carp is such a vital part of the Chinese fish market.

Research on spatial market integration spans a wide range of agricultural products and countries, as shown in Table 1. Few studies, however, take fish markets in China, as a subject. Overlooking China’s fish market presents a significant gap in the research, given the importance of China’s fishery sector.

In addition, studies on the effects of events or policies on spatial market integration have mainly focused on relatively localized phenomena, such as market liberalization or contagious animal diseases, as shown in Table 2. Few studies, however, have specifically explored the related effects of highly infectious events among the human population, such as COVID-19. COVID-19 significantly differs from the above-mentioned events in two ways. First, contagious animal diseases are transmitted between animals, while COVID-19 mainly affects humans. Second, COVID-19 results in lockdown policies worldwide, while the effects of contagious animal diseases are often localized. To the knowledge of the study, no study has specifically investigated how a pandemic, such as COVID-19, affects the spatial market integration of agricultural products, especially fish. Therefore, to fill this research gap, we aim to empirically assess COVID-19’s effect on the spatial market integration of fish.

This study’s main contributions are threefold. First, this is the first empirical work to investigate the spatial market integration of fish in China. Since fish is an important part of the Chinese daily diet, this study provides insights on how to stabilize the fish industry’s livelihood and residents’ fish protein intake. Second, this is also the first empirical work to examine the effect of a large public health emergency on the market integration of agricultural products. Our study provides an analytical framework which can serve as a reference for future studies on large public health emergencies. Third, our results show that COVID-19 generally reduces the spatial market integration of fish, and the effect varies geographically. Such results offer evidence that COVID-19 has a negative effect on spatial market integration. The results also highlight the importance of considering geographic heterogeneity when making policies to recover the market integration of fish.

The rest of this paper is organized as follows. Section 2 describes the empirical method, and section 3 introduces the data set. Section 4 presents the empirical results while section 5 concludes and discusses the policy implications.

2. Method

There are mainly two methods to quantitatively measure COVID-19 in current literature. One is to quantify COVID-19 based on the daily number of emerging or existing confirmed cases (Yu et al., 2020). The other is to select COVID-19 outbreak nodes and divide the whole sample into the pre- and post-pandemic subsamples (Ruan et al., 2021; Ramsey et al., 2021). The daily number of emerging or existing confirmed cases of COVID-19, though, might not accurately reflect the true epidemiological situation, since there are people who are unaware of being infected or do not seek treatment after infection. In addition, models with partially varying parameters, such as the threshold vector error correction model, might not be suitable for investigating the effect of a substantial structural break (Chen and Saghafi, 2015). Therefore, we divide the whole sample into two subsamples according to the national lockdown timeline in China and use the exogenous structural change approach to assess the effect of COVID-19.

Based on the law of one price, the spatial market integration is expressed as the extent to which the price of a homogeneous good in one market is passed onto another market (Fackler and Goodwin, 2001). When there is a long-term equilibrium relationship between prices in two markets, those two markets are spatially integrated. Such a relationship can be tested by estimating:

\[
\begin{align*}
\text{Price}_{it} &= \alpha + \beta \text{Price}_{i,t-1} + \gamma \text{Price}_{j,t-1} + \delta \text{COVID}_{i,t} + \epsilon_{i,t} \\
\end{align*}
\]

Table 1

| Literature                        | Country | Species                  | Degree of spatial market integration |
|----------------------------------|---------|--------------------------|--------------------------------------|
| Lele (1967)                      | India   | Sorghum                  | High                                 |
| Delgado (1986)                   | Nigeria | Grain                    | Low                                  |
| Bailey, and V., Beursen, B. W. (1989) | U.S.    | Carole                  | High                                 |
| Goodwin and Schroeder (1991)     | U.S.    | Soft wheat, milk, potatoes, and pork | High |
| Zanias (1993)                    | European Union | Sorghum                  | High                                 |
| Alexander and Wyeth (1994)       | Indonesia | Rice                    | High                                  |
| Baulch (1997)                    | Philippines | Rice                    | High                                  |
| Zanias (1999)                    | European Union | Soft wheat              | High                                  |
| González-Rivera and Helfand (2001) | Brazil | Rice                    | High                                  |
| Goodwin and Piggott (2001)       | U.S.    | Corn and soybean         | High                                  |
| Sanjuan and Gil (2001)           | European Union | Pork and lamb         | High                                  |
| Meyer (2004)                     | European Union | Pork                    | High                                  |
| Getnet et al. (2005)             | Ethiopia | White teff               | High                                  |
| Bauch et al. (2008)              | Vietnam | Paddy                   | High                                  |
| Mose et al. (2009)               | Madagascar | Rice                    | High                                  |
| Asche et al. (2012)              | Tanzania | Sorghum                  | High                                  |
| Emmanouilides and Fousekis (2012) | European Union | Pork                  | High                                  |
| Esposito and Listorti (2013)     | Italy   | Wheat and corn           | High                                  |
| Mulazzani et al. (2015)          | Italy   | 18 species of fish       | High                                  |
| Sapkota et al. (2015)            | Bangladesh | 5 species of fish      | Low                                   |
| Wani et al. (2015)               | India   | Apple                    | High                                  |
| Iregui and Otero (2017)          | Colombia | 153 products             | High                                  |
| Tankari and Goundan (2018)       | Niger | Greenland, Denmark, and United Kingdom | Shrimp        |
| Nielsen et al. (2018)            | Colombia | Millet                   | Low                                   |
| Fernández-Polanco and Llorente (2019) | Spanish | Gilthead seabream       | High                                  |
| Karelakis (2019)                 | European Union | Shrimp                  | High                                  |

\footnote{A report on fish consumption, price, and trade.\url{https://www.sohu.com/a/294227607_120065720}}

\footnote{Data source: the official website of General Administration of Customs P.R. China.\url{http://www.customs.gov.cn/}}
Table 2

| Species Category | Event or policy | The impact of the event or policy |
|------------------|----------------|----------------------------------|
| Goletti and Babu (1994) | Malawi Maize | Market liberalization | Increase the degree of spatial market integration |
| Rozelle et al. (1997) | China Rice and maize | Market liberalization | Increase the degree of spatial market integration |
| Ismet et al. (1998) | Indonesian Rice | Achieved self-sufficiency in rice | Increase the degree of spatial market integration |
| Pendell and Schroeder (2006) | U.S. Cattle | Reporting | Increase the degree of spatial market integration |
| Awokuse and O. (2007) | China Rice | Market liberalization | Increase the degree of spatial market integration |
| Ghosh (2011) | India Grain | Agricultural Policy reforms and blue tongue disease | Decrease the degree of spatial market integration |
| Ihle et al. (2012) | European Union Cattle | Structural break of the hog market | Decrease the degree of spatial market integration |
| Pan and Li (2019) | China Hog | Structural break of the hog market | Decrease the degree of spatial market integration |
| Li and Chavas (2020) | China Hog | African swine fever | Decrease the degree of spatial market integration |

\[ y_{it} = \alpha + \beta y_{jt} + \varepsilon_t, \]  

(1)

where \( y_{it} \) is the logarithm of the fish price in province \( i \) at time \( t \), \( y_{jt} \) is the logarithm of the fish price in province \( j \) at time \( t \), \( \alpha \) is the constant term, \( \beta \) is a parameter of \( y_{jt} \), and \( \varepsilon_t \) is a stochastic error term. This equation is estimated using the ordinary least squares (OLS) method. When \( \beta = 0 \), provinces \( i \) and \( j \) are not spatially integrated. In case \( \beta = 1 \), provinces \( i \) and \( j \) are fully integrated. A \( \beta \) value between 0 and 1 indicates a partial market integration (Mulazzani et al., 2015; Nielsen et al., 2018; Fernández-Polanco and Lorente, 2019). This general regression analysis with OLS and conventional tests (e.g., Wald test, likelihood ratio test, or Lagrange multiplier test) can be used to test the long-term equilibrium relationship between prices when price series are stationary.

For nonstationary price series, cointegration tests are widely used in market integration studies (Scuderi and Chen, 2018; Pan and Li, 2019; Ozturk, 2020; Roman and Roman, 2020; Salazar and Dresdner, 2021; Jung et al., 2022). Therefore, we use the method outlined by Engle and Granger (1987) to test the long-term equilibrium price relationship between each pair of provinces (hereafter, the EG two-step cointegration test). The EG two-step cointegration test begins with the same static model as shown in Eq. (1). We then test whether \( \varepsilon _{it} \) is stationary. If \( \varepsilon _{it} \) is stationary, then a long-term equilibrium relationship between \( y_{it} \) and \( y_{jt} \) is considered to exist, indicating that provinces \( i \) and \( j \) are spatially integrated.

However, the estimator of \( \beta \) from Eq. (1) is not asymptotically normal with nonstationary price series. We, therefore, are unable to detect whether the market pairs are fully or partially integrated using the conventional tests. Instead, we adopt the Dynamic Ordinary Least Squares (DOLS) estimator (Stock and Watson, 1993):

\[ y_{it} = \alpha + \beta y_{jt} + \sum_{k=1}^{p} \phi_k \Delta y_{jt-k} + \epsilon_t, \]  

(2)

where \( \Delta y_{jt} \) is the first order difference of the logarithm of fish price in province \( j \) at time \( t \), and \( \phi_k \) is the parameter of \( \Delta y_{jt} \) with \( q \) leads and \( p \) lags. In this DOLS model, the Wald statistic is asymptotically chi-squared distributed. Thus, we can test whether the markets are fully or partially integrated by testing whether \( \beta \) is equal to or less than one with this Wald statistic.

3. Data

We narrow our study to three carp series as grass carp (Carassius gibelio), Prussian carp (Carassius gibelio), and Amur carp (Ctenopharyngodon idella). As shown in Fig. 1, their outputs are among the top five aquaculture fish in China (CFSY, 2021). In addition, their price data are more comprehensive than other fish.

3.1. Data source

The price data of whole fresh fish for the three aforementioned carp species are obtained from the National Agricultural Products Price Database. Since a significant portion of daily price data are missing in several provinces, we only retain provinces with relatively complete price series. The daily wholesale price data of the three carp species from wholesale markets are collected from twelve provinces (Anhui, Beijing, Gansu, Hebei, Hubei, Hunan, Inner Mongolia, Jiangsu, Ningxia, Shaanxi, Shandong, and Sichuan). Each provincial-level daily series is obtained by taking an average of the daily prices in the major wholesale markets of each province. We also use the linear interpolation method to supplement a few missing observations in each time series.

The abovementioned National Agricultural Product Price Database is administrated by the Ministry of Commerce of the People’s Republic of China. It collects and releases information on agriculture-related policies and market information. It has published more than 26.9 million pieces of agricultural price information in 486 categories from 183 wholesale markets in China. The price data from this database are timely and comprehensive. Thus, this database is often used to investigate agricultural markets and food prices in China (Ruan et al., 2021).

3.2. Subsamples

Out of the entire time series, we focus on two subsamples according to the timeline of China’s nationwide lockdowns. Here, we briefly review the entire COVID-19 lockdown process in China. The COVID-19 outbreak initially occurred in Wuhan, Hubei province, China in late 2019. The number of confirmed cases increased rapidly after then. To curb the spread of COVID-19, the Hubei province adopted a lockdown policy on January 23rd, 2020. As COVID-19 became a nationwide epidemic, the Chinese government soon published national lockdown and “stay-at-home” mandates. The lockdown policy helped cease the spread of COVID-19, and the number of emerging confirmed cases declined. On March 18th, 2020, no emerging case of COVID-19 was reported in China, for the first time since the beginning of the outbreak. Since then, provincial governments except Hubei gradually took

5 The official website of National Agricultural Products Price Database: http://nc.mofcom.gov.cn/jghq/index
6 News from the official website of China’s government: emerging confirmed cases, total confirmed cases, and deaths of COVID-19 in China as of March 18th, 2020, http://www.nhc.gov.cn/xcs/yqtb/202003/e644c2fc18b4448db7ed4b30f68b91a6.shtml
The lockdown in Wuhan was eventually lifted on April 8th. We would like to highlight two key time points for their implications regarding our design of the empirical analysis. The first date is January 23rd, 2020, the day when the lockdown policy was first implemented in Wuhan, Hubei Province. The second date is April 8th, 2020, the day when the lockdown policy was completely lifted across the nation.

During the period from January 24th, 2020 to April 8th, 2020, the markets are in a state of disarray and disorder because of the extremely strictest lockdown policies. The observations during this period are often either missing or incredible (i.e., without any variations). Such odd observations are mainly due to the fact that food is mostly delivered to homes by the government, rather than sold in markets during this period. Since the majority of Chinese food markets are neither existent nor functional during this period, these observations may not reflect the true level of market integration. Thus, we drop those observations and the remaining time series are grouped into the pre-pandemic sample (January 1st, 2016 to January 23rd, 2020) and the post-pandemic sample (April 9th, 2020 to September 15th, 2021).

Fig. 2 shows the prices of grass carp, Prussian carp, and Amur carp in China. Prices generally show an upward trend and fluctuated from 2016 to 2021. Prices remained stable before COVID-19 but increased significantly after it, reaching the highest point in the second half of 2021. There is also an obvious co-movement between prices in some provinces before COVID-19. That is, price differentials behave like a stationary process, a characteristically associated with spatial market integration. Table 3 reports the descriptive statistics of carp prices in different provinces during the periods before and after COVID-19 for each species. Such descriptive statistics, though, can only reflect general trends in the prices of carp. To clarify COVID-19’s effect on fish spatial market integration, further tests need to be conducted, as previously described.

4. Empirical results

It is necessary to assess the stationarity of each price series for the pre-pandemic and post-pandemic periods before testing the long-term equilibrium relationship among price series. We use the Augmented Dick Fuller (ADF) test (Dickey and Fuller, 1979) to evaluate such stationarity. The logarithm of price and the first order difference of the logarithm of price are tested against the null hypothesis that each time series is stationary with a constant but without a trend, respectively. The number of lags to be included in the ADF test is chosen based on the Schwarz information criterion (SIC) and Akaike information criterion (AIC). Table A1 reports the ADF test results for each price series of the pre-pandemic and post-pandemic subsamples. The results indicate that the pre-pandemic subsample of Amur carp is I(0), while the other price series are I(1).

We first explore the national market integration of all twelve provinces in our sample using the Johansen cointegration test (Johansen, 1988) and auto-regressive distributed lag (ARDL) bounds test. As shown in Appendix Table A2, the results indicate that the degree of the national market integration of each carp species decreased after COVID-19. The markets of grass carp and Prussian carp are integrated both before and after the COVID-19 pandemic. However, a substantial decline, measured by changes of the rank in the degree of market integration, is observed after COVID-19. The Amur carp market was integrated prior to COVID-19, but not after the pandemic, which is likely to highlight two key time points for their implications regarding our design of the empirical analysis. The first date is January 23rd, 2020, the day when the lockdown policy was first implemented in Wuhan, Hubei Province. The second date is April 8th, 2020, the day when the lockdown policy was completely lifted across the nation.

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Fig. 2. Price of the grass carp, Prussian carp, and Amur carp in China markets.
China was high before COVID-19, as shown in Table 4. Specifically, we use the general regression method for the pre-pandemic period. On the market integration between each pair of provincial markets. N indicates that there does not exist a long-term equilibrium price relationship, and Y indicates that there exists a long-term equilibrium price relationship.

Table 4

Summary statistics of the carp price.

| Species     | Subsample | Mean | Max  | Min  | Std. dev. |
|-------------|-----------|------|------|------|-----------|
| Grass carp  | Pre-pandemic | 12.049 | 15.267 | 9.467 | 1.149 |
| Prussian carp | Pre-pandemic | 12.392 | 45.000 | 7.267 | 1.613 |
| Amur carp   | Pre-pandemic | 15.070 | 21.000 | 11.833 | 2.366 |
|             | Anhui      |       |       |       |           |
|             | Beijing    |       |       |       |           |
|             | Gansu      |       |       |       |           |
|             | Hebei      |       |       |       |           |
|             | Hubei      |       |       |       |           |
|             | Hunan      |       |       |       |           |
|             | Inner Mongolia |       |       |       |           |
|             | Jiangsu    |       |       |       |           |
|             | Ningxia    |       |       |       |           |
|             | Shandong   |       |       |       |           |
|             | Sichuan    |       |       |       |           |
|             | Post-pandemic | 15.049 | 22.000 | 10.800 | 3.440 |
|             | Beijing    |       |       |       |           |
|             | Gansu      |       |       |       |           |
|             | Hebei      |       |       |       |           |
|             | Hubei      |       |       |       |           |
|             | Hunan      |       |       |       |           |
|             | Inner Mongolia |       |       |       |           |
|             | Jiangsu    |       |       |       |           |
|             | Ningxia    |       |       |       |           |
|             | Shandong   |       |       |       |           |
|             | Sichuan    |       |       |       |           |

Note: / indicates that relevant data are missing.

Table 5

Summary of the Cointegration test results.

| Species | No. of pairs | Percent | No. of pairs | Percent | No. of pairs | Percent | Total |
|---------|--------------|---------|--------------|---------|--------------|---------|
| Grass carp | 11 | 21 | 3 | 1 | 36 |
| Prussian carp | 30.56% | 58.33% | 8.33% | 27.8% | 100% |
| Amur carp | 23.81% | 28.57% | 9.52% | 38.10% | 100% |

Note: pre-yes & post-no indicates that a long-term equilibrium price relationship between pairs of carp markets exists in both the pre-pandemic and post-pandemic period; pre-no & post-yes indicates that a long-term equilibrium price relationship between pairs of carp markets exists in both the pre-pandemic and post-pandemic periods.

The full results are presented in Appendix Tables A3(a)-A3(f). In addition, for the I(0) price series, the price of Amur carp prior to the COVID-19 pandemic, we also use the Newey-West's heteroskedasticity and autocorrelation corrected (HAC) standard errors (Newey and West, 1987) to account for the possible heteroskedasticity and autocorrelation. As shown in Appendix Table A7, the results with and without HAC standard errors are consistent.
price relationship between a pair of carp markets does not exist in the pre-pandemic or the post-pandemic periods. The first scenario is presented in the column “pre-yes & post-no”. Similarly, we have “pre-yes & post-yes”, “pre-no & post-yes”, and “pre-no & post-no” to stand for the second, third, and fourth scenarios, respectively. Since there are very few cases in the last two scenarios, we mainly focus on the first two scenarios.

We find that COVID-19 significantly reduced the degree of spatial market integration. As shown in Table 5’s column “pre-yes & post-no”, a long-term equilibrium price relationship no longer exists during the post-pandemic period in eleven pairs of grass carp markets, accounting for 30.56% of all the pairs of grass carp markets. In 23.81% of all the pairs of Prussian carp markets, a long-term equilibrium price relationship no longer exists. The long-term equilibrium price relationship in 58.33% of all the pairs of Amur carp markets no longer remain.

There may be two reasons for these results. First, a supply shortage of fish decreases the degree of spatial market integration. Compared with 2019, the output of grass carp, Prussian carp, and Amur carp in most of the selected provinces decreased in 2020, as shown in Appendix Table A5. The national lockdown policy during the period from January 24th, 2020 to April 8th, 2020 led to a shortage of the supply of fish feed and seed (Soto et al., 2021). These input shortages caused a supply shortage of fish in the post-pandemic period. As the supply of fish decreased, traders did not have enough goods to carry out cross-region arbitrage. Then the arbitrage behavior was negatively impacted, which is positively correlated with the level of spatial market integration. Second, the local lockdown policy during the post-pandemic period decreases the degree of spatial market integration. In the post-pandemic period, a few small-scale COVID-19 outbreaks occurred in several Chinese provinces. Instead of another nationwide lockdown, the Chinese government categorized affected neighborhoods as high-risk, medium-risk, and low-risk areas based on the number of cases and implemented local lockdown policies accordingly. Such policies impeded the transportation of fish from and to the high- and medium-risk areas, which lessened the spatial market integration.

To further investigate COVID-19’s effect on spatial market integration, we split the pairs of fish markets into three types according to the severity level of COVID-19. First, we label each province as either a low-infection province or a high-infection province. Provinces ranked in the top half are defined as high-infection provinces while the other provinces are defined as high-infection provinces, as presented in Appendix Table A6. Then, we classify the pairs of markets into three types: (1) a low–low pair includes one high-infection province and one low-infection province, (2) a high–high pair includes two high-infection provinces, and (3) a low–low pair includes two low-infection provinces. For these three types of market pairs, Table 6 again presents four aforementioned scenarios which can be used to assess the impact of COVID-19 on spatial market integration. The results indicate that COVID-19 has heterogeneous effects on fish spatial market integration across China.

Specifically, spatial market integration is reduced the most by COVID-19 in provinces with high infection rates. As shown in Table 6’s column “pre-yes & post-no”, the high–low pairs and high–high pairs in the scenario where a long-term equilibrium price relationship no longer exists during the post-pandemic period account for the top two largest proportions among the three types of market pairs in all carp markets. The low–low pairs in such a scenario account for a much smaller proportion compared to the high–low pairs and high–high pairs. This is mainly because the producers in high-infection provinces suffered the most from COVID-19. High-infection provinces lifted the lockdown policy much later than low-infection provinces. For example, as a low-infection province, the Ningxia province lifted the lockdown policy on February 24th, 2020. However, with the highest infection rate, the Hubei province, including the city of Wuhan, lifted the lockdown mandates on April 8th, 2020. Longer lockdown periods might have seriously affected the production and cross-regional arbitrage of fish in high-infection provinces. In these provinces, the decline in production may have discouraged traders’ arbitrage behavior and reduced the degree of spatial market integration.

Provinces with low infection rates maintain a high level of spatial market integration. As shown in Table 6’s column “pre-yes & post-yes”, the low–low pairs of markets in the scenario where a long-term equilibrium price relationship exists in both the pre-pandemic period and the post-pandemic period account for the largest proportion among the three types of market pairs in all carp markets. A long-term equilibrium price relationship still exists during the post-pandemic period in more than 60.00% of all low–low carp market pairs. This result suggests that COVID-19 has a minor influence on the degree of spatial market integration between low-infection provinces. With low infection rates, lockdown policies in such provinces were lifted earlier, and market activity also resumed earlier. The supply of fish is sufficient in such provinces after the pandemic because of the minimal effects on production. In addition, the quickly restored transportation of fish in these provinces keeps the degree of market integration at a high level.

To ensure the reliability of the results, we conduct two robustness checks. In the first robustness check, we focus our attention on several price series which sometimes behave non-randomly. Those price series have little variability during some periods. As shown in Appendix Table A8, the results with and without those price series are generally consistent, which confirms the robustness of our findings.

In the second robustness check, we test the long-term equilibrium relationship between price series using the entire sample. We first apply the unit root test allowing for possible structural breaks (Perron, 1989; Zivot and Andrews, 2002; Vogelsang and Perron, 1998). The results indicate that prices of grass carp and Prussian carp in all provinces are I(1) series, as shown in Appendix Table A1. We then apply the Gregory and Hansen cointegration test (Gregory and Hansen, 1996), which detects the cointegration relationship allowing for a structural break, for prices of grass carp and Prussian carp. However, prices of Amur carp appear to be a mixture of I(0) and I(1) series. We, therefore, apply the ARDL bounds test that is capable to test the long-term equilibrium relationship among time series with different orders of integration (Pesaran et al., 2001). Although the number of non-integrated market pairs of post-pandemic subsample slightly decreased, the results of the

12 As suggested by one anonymous referee, even with the existence of market integration, each integrated market pair might be fully or partially cointegrated (defined by the value of the parameter in the cointegration vector, β). Ignoring changes in fully or partially cointegrated might underestimate the impact of COVID-19 on market integration. As discussed in Section 2, we use the DOLS and the Wald test to explore whether each integrated market pair is fully or partially cointegrated. The results indicate that COVID-19 does not significantly affect the fully or partially cointegrated relationship, as shown in Appendix Table A4. Therefore, we focus on our discussion on the existence of market integration.

13 Despite the higher infection rate in Ningxia Province, the low population density and number of confirmed cases of COVID-19 make it less affected by COVID-19. So, Ningxia Province is defined as a low-infection province. Low-infection provinces: Gansu, Hebei, Inner Mongolia, Jiangsu, Ningxia, Shandong, and Sichuan. High-infection provinces: Anhui, Beijing, Hubei, Hunan, and Shanxi.

14 Specifically, we drop prices of grass carp and Prussian carp in Inner Mongolia province and the price of Amur carp in Gansu province.

15 Following Ozturk and Acaravci (2011) and Fuinhas and Marques (2012), we introduce a zero-one dummy variable to the ARDL model to account for the structural break caused by COVID-19. As shown in Table A1, prices of Amur carp in most provinces are I(1) series except for Sichuan. We, therefore, also conduct the Gregory and Hansen cointegration test using the non-Sichuan sample. As shown in Appendix Tables A3(g)-A3(j), the results suggested by the ARDL bounds test and Gregory and Hansen cointegration test are consistent.
entire sample in Appendix Table A9 are consistent with those of two subsamples in Table 6.

5. Conclusion

Taking daily price data of grass carp, Prussian carp, and Amur carp, this study evaluates COVID-19’s effect on fish markets in China by comparing their spatial market integration before and after the pandemic. The results show a high degree of spatial market integration before COVID-19 while such integration is heavily reduced by the pandemic in most provinces. The results also show that COVID-19’s effects are spatially varied. Specifically, spatial market integration declines the most among provinces with high infection rates. The degree of spatial market integration between provinces with low infection rates maintains a high level.

These findings have three important policy implications. First, the government may need to consider developing an emergency supply system for fish. We find COVID-19 reducing integration in most provinces. An emergency supply system for fish helps improve the ability to adjust to external shocks, thus avoiding the reduction in spatial market integration when we might be again facing a potentially large-scale public health emergency in the future. Second, policies for reducing or even eliminating tolls for fish trucks should be considered for provinces with high infection rates. Since COVID-19 significantly breaks the spatial market integration of fish in provinces with high infection rates, supporting policies are most needed in such provinces. Reducing tolls can alleviate transportation costs for dealers and increase trade flows between the high-infection provinces and other provinces. This will help improve the overall market integration. Third, the government might also subsidize truckers and dealers to encourage cross-region arbitrage in provinces with high infections. It can help compensate for some hidden costs associated with transporting fresh fish from and to those high-infection provinces, where strict lockdown policies often require truckers to endure mandatory quarantines.

Because of limited data, we only obtain wholesale market price data from twelve provinces for three carp species. Future research can expand to all the provinces and more fish species in China. This will help researchers get a full picture of COVID-19’s effect on the spatial integration of fish markets in China.

Credit author statement

Yutian Wang: Data analysis, Writing-original draft preparation.
Xuan Chen: Conceptualization, Data Curation, Supervision, Project administration, Writing – review and editing.
Longzhong Shi: Methodology, Software, Writing – review and editing.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

Appendix A. Tables

Table A1

ADF tests results.

| Market     | Grass carp | Prussian carp | Amur carp | Grass carp | Prussian carp | Amur carp | Grass carp | Prussian carp | Amur carp |
|------------|------------|---------------|-----------|------------|---------------|-----------|------------|---------------|-----------|
| Anhui      | I(1)       | I(1)          | I(0)      | I(1)       | I(1)          | I(1)      | I(1)       | I(1)          | I(1)      |
| Beijing    | 4          | 4             | 0         | 0          | 0             | 0         | 0          | 0             | 0         |
| Gansu      | 4          | 6             | 0         | 0          | 0             | 0         | 0          | 0             | 0         |

Note: pre-yes & post-no indicates that a long-term equilibrium price relationship between pairs of carp markets exists in the pre-pandemic period but not in the post-pandemic period.
pre-yes & post-yes indicates that a long-term equilibrium relationship between pairs of carp markets exists in both the pre-pandemic and post-pandemic periods.
pre-no & post-yes indicates that a long-term equilibrium relationship between pairs of carp markets does not exist in the pre-pandemic period but exists in the post-pandemic period.
pre-no & post-no indicates that a long-term equilibrium price relationship between pairs of carp markets does not exist in the pre-pandemic or post-pandemic periods.

Table 6

Pairwise relationship of four scenarios for three market pairs.

| Species | Market type | pre-yes & post-no | pre-yes & post-yes | pre-no & post-yes | pre-no & post-no | Total |
|---------|-------------|-------------------|--------------------|-------------------|-------------------|-------|
| Grass carp | High-low pair | No. of pairs 8 | 9 | 2 | 1 | 20 |
|         | Percent 40.00% | 45.00% | 10.00% | 5.00% | 100% |
|         | High-high pair | No. of pairs 2 | 4 | 0 | 0 | 6 |
|         | Percent 33.33% | 66.67% | 0.00% | 0.00% | 100% |
|         | Low-low pair | No. of pairs 1 | 8 | 1 | 0 | 10 |
|         | Percent 10.00% | 80.00% | 10.00% | 100% |
| Prussian carp | High-low pair | No. of pairs 4 | 2 | 2 | 4 | 12 |
|         | Percent 33.33% | 16.67% | 16.67% | 33.33% | 100% |
|         | High-high pair | No. of pairs 1 | 2 | 0 | 3 | 6 |
|         | Percent 16.67% | 33.33% | 0.00% | 50.00% | 100% |
|         | Low-low pair | No. of pairs 0 | 2 | 0 | 1 | 3 |
|         | Percent 0.00% | 66.67% | 0.00% | 33.33% | 100% |
| Amur carp | High-low pair | No. of pairs 11 | 4 | 1 | 4 | 20 |
|         | Percent 55.00% | 20.00% | 5.00% | 20.00% | 100% |
|         | High-high pair | No. of pairs 6 | 0 | 0 | 0 | 6 |
|         | Percent 100.00% | 0.00% | 0.00% | 100% |
|         | Low-low pair | No. of pairs 4 | 6 | 0 | 0 | 10 |
|         | Percent 40.00% | 60.00% | 0.00% | 0.00% | 100% |

Note: pre-yes & post-no indicates that a long-term equilibrium price relationship between pairs of carp markets exists in the pre-pandemic period but not in the post-pandemic period.
pre-yes & post-yes indicates that a long-term equilibrium relationship between pairs of carp markets exists in both the pre-pandemic and post-pandemic periods.
pre-no & post-yes indicates that a long-term equilibrium relationship between pairs of carp markets does not exist in the pre-pandemic period but exists in the post-pandemic period.
pre-no & post-no indicates that a long-term equilibrium price relationship between pairs of carp markets does not exist in the pre-pandemic or post-pandemic periods.
Table A1 (continued)

| Market         | Gravel carp | Prussian carp | Amur carp | Gravel carp | Prussian carp | Amur carp | Gravel carp | Prussian carp | Amur carp | Gravel carp | Prussian carp | Amur carp |
|----------------|-------------|---------------|-----------|-------------|---------------|-----------|-------------|---------------|-----------|-------------|---------------|-----------|
| Hebei          | I(1) /      | I(0)          | I(0)      | I(1) /      | I(0)          | I(0)      | I(1)        | I(1) /        | I(0)      | I(1)        | I(1) /        | I(0)      |
| Hubei          | I(1) /      | I(1)          | I(0)      | I(1) /      | I(0)          | I(0)      | I(1)        | I(1) /        | I(0)      | I(1)        | I(1) /        | I(1)      |
| Hunan          | I(1) /      | I(1)          | I(0)      | I(1) /      | I(0)          | I(0)      | I(1)        | I(1) /        | I(0)      | I(1)        | I(1) /        | I(1)      |
| Inner Mongolia | I(1) /      | I(1)          | I(0)      | I(1) /      | I(0)          | I(0)      | I(1)        | I(1) /        | I(0)      | I(1)        | I(1) /        | I(0)      |
| Jiangsu        | I(1)        | I(1)          | /         | I(1)        | I(1)          | /         | I(1)        | I(1)          | /         | I(1)        | I(1)          | /         |
| Ningxia        | I(1) /      | /             | /         | I(1)        | I(1)          | /         | I(1)        | I(1)          | /         | I(1)        | I(1)          | /         |
| Shandong       | /           | /             | /         | /           | /             | /         | /           | /             | /         | /           | /             | /         |
| Sichuan        | /           | /             | /         | /           | /             | /         | /           | /             | /         | /           | /             | /         |

Note: We use the unit root test with additive outlier breaks to evaluate the stationarity for entire samples. The logarithm of prices and their first order differences are tested against the null hypothesis that each time series is stationary with a constant but without a trend. The appropriate number of lags and the breakpoint are selected by SIC, AIC, and intercept break t-statistic.

I(0) indicates that the price series is stationary. I(1) indicates that the price series is non-stationary but its first order difference is stationary.

/ indicates that relevant data are missing. The detailed analysis report is available upon request.

Table A2

Results of Johansen cointegration test and ARDL bounds test.

| Species          | Subsample         | Johansen cointegration test (trace test) | ARDL bounds test |
|------------------|-------------------|-----------------------------------------|-----------------|
|                  |                   | Rank – 0 | Rank – 1 | Rank – 2 | Rank – 3 | Rank – 4 | Rank – 5 | Rank – 6 | Rank – 7 | Rank – 8 | F-statistic |
| Grass carp       | Pre-pandemic      | 465.183*** | 339.499** | 239.008** | 171.477** | 106.506** | 67.654** | 34.357* | 13.573 | 4.127 | /          |
|                  | Post-pandemic     | 334.442*** | 233.628** | 160.360** | 111.004*  | 72.397*   | 42.376*  | 23.191  | 10.354 | 1.200 | /          |
| Prussian carp    | Pre-pandemic      | 292.472**  | 169.301** | 93.052**  | 38.086    | 21.238    | 9.430    | 2.089   | 1.000  | /     | /          |
|                  | Post-pandemic     | 155.175**  | 101.612*  | 66.495    | 39.837    | 15.247    | 3.187    | 0.009   | /      | /     | 1.754      |
| Amur carp        | Pre-pandemic      | /      | /      | /      | /      | /      | /      | /      | /      | /     | 2.652*      |
|                  | Post-pandemic     | /      | /      | /      | /      | /      | /      | /      | /      | /     | 1.000      |

Note: The number of lags in the Johansen cointegration test is chosen based on the Schwarz information criterion (SIC). For the ARDL bounds test, we use the critical values of I(1) bounds developed by Kripfganz and D. Schneider (2020).

* and ** indicate significance at the 10% and 5% significance levels, respectively. / indicates that relevant data are missing.

Table A3

(a) EG two-step cointegration test results of the grass carp: the pre-pandemic subsample.

| Market          | Beijing | Hebei | Hubei | Hunan | Inner Mongolia | Jiangsu | Ningxia | Shandong |
|-----------------|---------|-------|-------|-------|----------------|---------|---------|----------|
| Anhui           | -5.008*** | -4.435*** | -4.119*** | -4.776*** | -4.039*** | -5.915*** | -2.985 | -4.776*** |
| Beijing         | /       | -5.217*** | -4.390*** | -4.660*** | -3.588**  | -5.654*** | -2.616 | -3.962**  |
| Hebei           | /       | /       | -3.622**  | -4.010*** | -4.809*** | -5.098*** | -2.983 | -3.615**  |
| Hubei           | /       | /       | /       | -3.582**  | -4.162*** | -5.798*** | -2.531 | -3.710**  |
| Hunan           | /       | /       | /       | /       | -4.776*** | -7.015*** | -3.734** | -5.717*** |
| Inner Mongolia  | /       | /       | /       | /       | /       | -4.694**  | -3.306* | -4.452**  |
| Jiangsu         | /       | /       | /       | /       | /       | /       | -3.727** | -6.116**  |
| Ningxia         | /       | /       | /       | /       | /       | /       | /       | -4.762**  |

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.

(b) EG two-step cointegration test results of the Prussian carp: the pre-pandemic subsample.

| Market          | Beijing | Hubei | Hunan | Inner Mongolia | Jiangsu | Ningxia |
|-----------------|---------|-------|-------|----------------|---------|---------|
| Anhui           | -3.276* | -3.654** | -3.052* | -3.037          | -8.010*** | -3.359** |
| Beijing         | /       | -2.132 | -1.503 | -2.545          | -3.465*** | -1.276  |
| Hubei           | /       | /       | -1.978 | -2.039          | -1.873   | -3.081* |
| Hunan           | /       | /       | /       | -1.938          | -3.322*  | -3.155* |
| Inner Mongolia  | /       | /       | /       | /               | -3.571** | -1.900  |
| Jiangsu         | /       | /       | /       | /               | /        | -3.067* |

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.
Table A3

(c) General regression test results of the Amur carp: the pre-pandemic subsample.

| Market       | Gansu  | Hebei   | Hubei   | Hunan  | Inner Mongolia | Shaanxi | Shandong | Sichuan |
|--------------|--------|---------|---------|--------|----------------|---------|----------|---------|
| Anhui        | 18.61** | 0.45    | -6.67***| 8.63***| 4.83***        | 12.80** | -0.35    | -1.30   |
| Gansu        | 12.72***| 3.65*** | -2.26***| 20.69***| 12.98***       | 10.78***| 9.58***  | 2.23**  |
| Hebei        | /      | /       | -3.78***| 21.22***| 2.23**         | 9.58*** | 9.58***  | 2.23**  |
| Hubei        | /      | /       | -11.93***| -0.85  | 6.46***        | 2.60*** | -2.41**  |        |
| Hunan        | /      | /       | /       | 3.31*** | 3.53***        | 0.45    | 0.30     |        |
| Inner Mongolia| /   | /       | /       | /      | 20.30***      | 8.60*** | 13.23*** |        |
| Shaanxi      | /      | /       | /       | /      | /             | 9.04*** | 9.29***  |        |
| Shandong     | /      | /       | /       | /      | /             | /       | -10.02** |        |

Note: This table reports the t-statistic. *, **, and *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.

Table A3

(d) EG two-step cointegration test results of the grass carp: the post-pandemic subsample.

| Market       | Beijing | Hebei   | Hubei   | Hunan  | Inner Mongolia | Jiangsu | Ningxia | Shandong |
|--------------|---------|---------|---------|--------|----------------|---------|----------|----------|
| Anhui        | -3.347* | -3.178* | -2.468  | -4.662***| -2.858        | -6.911***| -4.758***| -2.636   |
| Beijing      | /       | -2.245  | -1.648  | -3.546** | -2.672        | -3.472** | -3.930***| -3.158*  |
| Hebei        | /       | /       | -2.066  | -4.553***| -3.244*       | -4.905***| -3.865** | -2.016   |
| Hubei        | /       | /       | /       | -3.265*  | -1.731        | -3.360***| -2.610   | -1.343   |
| Hunan        | /       | /       | /       | /       | -3.592**       | -5.758***| -4.090***| -2.887   |
| Inner Mongolia| /    | /       | /       | /       | -3.852**       | -4.321***| -3.069*  |        |
| Jiangsu      | /       | /       | /       | /       | /             | -3.780** | -3.216*  |        |
| Ningxia      | /       | /       | /       | /       | /             | /       | -3.953***|        |

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.

Table A3

(e) EG two-step cointegration test results of the Prussian carp: the post-pandemic subsample.

| Market       | Beijing | Hebei | Hubei | Hunan | Inner Mongolia | Jiangsu | Ningxia | Shandong |
|--------------|---------|-------|-------|-------|----------------|---------|----------|----------|
| Anhui        | -3.727**| -4.222***| -2.299 | -4.672***| -4.425***       | -4.291***| -3.091**   |        |
| Beijing      | /       | -2.897 | -2.923 | -2.723 | -2.122         | -3.030  | -2.938    |        |
| Hubei        | /       | /      | -1.967 | -2.509 | -3.078*        | -2.955  | -2.955    |        |
| Hunan        | /       | /      | /      | -0.644 | -2.358         | -2.482  | -2.482    |        |
| Inner Mongolia| /   | /      | /      | /      | -4.615***       | -3.244*  |          |        |
| Jiangsu      | /       | /      | /      | /      | /             | /       | -3.244*   |        |
| Ningxia      | /       | /      | /      | /      | /             | /       |          |        |

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.

Table A3

(f) EG two-step cointegration test results of the Amur carp: the post-pandemic subsample.

| Market       | Gansu  | Hebei   | Hubei   | Hunan  | Inner Mongolia | Shaanxi | Shandong | Sichuan |
|--------------|--------|---------|---------|--------|----------------|---------|----------|---------|
| Anhui        | -1.410 | -0.460  | -0.636  | -1.945 | -2.261         | -2.846  | -0.833   | -2.653  |
| Gansu        | /      | -4.261***| -3.262* | -2.992 | -4.447***       | -1.929  | -4.717***| -2.632  |
| Hebei        | /      | /       | -1.676  | -2.624 | -3.849**        | -1.103  | -3.710***| -1.718  |
| Hubei        | /      | /       | /       | -1.806 | -2.175         | -1.143  | -2.081   | -1.492  |
| Hunan        | /      | /       | /       | -3.915**| -1.958         | -4.068***| -3.554** |        |
| Inner Mongolia| /    | /       | /       | /      | -3.043         | -4.334***| -2.916   |        |
| Shaanxi      | /      | /       | /       | /      | /             | -1.437  | -3.312** |        |
| Shandong     | /      | /       | /       | /      | /             | /       | -2.482   |        |
| Sichuan      | /      | /       | /       | /      | /             | /       |          |        |

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.

Table A3

(g) Gregory and Hansen cointegration test results of the grass carp: the entire sample.

| Market       | Beijing | Hebei   | Hubei   | Hunan  | Inner Mongolia | Jiangsu | Ningxia | Shandong |
|--------------|---------|---------|---------|--------|----------------|---------|----------|----------|
| Anhui        | -5.31***| -4.98** | -4.33   | -6.28***| -5.27***       | -7.44***| -5.44*** | -4.78**  |
| Beijing      | /       | -5.40***| -4.24   | -6.14***| -5.79***       | -6.63***| -5.76*** | -4.91**  |
| Hebei        | /       | /       | -4.07   | -5.95***| -5.53***       | -6.82***| -5.33*** | -4.19    |
| Hubei        | /       | /       | /       | -4.75**  | -3.78         | -6.45***| -4.33    | -4.04    |
| Hunan        | /       | /       | /       | -5.61***| -8.80***       | -5.41***| -6.51*** |        |
| Inner Mongolia| /    | /       | /       | /      | -5.59***       | -5.33***| -5.02*** |        |
| Jiangsu      | /       | /       | /       | /      | /             | -5.44***| -7.09*** |        |
| Ningxia      | /       | /       | /       | /      | /             | /       | -5.55*** |        |

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.
Table A3

(h) Gregory and Hansen cointegration test results of the Prussian carp: the entire sample.

| Market          | Beijing | Hubei | Hunan | Inner Mongolia | Jiangsu | Ningxia |
|-----------------|---------|-------|-------|----------------|---------|---------|
| Anhui           | -5.00** | -5.36*** | -4.21 | -5.07**         | -7.02*** | -4.48*  |
| Beijing         | /       | -4.59* | -4.37* | -5.04**         | -4.77** | -4.07   |
| Hubei           | /       | /     | -3.66 | -3.91          | -4.19   | -4.22   |
| Hunan           | /       | /     | /     | -2.51          | -3.06   | -4.26   |
| Inner Mongolia  | /       | /     | /     | /              | -3.92   | -4.02   |
| Jiangsu         | /       | /     | /     | /              | /       | -4.28   |

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.

Table A3

(i) ARDL bounds test results of the Amur carp: the entire sample.

| Market          | Gansu  | Hebei | Hubei | Hunan | Inner Mongolia | Shaanxi  | Shandong | Sichuan |
|-----------------|--------|-------|-------|-------|----------------|----------|----------|---------|
| Anhui           | 10.695*** | 7.042*** | 1.896 | 2.561 | 10.856***       | 2.959    | 4.926    | 3.186   |
| Gansu           | /      | 16.125*** | 5.083* | 5.825** | 9.685***       | 5.247*   | 11.666*** | 7.299*** |
| Hebei           | /      | /     | 5.062* | 4.087 | 5.051*         | 3.750    | 4.962*   | 3.723   |
| Hubei           | /      | /     | /     | 6.814** | 7.166**         | 7.857**  | 7.376**  | 6.437** |
| Hunan           | /      | /     | /     | /     | 8.396***       | 8.971*** | 7.690**  | 7.461** |
| Inner Mongolia  | /      | /     | /     | /     | /              | 11.034*** | 24.552*** | 12.279*** |
| Shaanxi         | /      | /     | /     | /     | /              | /        | 11.127*** | 8.642*** |
| Shandong        | /      | /     | /     | /     | /              | /        | /        | 4.182   |

Note: We use the critical values developed by Kripfganz and D. Schneider (2020). Specifically, given our sample size, critical values of I(0) bounds at 1%, 5%, and 10% significance levels are 6.883, 4.935, and 4.052, respectively. Critical values of I(1) bounds at 1%, 5%, and 10% significance levels are 7.859, 5.761, and 4.803, respectively.

If price series of two markets are both I(0), we focus on I(0) bounds. When the F-statistic lies above the critical values, the null hypothesis is rejected.
If price series of two markets are both I(1) or a mixture of I(0) and I(1), we focus on I(1) bounds. When the F-statistic lies above the critical values, the null hypothesis is rejected.
*, **, and *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.

Table A3

(j) Gregory and Hansen cointegration test results of the Amur carp: the non-Sichuan sample.

| Market          | Gansu  | Hebei | Hubei | Hunan | Inner Mongolia | Shaanxi  | Shandong |
|-----------------|--------|-------|-------|-------|----------------|----------|----------|
| Anhui           | -3.54  | -2.94 | -2.73 | -3.15 | -4.57*         | -5.33*** | -3.50    |
| Gansu           | /      | -6.19*** | -3.70 | -3.32 | -7.25***       | -4.46*   | -6.61*** |
| Hebei           | /      | /     | -3.31 | -3.30 | -7.54***       | -3.90    | -6.54*** |
| Hubei           | /      | /     | /     | -3.42 | -3.75          | -5.85    | -3.64    |
| Hunan           | /      | /     | /     | /     | -4.80***       | -4.81**  | -4.60*   |
| Inner Mongolia  | /      | /     | /     | /     | /              | -5.93*** | -7.74*** |
| Shaanxi         | /      | /     | /     | /     | /              | /        | -5.11**  |
| Shandong        | /      | /     | /     | /     | /              | /        | /        |

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.

Table A4

Number of the market pairs fully integrated in the pre-pandemic period but partial integrated in the post-pandemic period.

| Category      | Pairs |
|---------------|-------|
| Grass carp    | 0     |
| Prussian carp | 0     |
| Amur carp     | 0     |

Note: The detailed analysis report is available upon request.

Table A5

Comparison in carp output from 2019 to 2020

| Market | Grass carp | Prussian carp | Amur carp |
|--------|------------|---------------|-----------|
| Anhui  | Increase   | Decrease      | Decrease  |
| Beijing| Decrease   | Decrease      | Decrease  |
| Gansu  | Increase   | Decrease      | Decrease  |
| Hebei  | Decrease   | Decrease      | Decrease  |
| Hubei  | Increase   | Decrease      | Decrease  |
| Hunan  | Increase   | Increase      |          |

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Table A5 (continued)

| Market          | Grass carp | Prussian carp | Amur carp |
|-----------------|------------|---------------|-----------|
| Inner Mongolia  | Decrease   | Decrease      | Decrease  |
| Jiangsu         | Decrease   | Decrease      | Increase  |
| Ningxia         | Decrease   | Decrease      | Decrease  |
| Shandong        | Decrease   | Decrease      | Decrease  |
| Shaanxi         | Decrease   | Decrease      | Increase  |
| Sichuan         | Increase   | Increase      | Increase  |

Data source: China Fishery Statistics Yearbooks (2021).
Note: Increase indicates that the production in 2020 is higher than that in 2019. Decrease indicates that the production in 2020 is lower than that in 2019.

Table A6
The infection rate of COVID-19.

| Market | Confirmed cases | Population/10^4 | Infection rate/‰ |
|--------|-----------------|-----------------|------------------|
| Hebei  | 327             | 7447            | 0.0044           |
| Gansu  | 142             | 2509            | 0.0057           |
| Inner Mongolia | 126 | 2415            | 0.0052           |
| Sichuan          | 560   | 8351            | 0.0067           |
| Jiangsu          | 651   | 8469            | 0.0077           |
| Shandong         | 783   | 10,106          | 0.0077           |
| Shaanxi          | 323   | 3944            | 0.0082           |
| Ningxia          | 75    | 717             | 0.0100           |
| Hunan            | 1019  | 6640            | 0.0150           |
| Anhui            | 992   | 6092            | 0.0160           |
| Beijing          | 588   | 2190            | 0.0270           |
| Hubei            | 67,803| 5927            | 1.1400           |

Data source: The data of confirmed cases are collected from the local Health Commission official website and center for Disease prevention and control official website. The data of population were collected from the China Statistical Yearbook (2021).
Note: Infection rate = \frac{Confirmed cases}{Population}.

Table A7
Adjusted pairwise relationship of four scenarios for three market pairs.

| Species    | Market type | pre-yes & post-no | pre-yes & post-yes | pre-no & post-yes | pre-no & post-no | Total |
|------------|-------------|-------------------|-------------------|------------------|-----------------|-------|
| Grass carp | High-low pair | No. of pairs 5 | 8 | 2 | 1 | 16 |
|            |              | Percent 31.25% | 50% | 12.5% | 6.25% | 100% |
|            | High-high pair | No. of pairs 2 | 4 | 0 | 0 | 6 |
|            |              | Percent 33.33% | 66.67% | 0.00% | 0.00% | 100% |
|            | Low-low pair | No. of pairs 1 | 4 | 1 | 0 | 6 |
| Prussian carp | High-low pair | No. of pairs 3 | 3 | 1 | 1 | 8 |
|            |              | Percent 37.50% | 37.50% | 12.5% | 12.5% | 100% |
|            | High-high pair | No. of pairs 1 | 2 | 0 | 3 | 6 |
|            |              | Percent 16.67% | 33.33% | 0.00% | 50.00% | 100% |
|            | Low-low pair | No. of pairs 0 | 1 | 0 | 0 | 1 |
| Amur carp | High-low pair | No. of pairs 7 | 1 | 4 | 8 | 20 |
|            |              | Percent 35.00% | 5.00% | 20.00% | 40.00% | 100% |
|            | High-high pair | No. of pairs 4 | 1 | 0 | 1 | 6 |
|            |              | Percent 66.67% | 16.67% | 0.00% | 16.67% | 100% |
|            | Low-low pair | No. of pairs 3 | 6 | 0 | 1 | 10 |
|            |              | Percent 30.00% | 60.00% | 0.00% | 10.00% | 100% |

Note: It presents the result based on the EG two-step cointegration test and the general regression with HAC standard errors. The detailed test results are available upon request.

Table A8
Robustness test 1 results.

| Species | Market type | pre-yes & post-no | pre-yes & post-yes | pre-no & post-yes | pre-no & post-no | Total |
|---------|-------------|-------------------|-------------------|------------------|-----------------|-------|
| Grass carp | High-low pair | No. of pairs 5 | 8 | 2 | 1 | 16 |
|            |              | Percent 31.25% | 50% | 12.5% | 6.25% | 100% |
|            | High-high pair | No. of pairs 2 | 4 | 0 | 0 | 6 |
|            |              | Percent 33.33% | 66.67% | 0.00% | 0.00% | 100% |
|            | Low-low pair | No. of pairs 1 | 4 | 1 | 0 | 6 |
| Prussian carp | High-low pair | No. of pairs 3 | 3 | 1 | 1 | 8 |
|            |              | Percent 37.50% | 37.50% | 12.5% | 12.5% | 100% |
|            | High-high pair | No. of pairs 1 | 2 | 0 | 3 | 6 |
|            |              | Percent 16.67% | 33.33% | 0.00% | 50.00% | 100% |
|            | Low-low pair | No. of pairs 0 | 1 | 0 | 0 | 1 |

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Table A8 (continued)

| Species          | Market type | pre-yes & post-no | pre-yes & post-yes | pre-no & post-yes | pre-no & post-no | Total  |
|------------------|-------------|-------------------|-------------------|------------------|-----------------|--------|
|                  |             | No. of pairs      | Percent           | No. of pairs     | Percent         | No. of pairs |
| Grass carp       | High-low pair | 1                 | 100%              | 0                | 0%              | 20     |
|                  | High-high pair | 5                 | 100%              | 2                | 0%              | 7      |
| Prussian carp    | Low-low pair | 2                 | 100%              | 3                | 0%              | 10     |
| Amur carp        | High-low pair | 3                 | 100%              | 4                | 0%              | 12     |
|                  | High-high pair | 1                 | 100%              | 0                | 0%              | 3      |
|                  | Low-low pair | 3                 | 100%              | 0                | 0%              | 9      |

Note: It represents the result of the cointegration test corrected by using the entire sample. The full results of the corrected cointegration test are presented in Appendix A3(g)-A3(i).

Table A9

Robustness test 2 results.

| Species          | Market type | pre-yes & post-no | pre-yes & post-yes | pre-no & post-yes | pre-no & post-no | Total  |
|------------------|-------------|-------------------|-------------------|------------------|-----------------|--------|
|                  |             | No. of pairs      | Percent           | No. of pairs     | Percent         | No. of pairs |
| Grass carp       | High-low pair | 1                 | 100%              | 0                | 0%              | 20     |
|                  | High-high pair | 5                 | 100%              | 2                | 0%              | 7      |
| Prussian carp    | Low-low pair | 2                 | 100%              | 3                | 0%              | 10     |
| Amur carp        | High-low pair | 3                 | 100%              | 4                | 0%              | 12     |
|                  | High-high pair | 0                 | 100%              | 0                | 0%              | 3      |
|                  | Low-low pair | 0                 | 100%              | 0                | 0%              | 9      |

Note: It represents the result of the cointegration test corrected by using the entire sample. The full results of the corrected cointegration test are presented in Appendix A3(g)-A3(i).

Appendix B. ARDL bounds test

The ARDL bounds test, proposed by Pesaran et al. (2001), is capable to test the long-run relationship among series that are I(0), I(1), or mutually cointegrated. The specifications of a bivariate case are in the form of

\[ \Delta y_t = \alpha + \beta_1 y_{1t-1} + \beta_2 y_{2t-1} + \sum_{i=1}^p \delta_i \Delta y_{1t-i} + \sum_{j=0}^q \theta_j \Delta x_{2j} + \epsilon_t. \]

In our carp market case, \( y \) and \( x \) are the logarithm of the fish price in two different provinces at time \( t \), \( \alpha \) is the constant term, and \( \epsilon_t \) is a white noise stochastic error. The \( p \) and \( q \) are the lengths of lags. Then, an F-test is used to test the joint significance of \( \beta_1 \) and \( \beta_2 \) (i.e., \( H_0: \beta_1 = \beta_2 = 0 \)). Pesaran et al. (2001) reported asymptotic critical values for such F-statistic with various specifications of deterministic terms. Here, we apply the model with unrestricted intercept and no time trend (The Case 3 in Pesaran et al. (2001)), which is consistent with formats using in our other tests. Kripfganz and Schneider (2020) update those critical values for finite samples. The existence of a long-term equilibrium relationship is suggested by rejecting the null hypothesis when the F-statistic exceeds the upper bound critical values.

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