A General Equilibrium Assessment of COVID-19’s Labor Productivity Impacts on China’s Regional Economies

BY Xi He a
Edward J. Balistreri b
Gyu Hyun Kim c
Tao Xiong d
Wendong Zhang e

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a Postdoctoral Research Associate, Department of Economics and Center for Agricultural and Rural Development, Iowa State University, xihe@iastate.edu
b Duane Acklie Chair of International Trade and Finance and Associate Professor, Department of Economics, the University of Nebraska-Lincoln, edward.balistreri@unl.edu
c Associate Research Fellow, Korea Energy Economics Institute, gyuhyun@keei.re.kr
d Professor and Department Chair, Department of Agricultural Economics and Management, Huazhong Agricultural University, taoxiong@mail.hzau.edu.cn
e Associate Professor, Department of Economics and Center for Agricultural and Rural Development, Iowa State University, wdzhang@iastate.edu
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Abstract: This study introduces a database that can be used to analyze COVID-19’s impacts on China’s regional economies. This database contains various sectoral and regional economic outcomes at the weekly and monthly level. In the context of a general equilibrium trade model, we first formulate a mathematical representation of the Chinese regional economy and calibrate the model with China’s multi-regional input-output table. We then utilize the monthly provincial and sectoral value-added and national trade series to estimate COVID-19’s province-by-month labor-productivity impacts from February 2020 to September 2020. Compared to February 2019 levels, we find an average 39.5% decrease in labor productivity (equivalent to around 305 million jobs) and an average 25.9% decrease in welfare across provinces in February 2020. Both labor productivity and welfare have recovered quickly since April 2020. As of September 2020, average provincial labor productivity increased by 12.2% (equivalent to around 94 million jobs) and average welfare increased by 8.2% relative to their September 2019 levels.

JEL codes: J01, E20, F10, R13

Keywords: COVID-19, China’s regional economies, computable general equilibrium (CGE), labor productivity, welfare analysis

1. Introduction

In late 2019, the COVID-19 pandemic started in Hubei, China. The pandemic quickly spread to other countries over the first several months of 2020 causing significant global economic and social costs. According to the International Monetary Fund, global gross domestic product (GDP) decreased by 3.5% in 2020 compared to 2019, with a decrease of 4.9% for advanced economies and a decrease of 2.4% for emerging markets and developing economies. China was the only major economy reporting an economic expansion, with a growth rate of 2.3% (IMF 2021). During the early stages of the pandemic, China took strict lockdown and quarantine measures, then gradually loosened mobility restrictions and resumed economic activities in late March (Fang et al. 2020). China’s negative year-to-year
GDP growth rate of -6.8% in the first quarter of 2020 reflects the significant economic costs associated with the stagnation of economic activities. According to the Chinese National Bureau of Statistics (CNBS), since April 2020, China’s economy has gradually recovered with GDP growth rates of 3.2%, 4.9%, and 6.5% in the second, third, and fourth quarters of 2020, respectively (CNBS 2020). The spread of COVID-19 in other economies also significantly affected China’s economy via trade links formed during the past decades of globalization. In the first quarter of 2020, while China’s goods export value reduced by 11.4%, exports increased by 4.5%, 10.2%, and 4% in the second, third, and fourth quarters, respectively. The export growth reflects both China’s productivity recovery and other countries’ production and distribution capabilities contraction, which helped create favorable conditions for China’s exports.

National economic outcomes, however, cannot capture the uneven impacts of COVID-19 across China’s regions and sectors. This heterogeneity is not only rooted in the regional disparities in economic development levels and reliance on exports, but also caused by COVID-19’s spatial propagation patterns and the varying stringency of control measures across China. Understanding how COVID-19 affects China’s regional economies is important for designing and evaluating relevant economic recovery policies.

This article first introduces a subnational database, the CARD COVID-19 Economic Database: China, which contains various regional and sectoral economic outcomes (He et al. 2020). The database can be used to assess COVID-19’s impacts on China’s national and subnational economy. We then use a computable general equilibrium (CGE) modeling approach that accounts for extensive sectoral and regional economic linkages in China to quantify the regional implied labor productivity shocks that best fit the observed changes in monthly provincial and sectoral value-added and national trade series. Specifically, we use the Mathematical Programming System for General Equilibrium System analysis (MPSGE, (Rutherford 1999)) within the Generalized Algebraic Modeling Systems (GAMS, (Brooke et al. 1988)) calibrated to a 30 provinces by 30 sectors Multi-Regional Input-Output (MRIO) table developed by Mi et al. (2018).¹ By explicitly modeling the monthly sectoral and provincial output changes, we can quantify the implied the monthly provincial labor productivity and welfare impacts. We run the model with and without incorporating national import and export shocks, and get two sets of labor productivity and welfare estimates. The comparison of the two sets of results provides insights on how trade impacts China’s labor productivity recovery from the COVID-19 pandemic.

Our main results show the COVID-19 pandemic had substantial yet short-lived impacts on labor productivity across Chinese provinces, especially in the epicen-

¹ Note that the subnational MRIO table compiled by Mi et al. (2018) does not include Tibet, Hong Kong, Macau, and Taiwan.
ter, Hubei province. First, across provinces, when we do not include trade shocks in the modeling, average labor productivity reduces by 37.9% and average welfare reduces by 20.8% in February 2020. The 37.9% decrease in labor productivity is equal to 293 million jobs based on an employment of 774 million in 2019. In Hubei, labor productivity reduced by 74.1% (26.3 million job equivalent) in February 2020.\(^2\)

Second, both labor productivity and welfare have recovered quickly since April. In September 2020, average labor productivity increased by 29.8% (230 million job equivalent) and average welfare increased by 14.7% across all provinces. Hubei’s labor productivity increased by 19.4% (6.9 million job equivalent) as of September 2020. In addition, we also find significantly heterogeneous recovery patterns across regions. Specifically, provinces in eastern China recovered the fastest, from a population-weighted average labor productivity shock of -45.1% in February to 39.2% in September 2020. The labor productivity recovery in northwestern China is most modest and increased from a negative shock of -23.3% in February to 23.3% in September 2020.

Finally, while the patterns of the COVID-19 pandemic’s spatial and temporal impacts on labor productivity are quite similar across models with and without trade shocks, labor productivity grew faster in April-June and grew slower in August and September 2020 in models that include national trade shocks. Specifically, when trade series are included in the modeling, compared to February 2019 levels, we find an average 39.5% decrease in labor productivity (equivalent to around 305 million jobs) and an average 25.9% decrease in welfare across provinces in February 2020. As of September 2020, average provincial labor productivity increased by 12.2% (equivalent to around 94 million jobs) and average welfare increased by 8.2% relative to their September 2019 levels. An explanation for this difference is that China’s net-export demand decreased from April-June and has increased since July. Therefore, the models without national trade shocks underestimate the labor productivity from April-June and overestimate the labor productivity in August and September.

This article relates to and makes contributions to three strands of literature. First, this paper contributes to a large line of literature that use general equilibrium models to investigate COVID-19’s impacts in different countries, including China (Zhao 2020), the UK (Keogh-Brown et al. 2020), India (Sahoo and Ashwani 2020), and Brazil (Porsse et al. 2020). The unique contribution of this paper is that we conduct the analysis at the province level and we are able to quantify the labor productivity impacts at the province-by-month level, while most studies are at the national and annual level (McKibbin and Fernando 2020; Maliszewska et al.

\(^2\) Note that the estimated labor productivity shocks do not differentiate loss of jobs and reduction in working hours. Therefore, the employment impacts are 293 million full-time equivalent (FTE) jobs.
2020; Zhang et al. 2020; Zhao 2020; Keogh-Brown et al. 2020; Sahoo and Ashwani 2020). For example, Maliszewska et al. (2020) simulate the impacts of a global pandemic using Envisage (a well documented CGE model) calibrated to GTAP 10 accounts and find global GDP decreased by 2.0% in a full global pandemic and decreased by 4.0% in an amplified global pandemic. Similarly, Zhang et al. (2020) utilize an economy-wide multi-sector multiplier model built on China’s 2017 social accounting matrix with 147 economic sectors to assess COVID-19’s impacts on China’s macroeconomy and find that China’s economy will grow less than 1.0% in 2020 without resumed export demand and 1.7% with resumed export demand. Notable exceptions that use subnational CGE models to investigate COVID-19’s impacts are Porsse et al. (2020) and Modrego et al. (2020). Porsse et al. (2020) use a dynamic inter-regional CGE model to project COVID-19’s economic impacts in Brazil. Modrego et al. (2020) estimate COVID-19’s regional employment effects across Chile’s regions. Considering COVID-19’s impacts could be quite heterogeneous across subnational regions and the paucity of regional data suitable for CGE modeling has long been a constraint (Giesecke and Madden 2013), the subnational labor productivity estimates provided in this paper are important to inform regional recovery and support strategies.

Second, this paper introduces two complete datasets of estimated COVID-19’s impacts on China’s province-by-month labor productivity. These estimates are not officially reported and would be useful for future studies and relevant labor policies. In this way, this paper contributes to the large strand of literature on COVID-19’s impacts on regional employment (Barwick et al. 2020; Bartik et al. 2020; Forsythe et al. 2020; Bottan et al. 2020). Barwick et al. (2020) use mobile phone records for 71 million users and a difference-in-differences (DID) framework to study the COVID-19 pandemic’s labor market impacts in Guangdong, China and find that the pandemic increased unemployment by 27%–62% from late January to the end of September 2020. Most studies on COVID-19’s labor market impacts are based on reduced-form analysis, which could neglect the feedback effects by broader supply and demand factors. Our paper contributes by utilizing a CGE modeling framework that accounts for broad linkage between regions and sectors.

Finally, while CGE models are often used to simulate the impact of actual or hypothetical policies (Giesecke and Madden 2013), we use CGE models to uncover unobserved parameters as in Bauer et al. (2005) and Monte et al. (2018). Specifically, Monte et al. (2018) use a general equilibrium model to recover unique values of the unobserved productivity and amenities fundamentals that rationalize observed wages, employment, commuting flows, and land area. We contribute to the CGE modeling literature by providing an example of utilizing observed output and trade data to uncover unobserved labor productivity shocks. This is especially useful when subnational labor statistics are not collected or reported timely. Considering some important regional labor statistics are often non-existent
or outdated in developing countries, future studies can follow this method and use observed output and trade data to back out labor statistics that are not reported in a timely manner.

The rest of the paper proceeds as follows. Section two offers a description of the database and the value-added and trade data used in the analysis. Section three describes the general equilibrium modeling structure. Section four presents the labor productivity and welfare estimates. The last section discusses the limitations of the model and potential future extensions.

2. Data

2.1 CARD COVID-19 Economic Database: China

He et al. (2020) develop the CARD COVID-19 Economic Database: China to track COVID-19’s evolving impacts on China’s regional economy and to facilitate research on COVID-19’s global impact via economic linkages between China and the rest of the world. This database was first released in April 2020 and has been updated monthly through September 2020. There are 45 tables in the database. Table 1 describes the main data categories in the database: sectoral level data using China’s IO (input-output) classification; sectoral level data using GTAP classification; provincial data; province-by-IO sectoral data; province-by-GTAP sectoral data; provincial and sectoral GDP; monthly agricultural trade; timing of prevention and control measures; and raw datasets. These data are updated on a quarterly, monthly, bi-weekly, or weekly basis and are collected from various sources, including, but not limited to, China’s National Bureau of Statistics (CNBS), various provincial bureaus of statistics, China’s Ministry of Agricultural and Rural Affairs, the Global Agricultural Trade System at the U.S. Department of Agriculture (USDA), and USDA’s weekly agricultural export query system.

Given the necessity of converting the sectoral GB (Guobiao) data into IO or GTAP sectoral data that can be used in GTAP and regional equilibrium modeling, He et al. (2020) develop crosswalks between GB and IO, and GB and GTAP sectors. He et al. (2020) obtain the IO and sectoral GTAP data by concording the GB sectoral level data reported by CNBS with the crosswalks between different classifications.

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3 The 30 IO sectors correspond to the 30 input-output sectors in the MRIO table in Mi et al. (2018).
4 GB (Guobiao) is short for GB/T 4754-2017, which is China’s industrial classification for national economic activities. This industrial classification can be accessed at http://www.stats.gov.cn/tjsj/tjbz/201709/t20170929_1539288.html.
| Number | Category                          | Classification | Variables                                                                 | Frequency          |
|--------|----------------------------------|----------------|---------------------------------------------------------------------------|--------------------|
| 1-4    | Sectoral data                    | China IO       | Value-added growth rate (manufacturing sectors only); Fixed capital investment growth rate | Monthly            |
|        |                                  | GTAP           | Same as above                                                             | Monthly            |
| 5-9    | Provincial data                  | N/A            | Value-added growth rate (manufacturing sectors only); Fixed capital investment growth rate; Baidu Huiyan Provincial Resumption Index; Firm and labor resumption data (for enterprises above a designated size) | Monthly, weekly, bi-weekly |
| 10-13  | Province-by-sector data          | China IO       | Value-added growth rate (manufacturing sectors only); Fixed capital investment growth rate | Monthly            |
|        |                                  | GTAP           | Same as above                                                             | Monthly            |
| 14-18  | Concordance and sector classifications | N/A          | Concordance between IO, GB, and GTAP sectors                              | N/A                |
| 19-35  | Raw datasets                     | N/A            | Various datasets used to generate the database                            | Quarterly, monthly, weekly, bi-weekly |
| 36-37  | Industry and provincial GDP      | N/A            | Quarterly cumulative GDP (100 million RMB), Provincial cumulative GDP (100 million RMB) | Quarterly          |
| 38-43  | Agricultural trade               | N/A            | China’s monthly agricultural import/export quantity/value; U.S. monthly agricultural exports to China; U.S. weekly key agricultural commodities exports to China | Monthly            |
| 44     | Timing of prevention and control measures | N/A          | Levels of prevention and control measures in different cities            |                    |
| 45     | Aggregate trade shocks           | N/A            | National-level growth rate of total imports and exports                   | Monthly            |

Note: This table presents the main data categories in CARD COVID-19 Economic Database: China available at [https://www.card.iastate.edu/china/covid-19/](https://www.card.iastate.edu/china/covid-19/). The number denotes the order of tables in the database.
The main sectoral and provincial outcomes are the monthly growth rate of value-added and fixed capital investment. In addition to monthly data in 2020, He et al. (2020) collect data in November and December 2019 as reference points.

2.2 Provincial and sectoral value-added growth rate and national trade shocks

The outcomes utilized in the CGE modeling are province- and sector-by-month growth rate of value-added and trade flows from Tables 1, 4, and 45 in the CARD database. While some datasets in the database track labor shocks, like the Baidu resumption index calculated based on mobile phone usage, there are no systematic labor productivity shocks available. We are interested in the implied labor productivity shocks and welfare impacts reflected by the observed output growth rate and trade flows. Therefore, we use the monthly growth rate of provincial and sectoral value-added and national export and import data from November 2019 to September 2020 as output targets in the CGE modeling.

Table 2 presents the growth rate of value-added in five typical provinces: Beijing, Hubei, Zhejiang, Xinjiang, and Heilongjiang, and six administrative regions, as well as the national growth rate of export and import values. We select these five provinces because of their differing COVID-19 outbreak timing and lockdown measures as well as great heterogeneity in economic reliance on manufacturing and trade. All five provinces are representative of the recovery in China’s different regions. Figure A.1 in the appendix shows China’s provinces and regions. Table 2 shows Hubei’s value-added reduced by 46.2% and 46.9% in February and March 2020, respectively, compared to 2019 levels. Xinjiang’s value-added was barely affected in February, a reduction of 0.7%, and has quickly recovered since March 2020. Across regions, provinces in south-central China where Hubei is located experienced the largest drop in value-added, while provinces in northwestern China were least affected in terms of value-added. This geographical pattern is consistent with the spread of COVID-19 in China—the pandemic affected Hubei first and most and affected northwestern provinces the least.

In 2020, China’s exports also suffered severe reductions of 17.2% in February and 6.6% in March. However, exports have significantly increased since June, and reached a growth rate of 9.9% in September. The large export increase since June was partially caused by China’s production increase and other countries’ constrained supply capacities as they were gradually affected by the pandemic (IMF 2021). While China’s imports in 2020 reduced by only 4.0% and 1.0% in February and March, respectively, they dropped sharply by 14.2% and 16.7% in April and May, and have gradually recovered since June.

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5 We compare growth rate with the levels in the same month of the previous year. For example, the growth rate of value-added in February 2020 was the growth of value-added in February 2020 compared with that in February 2019.

6 Please note that value-added data do not include smaller firms and are only for enterprises with annual revenue above 20 million RMB.
Table 2. Observed monthly growth rate of provincial value-added and national trade flows(%)  

| Panel A: Growth rate of value-added (%) | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|----------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Beijing (BJ)                           | 2.5    | 4.8    | -16.2  | -13.0  | 4.8    | 5.3    | 10.8   | 8.8    | 5.9    | 5.4    |
| Hubei (HB)                             | 6.2    | 7.8    | -46.2  | -46.9  | -2.4   | 2.0    | 2.0    | 2.2    | 4.9    | 6.2    |
| Heilongjiang (HL)                      | -1.6   | 7.7    | -10.9  | -5.5   | 2.9    | 0.3    | -0.5   | -1.9   | 8.5    | 9.0    |
| Zhejiang (ZJ)                          | 9.0    | 9.8    | -18.5  | 1.3    | 9.5    | 9.9    | 6.5    | 6.1    | 9.9    | 10.7   |
| Xinjiang (XJ)                          | 2.8    | 1.6    | -0.7   | 7.2    | 7.0    | 9.6    | 12.2   | 4.8    | 2.7    | 11.2   |
| North (5 provinces)                    | 3.8    | 3.8    | -11.6  | -3.4   | 2.3    | 3.5    | 5.0    | 5.4    | 7.1    | 6.4    |
| Northeast (3 provinces)                | 6.8    | 10.3   | -13.5  | -6.1   | 3.1    | 6.9    | 7.3    | 3.6    | 11.6   | 7.9    |
| East (7 provinces)                     | 7.0    | 8.4    | -15.3  | 1.8    | 6.4    | 6.2    | 6.7    | 6.4    | 8.6    | 7.5    |
| South-central (6 provinces)            | 7.2    | 7.5    | -18.9  | -8.6   | 1.5    | 1.7    | 2.1    | 3.6    | 4.6    | 3.8    |
| Southwest (4 provinces)                | 3.4    | 5.3    | -13.5  | 6.1    | 4.3    | 8.2    | 8.2    | 7.8    | 7.5    | 7.5    |
| Northwest (5 provinces)                | 7.7    | 8.9    | -4.4   | 4.6    | 6.5    | 8.3    | 6.8    | 0.9    | 5.6    | 6.1    |

| Panel B: Growth rate of trade value (%) |        |        |        |        |        |        |        |        |        |        |
|----------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Imports                                | 0.8    | 16.5   | -4.0   | -1.0   | -14.2  | -16.7  | 2.7    | -1.4   | -2.1   | 13.2   |
| Exports                                | -1.3   | 7.9    | -17.2  | -6.6   | 3.5    | -3.3   | 0.5    | 7.2    | 9.5    | 9.9    |

Note: This table shows value-added growth rate in five provinces and six regions and China’s national trade value growth rate. Average growth rate in each region is the simple average of growth rate in all provinces in that region.
Figure 1 shows the COVID-19 pandemic’s shocks on value-added growth rates across 19 manufacturing sectors in China. The average value-added across all sectors decreased by 18.4% in February and gradually recovered to a growth rate of 5.0% in September 2020. WAP (Clothing, leather, fur, etc.) recovered slowest while EEQ (Electrical–Electronic equipment) recovered fastest. Given that WAP closely relates to TEX (Textile) and TEX recovered much faster than WAP, we modify the value-added growth rate of WAP with the combination of average growth rate across all sectors and the growth rate of TEX. Similarly, given EEQ closely relates to TEQ (Transportation sector), we modify the value-added growth rate of EEQ with the combination of average growth rate across all sectors and the growth rate of TEQ. Table 3 presents the actual sectoral shocks we use in our modeling. For WAP and EEQ, the values in bold are the actual shocks used, and values in brackets are the raw data in the CARD database. Note that for several sectoral shocks, we cannot find a reasonable value and omit them in the modeling (labeled as “–” in Table 3).

Figure 1. Value-added growth rate of China’s manufacturing sectors

Note: See Table 3 for sector descriptions. We only include manufacturing sectors. Based on authors’ compilation from China’s National Bureau of Statistics and concordance between IO sectors and industrial sectors in the industrial classification for national economic activities in GB/T 4754—2011.
Table 3. Observed monthly value-added growth rate of China’s manufacturing sectors (%)

| Sectors                                      | Abbr. | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|----------------------------------------------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 2. Coal mining                               | COL   | 7.2    | 9.2    | -8.2   | 9.1    | 3.7    | 0.3    | -0.3   | -4.0   | 2.8    | 2.7    |
| 3. Petroleum and gas                          | CRU   | 3.3    | 2.8    | 2.1    | -1.3   | -6.2   | 3.4    | 8.1    | 0.2    | 2.9    | 3.5    |
| 4/5. Metal mining - Non-metal mining          | OXT   | 1.2    | 6.5    | -25.5  | -6.3   | 5.5    | 4.0    | 2.5    | -0.3   | 3.7    | 3.9    |
| 6. Food processing and tobacco               | FOO   | -0.9   | 4.8    | -12.7  | 3.7    | 1.9    | 0.7    | 0.5    | 0.03   | -1.3   | 3.8    |
| 7. Textile                                   | TEX   | 2.5    | 0.2    | -20.0  | -5.5   | 2.0    | 4.3    | 3.2    | 0.7    | 3.3    | 5.6    |
| 8. Clothing, leather, fur, etc.              | WAP   | 2.5*   | -*     | -*     | **-12.9**| -3.1*  | -7.4   | -8.2   | -*     | -*     | 3.7*   |
|                                               |       | (0.7)  | (-0.8) | (-28.7)| (-9.5) |        |        |        | (10.7) | (-11.6)| (-10)  |
| 9. Wood processing and furnishing            | LUM   | 2.6    | 3.8    | -26.0  | -4.7   | -3.2   | -3.6   | -4.9   | -2.6   | -0.5   | 2.5    |
| 10. Paper making, printing, stationery, etc. | PPP   | 2.0    | 1.7    | -25.7  | -4.7   | 1.0    | -2.1   | -3.1   | -1.4   | 0.9    | 4.0    |
| 11. Petroleum refining, coking, etc.         | OIL   | 9.0    | 7.3    | -7.8   | -8.9   | -0.4   | 7.8    | 7.1    | 3.9    | 6.8    | 2.6    |
| 12. Chemical industry                        | CHM   | 7.6    | 6.6    | -15.1  | 1.0    | 3.4    | 3.4    | 4.2    | 3.3    | 4.5    | 6.9    |
| 13. Nonmetal products                        | NMM   | 8.6    | 8.4    | -21.1  | -4.5   | 4.2    | 5.5    | 4.8    | 3.1    | 5.0    | 9.0    |
| 14. Metallurgy                                | MET   | 8.6    | 7.9    | -5.3   | 3.5    | 5.8    | 5.1    | 4.6    | 5.3    | 7.0    | 6.3    |
| 15/16. Metal products–General and specialist machinery | FMP   | 6.3    | 6.0    | -26.6  | -2.7   | 9.9    | 7.7    | 5.6    | 8.9    | 9.7    | 11.4   |
| 17. Transport equipment                      | TEQ   | 3.9*   | 1.8*   | -30.0* | -11.0  | 5.8    | 7.4    | 6.1    | 10.1   | 7.3    | 10.2   |
| 18/19. Electrical–Electronic equipment        | EEQ   | 3.9*   | 1.8*   | -30.0* | -*     | 10.4   | 8.8    | 2.0*   | 2.2*   | 3.7*   | 7.0*   |
|                                               |       | (11.2) | (12.0) | (-19.3)| (4.8)  |        |        |        |        |        |        |

Note: * indicates significant changes.
| Sectors                                           | Abbr. | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|--------------------------------------------------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 20. Instrument and meter                         | OME   | 11.0   | 3.4    | -27.4  | 2.0    | 11.1   | 8.4    | 6.6    | 9.4    | 3.8    | 3.0    |
| 21. Other manufacturing                         | OMF   | 1.3    | -3.9   | -25.0  | -12.9  | -4.8   | -5.4   | -7.1   | -0.4   | 0.4    | 4.0    |
| 22. Electricity and hot water production and supply | ELE   | 6.8    | 7.0    | -6.0   | -1.7   | -0.2   | 4.0    | 6.3    | 1.7    | 5.9    | 4.2    |
| 23. Gas and water production and supply         | GAS   | 6.6    | 6.6    | -6.0   | -0.8   | 2.0    | 1.6    | 1.3    | 1.0    | 4.8    | 4.0    |
| **Average**                                     |       | 5.2    | 4.8    | -18.4  | -3.0   | 2.3    | 2.8    | 2.4    | 2.2    | 3.6    | 5.0    |

Note: We only include manufacturing sectors. Based on authors’ compilation from China’s National Bureau of Statistics and concordance between IO sectors and industrial sectors in the industrial classification for national economic activities in Guobiao (GB)/T 4754–2011. We use the average growth rate of all GB sectors that correspond with the IO sector as the growth rate of a specific IO sector. Please note that the data are for enterprises with annual revenue above 20 million RMB and we combine metal and non-metal mining (sector 4 and 5), and metal products and general and specialist machinery (sector 15 and 16) to be consistent with the sectors in the general equilibrium trade model.

* For WAP and EEQ, values in bold value are the actual shocks used in the modeling, and values in brackets are the raw data in the CARD database. Note that for several sectoral shocks (labeled as “–”), we cannot find a reasonable value and omit them in the modeling.
3. General Equilibrium Structure

3.1 MPSGE formulation

To quantify the implied labor productivity shocks that fit the observed monthly provincial and sectoral value-added growth rates and national trade shocks, we formulate a benchmark mathematical representation of the Chinese economy. The formulation relies on MPSGE (Rutherford 1999) software embedded in GAMS (Brooke et al. 1988). MPSGE allows solving Arrow-Debreu equilibrium models as a mixed complementary problem and is the preferred programming environment for many economists (Horridge et al. 2013). The model is calibrated to the China MRIO table developed by Mi et al. (2018). The GAMS/MPSGE formulation has a number of advantages for economic modeling and facilitates a compact representation of the full set of technologies, markets, and resource constraints. The quantitative model consists of nested constant elasticity of substitution production functions and Cobb-Douglas preferences across the regional representative agents. The trade formulation includes a constant elasticity of substitution (Armington) import-demand system and a constant elasticity of transformation export-supply technology. A set of MPSGE side constraints (auxiliaries) are used to adjust labor productivities, sectoral total-factor-productivity, and trade shocks to meet the targets. Otherwise the formulation complies with a standard Rutherford (1999) formulation that includes zero-profit, market-clearance, and income-balance equilibrium conditions.

The model is solved using the PATH algorithm within GAMS. The overall scope of the model includes inter-regional and inter-sectoral economic flows among 30 economic sectors in 30 Chinese provinces. The base year for the social accounts establishing these relationships is 2012, the most recent year China published regional-level input-output tables at the province level (Mi et al. 2018).

3.2 Observed value-added and trade outcomes as modeling targets

To quantify the implied labor productivity shocks at the province-by-month level, we first use the observed province-by-month and sector-by-month value-added growth rate as targets. This approach might, however, generate biased estimates because it does not account for the global nature of the pandemic as it impacts China’s trade opportunities. Thus, in an important extension we consider monthly national import and export shocks as additional targets in the same model to get another set of labor productivity shock estimates. The observed national exports and imports are accommodated through additional export-demand and import-supply shocks. We find that China’s imports and exports were significantly affected by the global propagation of the COVID-19 pandemic, and this has important implications for estimating regional labor productivity shocks.

Other than labor productivity shocks, we also compute the implied money-metric measure of equivalent variation, which measures households’ welfare loss.
(gain). Equivalent variation is a common measure of consumer surplus. It measures the amount of compensation paid or received, that will leave the consumer in his subsequent welfare position in the absence of the price change if he is free to buy any quantity of the commodity at the old price (Currie et al. 1971). While nominal value-added measures are useful indicators of economic performance, proper welfare calculations indicate the true value of the estimated productivity and trade shocks to the representative household agents.

4. Results

4.1 Regional labor productivity shocks

Table A.1 and A.2 in the appendix provide two full sets of COVID-19 province-by-month labor productivity shock estimates for 30 provinces from November 2019 to September 2020 including and not including trade shocks as modeling targets, respectively. In February 2020, when compared with February 2019 levels and when trade series are included in the modeling, we find an average 39.5% decrease in labor productivity (equivalent to around 305 million jobs) and an average 25.9% decrease in welfare across provinces.7 Both China’s labor productivity and welfare have recovered quickly since April 2020. As of September 2020, average labor productivity increased by 12.2% (equivalent to around 94 million jobs) and average welfare increased by 8.2% across provinces compared to September 2019 levels.

For illustration purposes, Figure 2 presents the monthly percentage changes in labor productivity in Beijing, Hubei, Heilongjiang, Zhejiang, and Xinjiang. Panel A presents the estimates without trade shocks as additional modeling targets, and panel B presents the estimates with trade shocks as targets.

In panel A, compared with levels in February and March 2019, Hubei’s labor productivity reduced by 74.1% and 72.9% in February and March 2020, respectively. However, Hubei’s labor productivity has rebounded since May 2020 and increased to 19.4% as of September 2020 compared to 2019 levels. This pattern is consistent with the draconian lockdown measures Hubei adopted. Beijing and Zhejiang’s labor productivity reduced by 43.9% and 46.0% in February 2020, while Xinjiang’s labor productivity reduced by only 14.7% in February 2020. These patterns are in line with COVID-19’s spatial progression patterns. In addition, the labor productivities in all the five provinces have gradually recovered since May 2020 and reached an average growth rate of around 32.0% as of September 2020. While Beijing was initially one of the fastest-recovering provinces (cities), the COVID-19 outbreak in Beijing in August and the associated strict lockdown measures thereafter have since slowed Beijing’s recovery.

7 This decrease is based on the baseline employment of 774 million in 2019.
Figure 2. Labor productivity shock estimates in five typical provinces with and without trade shocks (%)
Compared with panel A, panel B in Figure 2 accounts for trade shocks and thus shows different recovery patterns. From April to June, labor productivity recovered faster when not including trade shocks as additional targets in the modeling. For example, Zhejiang’s labor productivity grew by 31.9%, 32.3%, and 14.2% in April, May, and June, respectively, when we do not include trade shocks as additional targets, which is much lower than its labor productivity growth rates of 45.8%, 43.6%, and 28.9% in April, May, and June, respectively, when we include trade shocks as additional targets. This pattern can be explained by the fact that China’s net export demand declined in April to June. Therefore, to achieve the same output when net export demand remained unchanged, we need to compensate export demand decline with higher labor productivity growth. These patterns reversed in August and September, partially because China’s exports began accelerating in August (this is especially true for provinces in eastern China). As a result, labor productivity growth without trade shocks as targets was smaller than the labor productivity growth with trade shocks in August and September 2020.

To examine the spatial patterns of labor productivity shocks, we present the monthly population-weighed average labor productivity shocks in six regions in Figure 3. In February 2020, there is a clear pattern that provinces in south-central and eastern China were most affected while northwestern provinces were least affected. We also find significant heterogeneity in recovery patterns across regions. Specifically, provinces in eastern China recovered fastest from a labor productivity shock of -45.1% in February to 39.2% in September 2020. The labor productivity recovery in northwestern China is most stable and increased from a negative shock of -23.3% in February to 23.3% in September 2020. The south-central region, where Hubei is located, recovered from a negative shock of -43.8% in February to 24.0% in September. Similar to provincial patterns, regional recovery patterns from April to June differ depending on whether we account for national trade shocks. Most regions’ labor productivity grew faster in April, May, and June, and reached a smaller growth rate in August and September when we do not include trade shocks. The net-export growth since August 2020 can help explain this change.

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8 We weight the provincial labor productivity shocks with 2019 provincial population.
Figure 3. Labor productivity shock estimates in six regions with and without trade shocks (%)

Note: The average labor productivity shock estimates in a region is the average labor productivity shock estimates weighted by 2019 population across provinces.
There are several points worthy of attention when interpreting the labor productivity estimates. First of all, the labor productivity estimates are combinations of extensive and intensive margins of the COVID-19 pandemic’s employment effects, which suggests that the labor productivity estimates include changes in both employment status and working hours. Therefore, the estimated 293 million job loss in February 2020 should be interpreted as a 293 million full-time-equivalent job loss that can be any combination of changes in working hours and employment status. Second, the value-added and trade targets used in the CGE modeling are the results of both the COVID-19 pandemic and various government policies, such as deferred tax payments for small and medium-sized firms, lower lending rates, and subsidies for infected medical workers’ compensations. Therefore, the labor productivity impacts estimates capture the net impacts of the pandemic and the various government policies.

4.2 Labor productivity shock estimates and COVID cases

Figure 4 plots the relationship between estimated labor productivity shock estimates and the ratio of cumulative confirmed cases in China’s 2019 population in February, March, and April 2020 across provinces. There is a clear negative relationship between ratio of confirmed cases and labor productivity shock estimates in February; however, the negative relation disappears in March and April. This shows that areas hit harder by COVID-19 suffered greater labor productivity loss initially; however, it is only evident in February, which is in line with the fact that the pandemic was largely contained and the economic activities resumed since April 2020.

4.3 Regional welfare impacts

Table A.3 and Table A.4 in the appendix provide two full sets of COVID-19 province-by-month welfare impacts for 30 provinces from November 2019 to September 2020 estimated from models with and without trade shocks as additional targets, respectively. We base our welfare calculations on equivalent variation and measure households’ money-metric income loss (gain). Figure 5 presents the monthly percentage changes in welfare in Beijing, Hubei, Heilongjiang, Zhejiang, and Xinjiang. Panel A shows welfare changes without trade shocks as targets, and panel B shows the estimated welfare impacts when we incorporate national shocks in the modeling. Compared with the monthly levels in 2019, Hubei’s welfare reduced by 54.1% and 54.3% in February and March 2020, respectively, and rebounded to a growth rate of 3.9% in September 2020. In addition, although Xinjiang’s value-added only reduced by 0.7% in February 2020, its welfare reduced by 8.8% that same month, which indicates that output impacts might disguise la-

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9 COVID-19’s employment effects are quite heterogeneous across demographic subgroups, regions, and industries (Barwick et al. 2020).
Figure 4. Scatter plot of labor productivity shock estimates and ratio of cumulative confirmed cases to population, 2020

Note: We base the ratio of confirmed cases to population on 2019 population. Data on cumulative confirmed cases come from China’s Center for Disease Control and Prevention (China CDC). Labor productivity shock estimates are estimated with trade shocks as additional targets. For clear illustration, we exclude Hubei from the figure due to its quite large ratio of confirmed cases to population. Labor productivity and welfare impacts. In addition, welfare in all five provinces has gradually recovered since May and reached a growth rate of around 17.0% as of September 2020. The welfare shocks over time are consistent with the temporal labor productivity shocks in that Zhejiang recovered fastest, followed by Beijing. Beijing’s welfare recovery has slowed since August due to a COVID-19 outbreak. In addition, the magnitudes of the percentage changes in welfare are smaller than the percentage changes in labor productivity.
Figure 5. Welfare changes in five typical provinces with and without trade shocks (%)
Figure 6 presents the monthly percentage changes in welfare in six regions when not including and including trade shocks as additional targets, respectively. Figure 6 shows that patterns are consistent with our welfare estimates—eastern China recovered fastest. Similar to provincial patterns, regional recovery patterns from April to June differ depending on whether we account for national trade shocks. Most provinces’ welfare recovered faster from April to June, when not accounting for trade shocks, and returned to lower levels starting in August, also when not accounting for trade shocks.

4.4 Spatial dynamics of labor productivity shocks

The three maps in Figure 7 illustrate the spatial distribution of estimated provincial labor productivity shocks in February, June, and September 2020 without using national trade shocks as additional targets. There is great spatial heterogeneity. While the initial negative labor productivity shocks concentrated in Hubei, eastern China, and parts of northeast and southwest China, the negative labor productivity shocks mostly disappeared in June. The severity of labor productivity shocks are related to provinces’ proximity to Hubei and the stringency of control measures. Eastern China recovered the fastest while south-central provinces recovered slowly. In September, labor productivity shocks in several provinces in northwestern China, such as Qinghai, recovered much slower than other provinces. The patterns are consistent with the COVID-19 pandemic hitting the northern and northwestern regions in July.
Figure 6. Welfare changes in six regions with and without trade shocks (%)

Note: The average labor productivity shock in a region is the average labor productivity shocks weighted by 2019 population across provinces.
5. Conclusion and Discussion

This paper first introduces a database that documents various monthly sectoral and regional economic outcomes in China, which can be used to analyze COVID-19’s impacts on China’s economy. We use a general equilibrium model calibrated to a 30 provinces by 30 sectors MRIO table to quantify COVID-19’s impacts on provincial labor productivity and welfare. Compared with the February 2019 levels, in February 2020, when the trade series are included in the modeling, we find an average 39.5% decrease in labor productivity (equivalent to around 305 million jobs) and an average 25.9% decrease in welfare across provinces; however, both labor productivity and welfare have recovered quickly since April 2020. As of September 2020, average labor productivity increased by 12.2% (equivalent to around 94 million jobs) and average welfare increased by 8.2% across provinces compared to their September 2019 levels.

In addition, we find significant heterogeneity in recovery patterns across provinces. Provinces in eastern China recovered fastest—we find labor productivity shocks of -45.1% in February 2020 and 39.2% in September 2020. The labor productivity recovery in northwestern China is most stable and increased from a negative shock of -23.3% in February to 23.3% in September 2020. The south-central region, where Hubei is located, recovered from a negative shock of -43.8% in February 2020 to 24% in September 2020. Finally, we find that labor productivity grew faster in the second quarter when we include national trade shocks in the model than when we only use regional and sectoral value-added as output targets.

Compared with the numerous general equilibrium analysis of COVID-19 on the national level (McKibbin and Fernando 2020; Maliszewska et al. 2020; Zhang et al. 2020; Zhao 2020; Keogh-Brown et al. 2020; Sahoo and Ashwani 2020), this paper provides both a regional general equilibrium analysis and an example of using observed output data to back out regional unobserved labor productivity shocks in developing countries like China, where high-frequency regional labor productivity shocks are not readily available. The two full sets of labor productivity shocks can be used in future related research.

Our model and estimates are also not without their limitations. First, the value-added data are only for manufacturing sectors, and we do not account for agricultural sectors. However, this is mainly caused by the fact that agricultural and industrial statistics are reported by different administrative departments: agricultural statistics are mainly reported by China’s ministry of Agricultural and Rural Affairs while industrial statistics are mainly reported by the Ministry of Information and Information Technology, and agricultural output statistics are not easily available on a monthly basis. In addition, the current model does not consider China’s bilateral trade linkages with other countries (China is modeled as an open economy trading with the rest of the world). Given that China’s regional economies are closely related to other countries on a bilateral basis, it will be fruitful to incorporate bilateral trade linkage between China and its main trade.
Figure 7. Labor productivity shocks in February, June, and September 2020 (%)

Note: There are no data for Tibet, Hong Kong, Macau, and Taiwan.
partners in future analysis. Finally, this model does not differentiate rural and urban labor, which are quite different and could have been impacted quite differently. For example, Crossley et al. (2021) find the lowest income quintiles and minority ethnic groups have worst labour market shocks during the pandemic in the UK. Again this would be a valuable extension for future research.

Declarations
Conflicts of interest: None

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Appendix.

Figure A.1 illustrates China’s provinces and regional classifications. Table A.1 and Table A.2 provide the full set of COVID-19’s monthly labor productivity impact for 30 provinces in the context of a general equilibrium trade model. Table A.3 and Table A.4 provide the corresponding monthly welfare shocks for the 30 provinces.

Figure A.1. China’s provinces and regional classifications
| Provinces   | Region          | 2019 GDP* | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|-------------|-----------------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Guangdong   | South-central   | 1563.7    | 23.9   | 18.9   | -53.5  | -16.7  | 12.9   | 4.3    | 9.1    | 28.2   | 30.9   | 39.0   |
| Jiangsu     | East            | 1428.6    | 31.1   | 24.8   | -46.0  | 4.7    | 26.9   | 25.1   | 19.2   | 19.5   | 32.4   | 44.5   |
| Shandong    | East            | 1021.4    | 20.5   | 9.5    | -42.9  | -3.6   | 17.4   | 21.2   | 17.5   | 19.6   | 36.9   | 42.0   |
| Zhejiang    | East            | 904.4     | 32.9   | 21.3   | -57.3  | -8.5   | 31.9   | 32.3   | 14.2   | 18.4   | 36.0   | 42.8   |
| Henan       | South-central   | 777.8     | 22.8   | 13.8   | -30.4  | 2.9    | 16.5   | 17.0   | 8.7    | -2.5   | 8.4    | 13.6   |
| Sichuan     | Southwest       | 671.3     | 25.4   | 19.3   | -22.7  | 7.2    | 18.7   | 17.2   | 11.1   | 15.0   | 15.4   | 26.7   |
| Hubei       | South-central   | 657.8     | 16.6   | 15.1   | -74.1  | -72.9  | -2.2   | 7.3    | 2.7    | 7.2    | 13.9   | 19.4   |
| Fujian      | East            | 612.9     | 24.5   | 16.6   | -38.3  | 0.8    | 13.3   | 16.8   | 10.6   | 15.9   | 16.8   | 23.5   |
| Hunan       | South-central   | 577.7     | 25.5   | 17.9   | -25.6  | 7.2    | 16.7   | 12.1   | 11.0   | 15.3   | 10.5   | 23.8   |
| Shanghai    | East            | 550.1     | 23.1   | 35.3   | -50.6  | -4.0   | 14.9   | 12.0   | 12.0   | 51.0   | 37.6   | 41.8   |
| Anhui       | East            | 533.5     | 19.8   | 16.5   | -33.1  | 12.6   | 26.8   | 23.1   | 16.1   | 12.8   | 24.9   | 28.3   |
| Beijing     | North           | 513.2     | 8.0    | 10.5   | -43.9  | -34.4  | 14.9   | 14.8   | 25.4   | 31.6   | 20.5   | 22.1   |
| Hebei       | North           | 506.5     | 7.3    | 11.0   | -25.0  | 2.3    | 13.1   | 16.9   | 5.6    | 14.7   | 16.9   | 19.7   |
| Shaanxi     | Northwest       | 373.5     | 19.5   | 21.9   | -33.2  | 5.9    | 18.5   | 26.5   | -1.6   | 2.0    | 22.8   | 18.1   |
| Liaoning    | Northeast       | 359.9     | 20.9   | 10.5   | -28.1  | -25.0  | 6.6    | 15.4   | 4.6    | 14.1   | 13.8   | 18.4   |
| Jiangxi     | East            | 357.2     | 47.0   | 28.1   | -47.4  | 24.2   | 32.9   | 25.0   | 27.1   | 31.3   | 34.5   | 46.3   |
| Chongqing   | Southwest       | 341.8     | 27.1   | 21.9   | -54.8  | 11.4   | 28.2   | 29.5   | 28.2   | 40.9   | 36.1   | 37.3   |
| Yunnan      | Southwest       | 336.3     | -19.1  | -22.0  | -42.3  | -9.2   | 0.2    | 43.8   | 29.6   | 34.4   | 43.6   | 28.8   |
| Guangxi     | South-central   | 307.5     | 25.8   | 12.8   | -37.4  | -7.6   | 5.6    | 17.3   | 5.6    | 15.7   | 15.1   | 18.9   |
| Inner Mongolia | North     | 249.2     | 5.6    | -0.8   | -27.0  | -5.8   | 6.5    | -8.5   | 1.8    | 0.6    | 6.0    | 3.8    |
| Shanxi      | North           | 245.6     | 13.9   | 2.6    | -34.5  | 22.1   | 5.0    | 6.2    | 9.6    | 16.2   | 37.6   | 52.7   |
| Guizhou     | Southwest       | 242.8     | 22.5   | 32.3   | -33.7  | 27.9   | 10.3   | 12.2   | 14.8   | 20.0   | 14.3   | 25.0   |
| Tianjin     | North           | 203.5     | 30.3   | 13.6   | -46.9  | -43.3  | -2.0   | 22.8   | 14.6   | 47.1   | 30.3   | 42.6   |
| Xinjiang    | Northwest       | 196.9     | 11.6   | 3.4    | -14.7  | 11.8   | 19.9   | 27.1   | 29.8   | 15.3   | 12.3   | 36.5   |
Table A.1. Implied labor productivity shocks in observed sectoral and provincial value-added targets (%)

| Provinces     | Region         | 2019 GDP* | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|---------------|----------------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Heilongjiang  | Northeast      | 196.1     | 1.6    | 23.6   | -41.3  | -19.8  | 13.4   | 5.7    | -2.3   | 0.0    | 36.4   | 42.6   |
| Jilin         | Northeast      | 169.8     | 49.0   | 51.1   | -63.9  | -22.4  | 17.2   | 58.1   | 74.4   | 48.2   | 42.7   | 85.7   |
| Gansu         | Northwest      | 126.2     | 31.4   | 19.6   | -20.6  | -18.3  | 26.6   | 45.1   | 19.9   | 21.1   | 32.1   | 24.7   |
| Hainan        | South-central  | 77.2      | 19.4   | 20.9   | -37.5  | -20.2  | -7.9   | -12.6  | -14.4  | 13.0   | 5.3    | 5.0    |
| Ningxia       | Northwest      | 54.3      | 18.0   | 28.2   | -9.5   | 26.4   | 21.0   | 11.4   | 17.2   | -32.3  | 9.4    | 17.4   |
| Qinghai       | Northwest      | 42.6      | 40.6   | 38.6   | -24.5  | 25.7   | 12.7   | 16.1   | 9.5    | 18.2   | 23.0   | 2.4    |
| East          | East           | 5408.1    | 27.7   | 19.5   | -45.1  | 1.2    | 24.0   | 23.3   | 17.3   | 21.2   | 31.9   | 39.2   |
| South-central | South-central  | 3961.7    | 23.0   | 16.2   | -43.8  | -15.1  | 10.8   | 10.4   | 7.4    | 13.5   | 18.4   | 24.0   |
| North         | North          | 1718.1    | 10.6   | 7.7    | -31.6  | -3.2   | 9.3    | 11.2   | 9.1    | 17.9   | 21.9   | 26.7   |
| Southwest     | Southwest      | 1592.3    | 14.3   | 12.1   | -34.5  | 7.6    | 14.2   | 24.7   | 18.9   | 24.7   | 25.3   | 28.6   |
| Northeast     | Northeast      | 1275.9    | 17.8   | 21.1   | -34.9  | -18.9  | 9.8    | 19.0   | 16.4   | 14.8   | 24.2   | 36.5   |
| Northwest     | Northwest      | 793.5     | 21.8   | 18.2   | -23.3  | 3.7    | 20.7   | 29.8   | 13.5   | 8.8    | 21.7   | 23.3   |
| Average       |                | 473.3     | 21.2   | 17.6   | -37.9  | -5.0   | 14.6   | 18.9   | 14.3   | 18.1   | 24.3   | 29.8   |

Note: This table presents calculated labor productivity shocks across 30 provinces from November 2019 to September 2020 using only value-added targets in the modeling. Please note that China’s National Bureau of Statistics does not report growth rate of value-added in January, and the productivity shocks in February denote the productivity shocks from January to February. Labor productivity shocks in regions are population weighted average labor productivity shocks across provinces in a region.

*GDP is measured in $US billion.
Table A.2. Implied labor productivity shocks in observed sectoral and provincial value-added and national trade targets (%)

| Provinces      | Region          | 2019 GDP* | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|----------------|-----------------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Guangdong      | South-central   | 1563.7    | 11.1   | 20.9   | -64.0  | -8.5   | -9.0   | -18.7  | 27.2   | 33.6   | 14.8   | 13.6   |
| Jiangsu        | East            | 1428.6    | 19.0   | 12.1   | -60.3  | 9.3    | 26.2   | 22.4   | 42.2   | 32.6   | 32.5   | 37.6   |
| Shandong       | East            | 1021.4    | 12.7   | 10.8   | -49.8  | 5.7    | 36.5   | 38.1   | 30.4   | 22.8   | 25.3   | 25.8   |
| Zhejiang       | East            | 904.4     | 23.0   | 16.8   | -66.0  | -0.8   | 45.8   | 43.6   | 28.9   | 25.3   | 30.3   | 31.8   |
| Henan          | South-central   | 777.8     | 19.7   | 22.8   | -28.4  | 7.7    | 7.8    | 5.4    | 8.4    | -6.7   | -2.3   | 0.9    |
| Sichuan        | Southwest       | 671.3     | 18.6   | 21.9   | -29.7  | 12.5   | 12.2   | 8.7    | 19.1   | 16.0   | 7.0    | 14.2   |
| Hubei          | South-central   | 657.8     | 11.3   | 13.2   | -76.8  | -72.0  | 3.3    | 12.3   | 11.0   | 10.7   | 10.4   | 13.6   |
| Fujian         | East            | 612.9     | 16.9   | 20.3   | -47.1  | 8.7    | 8.8    | 8.8    | 19.8   | 17.3   | 5.9    | 7.8    |
| Hunan          | South-central   | 577.7     | 19.9   | 19.5   | -30.8  | 12.5   | 16.5   | 10.5   | 18.2   | 16.5   | 12.4   | 13.9   |
| Shanghai       | East            | 550.1     | 9.6    | 43.5   | -68.8  | -31.5  | -5.2   | -11.1  | 33.6   | 54.8   | 14.4   | 9.9    |
| Anhui          | East            | 533.5     | 15.3   | 19.1   | -37.1  | 17.9   | 27.6   | 21.6   | 21.1   | 12.9   | 17.3   | 18.4   |
| Beijing        | North           | 513.2     | 0.7    | 18.9   | -49.5  | -26.1  | 12.5   | 7.9    | 41.6   | 32.0   | 3.1    | -0.1   |
| Hebei          | North           | 506.5     | 3.5    | 12.6   | -29.4  | 6.9    | 14.5   | 16.1   | 12.2   | 16.1   | 11.0   | 11.5   |
| Shaanxi        | Northwest       | 373.5     | 15.6   | 31.5   | -32.0  | 14.7   | 19.5   | 22.6   | 1.0    | -1.6   | 9.6    | 3.3    |
| Liaoning       | Northeast       | 359.9     | 16.7   | 13.5   | -32.1  | -21.2  | 8.6    | 16.1   | 9.5    | 13.9   | 6.8    | 9.4    |
| Jiangxi        | East            | 357.2     | 31.5   | 29.6   | -55.8  | 35.2   | 23.4   | 12.5   | 44.0   | 35.5   | 18.5   | 21.2   |
| Chongqing      | Southwest       | 341.8     | 21.3   | 25.5   | -58.2  | 17.0   | 23.9   | 24.1   | 35.7   | 39.7   | 26.3   | 25.4   |
| Yunnan         | Southwest       | 336.3     | -19.2  | 1.7    | -28.2  | -0.1   | -24.8  | 6.8    | 15.5   | 13.0   | 10.2   | -4.1   |
| Guangxi        | South-central   | 307.5     | 21.4   | 23.6   | -37.4  | -1.2   | -2.4   | 6.2    | 5.9    | 10.0   | 0.9    | 2.2    |
| Inner Mongolia | North           | 249.2     | -0.3   | 8.2    | -30.1  | 5.3    | 11.5   | -7.9   | 8.7    | -1.5   | -9.0   | -14.0  |
| Shanxi         | North           | 245.6     | 12.2   | 17.8   | -26.0  | 30.7   | -1.1   | -3.5   | 5.7    | 6.1    | 17.9   | 29.5   |
| Guizhou        | Southwest       | 242.8     | 18.9   | 47.8   | -29.9  | 37.7   | 2.1    | 0.9    | 13.4   | 12.1   | -1.6   | 5.7    |
| Tianjin        | North           | 203.5     | 23.5   | 22.9   | -49.9  | -38.3  | -11.0  | 7.5    | 22.5   | 44.0   | 18.9   | 20.5   |
| Xinjiang       | Northwest       | 196.9     | 9.4    | 17.9   | -10.0  | 20.8   | 12.7   | 15.5   | 27.2   | 6.3    | -4.6   | 14.6   |
| Provinces     | Region    | 2019 GDP* | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|--------------|-----------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Heilongjiang | Northeast | 196.1     | -3.4   | 34.6   | -42.1  | -12.0  | 13.7   | 1.6    | 2.3    | -3.2   | 18.4   | 20.1   |
| Jilin        | Northeast | 169.8     | 46.0   | 68.2   | -60.9  | -16.4  | 20.1   | 62.2   | 72.1   | 35.7   | 25.9   | 65.4   |
| Gansu        | Northwest | 126.2     | 27.9   | 36.0   | -15.0  | -11.9  | 13.1   | 25.2   | 16.9   | 11.7   | 11.9   | 3.5    |
| Hainan       | South-central | 77.2   | 13.1   | 33.5   | -38.0  | -12.3  | -15.8  | -24.1  | -12.2  | 7.7    | -11.1  | -14.3  |
| Ningxia      | Northwest | 54.3      | 16.3   | 40.4   | -3.3   | 33.6   | 12.4   | 1.8    | 13.9   | -36.8  | -2.0   | 4.2    |
| Qinghai      | Northwest | 42.6      | 42.5   | 85.8   | 0.8    | 40.1   | -15.2  | -18.9  | -9.4   | -7.2   | -10.9  | -26.8  |
| East         | East      | 5408.1    | 18.1   | 18.1   | -53.7  | 8.8    | 27.9   | 24.7   | 31.8   | 26.3   | 22.9   | 24.6   |
| South-central| South-central | 3961.7 | 16.1   | 20.6   | -47.6  | -9.6   | 2.0    | -0.2   | 15.1   | 13.9   | 7.2    | 8.5    |
| North        | North     | 1718.1    | 6.2    | 14.8   | -33.1  | 3.7    | 8.3    | 6.7    | 14.8   | 15.9   | 9.3    | 11.0   |
| Southwest    | Southwest | 1592.3    | 9.9    | 22.2   | -33.8  | 14.7   | 3.2    | 9.2    | 19.8   | 18.3   | 9.3    | 10.0   |
| Northeast    | Northeast | 1275.9    | 14.2   | 28.9   | -35.8  | -14.1  | 11.1   | 18.9   | 18.9   | 11.2   | 13.0   | 22.7   |
| Northwest    | Northwest | 793.5     | 18.9   | 33.1   | -18.4  | 12.1   | 13.7   | 17.7   | 11.7   | 1.0    | 4.7    | 4.4    |
| Average      |           | 473.3     | 15.8   | 26.4   | -39.5  | 2.1    | 9.6    | 10.5   | 19.5   | 15.6   | 10.3   | 12.2   |

Note: This table presents calculated labor productivity shocks across 30 provinces from November 2019 to September 2020 using both value-added and trade series in the modeling. The provinces and regions are ordered based on their GDP in 2019 ($US billion). Please note that the China’s National Bureau of Statistics does not report growth rate of value-added in January, and the productivity shocks in February denote the productivity shocks from January to February. Labor productivity shocks in regions are population weighted average labor productivity shocks across provinces in a region.
| Provinces     | Region       | 2019 GDP* | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|---------------|--------------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Guangdong     | South-central| 1563.7    | 11.6   | 10.6   | -31.4  | -7.6   | 6.2    | 1.5    | 5.7    | 12.6   | 14.4   | 17.4   |
| Jiangsu       | East         | 1428.6    | 17.6   | 15.9   | -29.6  | 5.3    | 14.6   | 13.9   | 13.3   | 10.7   | 18.0   | 23.7   |
| Shandong      | East         | 1021.4    | 10.5   | 6.6    | -16.9  | 0.4    | 6.9    | 8.5    | 9.1    | 8.0    | 16.7   | 17.8   |
| Zhejiang      | East         | 904.4     | 17.7   | 14.2   | -34.7  | -2.8   | 16.2   | 16.8   | 10.1   | 11.6   | 19.9   | 22.3   |
| Henan         | South-central| 777.8     | 13.3   | 9.0    | -13.7  | 1.7    | 8.1    | 8.4    | 6.1    | -0.4   | 7.1    | 9.2    |
| Sichuan       | Southwest    | 671.3     | 14.6   | 11.4   | -12.3  | 3.8    | 9.6    | 8.9    | 7.5    | 8.2    | 9.8    | 14.9   |
| Hubei         | South-central| 657.8     | 11.5   | 11.0   | -54.1  | -54.3  | -1.5   | 3.9    | 2.6    | 3.5    | 9.7    | 11.9   |
| Fujian        | East         | 612.9     | 13.4   | 10.0   | -20.9  | 1.8    | 6.7    | 8.8    | 7.5    | 8.7    | 9.3    | 12.0   |
| Hunan         | South-central| 577.7     | 15.4   | 11.6   | -13.2  | 5.4    | 9.2    | 6.9    | 7.4    | 8.0    | 12.3   | 14.3   |
| Shanghai      | East         | 550.1     | 10.3   | 16.9   | -32.8  | -19.9  | 5.8    | 4.9    | 6.5    | 19.9   | 15.5   | 16.2   |
| Anhui         | East         | 533.5     | 12.1   | 10.7   | -21.4  | 4.1    | 13.6   | 12.2   | 11.0   | 9.8    | 15.7   | 17.0   |
| Beijing       | North        | 513.2     | 6.1    | 6.7    | -25.5  | -19.1  | 7.5    | 7.8    | 14.3   | 15.4   | 12.0   | 11.9   |
| Hebei         | North        | 506.5     | 7.0    | 8.0    | -16.9  | 1.2    | 8.2    | 10.4   | 5.5    | 9.2    | 12.7   | 14.6   |
| Shaanxi       | Northwest    | 373.5     | 12.6   | 12.9   | -15.8  | 2.5    | 9.0    | 12.6   | 2.0    | 2.5    | 14.2   | 11.4   |
| Liaoning      | Northeast    | 359.9     | 14.0   | 8.5    | -13.6  | -13.4  | 4.1    | 8.9    | 4.1    | 7.0    | 9.7    | 11.8   |
| Jiangxi       | East         | 357.2     | 16.3   | 12.0   | -22.7  | 8.8    | 11.5   | 9.1    | 11.3   | 11.4   | 12.7   | 15.7   |
| Chongqing     | Southwest    | 341.8     | 14.8   | 12.1   | -34.5  | 5.1    | 13.3   | 14.1   | 14.8   | 18.8   | 19.1   | 19.4   |
| Yunnan        | Southwest    | 336.3     | -5.9   | -7.1   | -19.6  | -2.8   | 1.0    | 17.4   | 12.7   | 13.2   | 18.9   | 13.4   |
| Guangxi       | South-central| 307.5     | 15.4   | 9.5    | -16.9  | -1.3   | 3.1    | 8.8    | 3.5    | 5.7    | 9.6    | 11.1   |
| Inner Mongolia| North        | 249.2     | 5.4    | 3.2    | -7.4   | -0.1   | 3.6    | -2.6   | 1.7    | -1.5   | 4.2    | 2.9    |
| Shanxi        | North        | 245.6     | 9.4    | 3.7    | -17.9  | 9.1    | 2.8    | 3.5    | 5.8    | 6.4    | 18.1   | 23.2   |
| Guizhou       | Southwest    | 242.8     | 12.4   | 16.2   | -19.8  | 11.6   | 5.4    | 6.4    | 8.8    | 11.2   | 9.3    | 13.9   |
| Tianjin       | North        | 203.5     | 13.4   | 7.3    | -22.4  | -19.2  | -0.2   | 9.3    | 7.3    | 16.2   | 15.3   | 17.4   |
| Xinjiang      | Northwest    | 196.9     | 8.1    | 4.0    | -8.8   | 5.4    | 10.3   | 13.6   | 15.0   | 8.6    | 8.6    | 19.5   |
Table A.3. Implied welfare changes in observed sectoral and provincial value-added targets (%)

| Provinces | Region       | 2019 GDP* | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|-----------|--------------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Heilongjiang | Northeast    | 196.1     | 2.4    | 10.0   | -19.1  | -8.6   | 5.8    | 3.2    | 0.9    | 1.1    | 14.6   | 16.4   |
| Jilin      | Northeast    | 169.8     | 16.8   | 17.7   | -28.6  | -7.7   | 6.4    | 17.5   | 21.6   | 13.7   | 15.2   | 26.0   |
| Gansu      | Northwest    | 126.2     | 17.6   | 11.7   | -13.1  | -10.3  | 13.1   | 20.9   | 11.9   | 12.2   | 18.5   | 14.8   |
| Hainan     | South-central| 77.2      | 10.4   | 10.7   | -17.4  | -9.1   | -2.9   | -4.7   | -4.2   | 6.2    | 4.8    | 3.9    |
| Ningxia    | Northwest    | 54.3      | 12.0   | 16.3   | -8.9   | 11.1   | 11.1   | 6.5    | 11.1   | -15.6  | 8.6    | 12.5   |
| Qinghai    | Northwest    | 42.6      | 14.1   | 12.7   | -13.6  | 6.1    | 4.8    | 6.0    | 4.5    | 7.7    | 10.0   | 4.2    |
| East       | East         | 5408.1    | 12.6   | 14.8   | -25.0  | 2.3    | 11.3   | 11.2   | 12.5   | 11.4   | 14.6   | 16.9   |
| South-central | South-central | 3961.7   | 10.7   | 11.8   | -27.2  | -9.3   | 5.5    | 5.3    | 6.8    | 7.3    | 8.5    | 10.6   |
| North      | North        | 1718.1    | 6.2    | 8.1    | -18.1  | -0.7   | 5.6    | 6.7    | 7.8    | 8.5    | 11.0   | 12.6   |
| Southwest  | Southwest    | 1592.3    | 7.4    | 10.1   | -19.0  | 5.3    | 7.4    | 11.4   | 11.7   | 11.1   | 11.1   | 12.7   |
| Northeast  | Northeast    | 1275.9    | 8.3    | 12.2   | -16.5  | -7.5   | 4.5    | 7.7    | 7.9    | 5.7    | 10.0   | 13.3   |
| Northwest  | Northwest    | 793.5     | 11.5   | 13.3   | -12.6  | 2.0    | 10.3   | 14.2   | 10.5   | 5.7    | 11.7   | 11.9   |

Average: 473.3  11.7  10.1  -20.8  -3.1  7.1  8.8  8.0  8.3  12.8  14.7

Note: This table presents calculated welfare changes across 30 provinces from November 2019 to September 2020 using only value-added targets in the modeling. The provinces and regions are ordered based on their GDP in 2019 ($US billion). Please note that the China’s National Bureau of Statistics does not report growth rate of value-added in January, and the productivity shocks in February denote the productivity shocks from January to February. Welfare shocks in regions are population weighted average welfare shocks across provinces in a region.
Table A.4. Implied welfare changes in observed sectoral and provincial value-added and national trade targets (%)

| Provinces | Region            | Province Code | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|-----------|-------------------|---------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Guangdong | South-central     |               | 1563.7 | 8.2    | 16.8   | -31.9  | -3.4   | -4.4   | -10.7  | 7.3    | 9.9    | 4.5    | 4.8    |
| Jiangsu   | East              |               | 1428.6 | 18.2   | 36.1   | -14.1  | 11.5   | -8.3   | -13.8  | 0.0    | -6.0   | -3.8   | 0.8    |
| Shandong  | East              |               | 1021.4 | 8.0    | 11.7   | -17.1  | 4.6    | 5.7    | 6.2    | 10.2   | 5.6    | 8.6    | 8.0    |
| Zhejiang  | East              |               | 904.4  | 16.8   | 27.7   | -27.4  | 3.0    | 5.5    | 2.8    | 3.9    | 1.7    | 4.4    | 5.6    |
| Henan     | South-central     |               | 777.8  | 8.6    | 3.3    | -25.6  | 3.8    | 12.6   | 13.4   | 16.0   | 5.8    | 7.9    | 7.5    |
| Sichuan   | Southwest         |               | 671.3  | 11.2   | 13.6   | -16.5  | 7.2    | 7.2    | 5.7    | 11.1   | 8.1    | 4.4    | 7.5    |
| Hubei     | South-central     |               | 657.8  | 8.8    | 12.9   | -54.8  | -52.9  | -2.5   | 2.0    | 5.6    | 3.5    | 4.9    | 5.4    |
| Fujian    | East              |               | 612.9  | 10.7   | 11.9   | -24.9  | 5.0    | 5.9    | 7.0    | 10.5   | 8.7    | 4.7    | 5.7    |
| Hunan     | South-central     |               | 577.7  | 12.3   | 13.8   | -16.6  | 8.9    | 7.7    | 4.4    | 11.1   | 8.1    | 6.8    | 6.9    |
| Shanghai  | East              |               | 550.1  | 7.3    | 23.8   | -32.6  | -16.0  | -2.1   | -4.7   | 8.4    | 16.9   | 5.5    | 4.1    |
| Anhui     | East              |               | 533.5  | 9.6    | 14.9   | -22.5  | 8.1    | 11.3   | 8.8    | 13.1   | 8.2    | 8.7    | 8.5    |
| Beijing   | North             |               | 513.2  | 3.2    | 10.7   | -27.7  | -15.1  | 6.6    | 5.5    | 18.9   | 14.7   | 4.5    | 2.6    |
| Hebei     | North             |               | 506.5  | 4.5    | 12.0   | -18.3  | 5.0    | 5.8    | 6.7    | 7.6    | 7.7    | 5.8    | 6.0    |
| Shaanxi   | Northwest         |               | 373.5  | 8.5    | 11.0   | -23.6  | 6.0    | 12.7   | 15.8   | 9.4    | 6.0    | 11.6   | 6.8    |
| Liaoning  | Northeast         |               | 359.9  | 11.3   | 10.8   | -16.6  | -10.5  | 3.3    | 7.5    | 7.1    | 6.8    | 4.5    | 5.1    |
| Jiangxi   | East              |               | 357.2  | 12.9   | 16.1   | -24.4  | 13.2   | 7.5    | 3.6    | 14.2   | 10.1   | 4.9    | 5.9    |
| Chongqing | Southwest         |               | 341.8  | 12.0   | 15.9   | -35.7  | 8.9    | 11.0   | 10.8   | 17.6   | 17.4   | 12.4   | 11.3   |
| Yunnan    | Southwest         |               | 336.3  | -10.9  | -17.3  | -35.4  | -0.7   | 8.3    | 26.0   | 26.1   | 22.1   | 21.0   | 12.6   |
| Guangxi   | South-central     |               | 307.5  | 9.9    | 3.2    | -30.2  | 1.2    | 7.6    | 13.2   | 14.5   | 12.7   | 9.8    | 8.3    |
| Inner Mongolia | North |               | 249.2  | 1.0    | 0.9    | -16.9  | 3.5    | 6.8    | 0.0    | 10.1   | 2.7    | 1.7    | -2.1   |
| Shanxi    | North             |               | 245.6  | 5.8    | 1.2    | -25.3  | 12.0   | 8.0    | 8.6    | 12.5   | 9.8    | 16.1   | 19.0   |
| Guizhou   | Southwest         |               | 242.8  | 8.2    | 12.6   | -28.3  | 15.0   | 12.0   | 13.1   | 17.1   | 15.6   | 8.3    | 10.8   |
| Tianjin   | North             |               | 203.5  | 9.1    | 3.3    | -31.8  | -17.2  | 4.7    | 14.2   | 16.3   | 21.4   | 14.6   | 14.5   |
| Xinjiang  | Northwest         |               | 196.9  | 2.5    | -5.7   | -25.2  | 8.2    | 21.8   | 25.7   | 29.3   | 17.8   | 11.3   | 19.3   |
Table A.4. Implied welfare changes in observed sectoral and provincial value-added and national trade targets (%)

| Provinces    | Region   | 2019 GDP* | Nov 19 | Dec 19 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 |
|--------------|----------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Heilongjiang | Northeast| 196.1     | -1.0   | 8.7    | -25.5  | -5.5   | 10.1   | 7.4    | 7.5    | 4.0    | 11.9   | 11.8   |
| Jilin        | Northeast| 169.8     | 12.4   | 12.1   | -38.6  | -5.6   | 14.0   | 26.1   | 32.2   | 19.6   | 16.1   | 24.8   |
| Gansu        | Northwest| 126.2     | 12.9   | 7.7    | -23.2  | -7.6   | 18.6   | 26.4   | 20.9   | 16.9   | 16.8   | 11.1   |
| Hainan       | South-central| 77.2   | 5.6    | 5.2    | -28.4  | -6.7   | 3.0    | 1.4    | 5.4    | 12.4   | 5.1    | 2.1    |
| Ningxia      | Northwest| 54.3      | 9.5    | 18.6   | -11.6  | 14.7   | 10.5   | 5.4    | 13.7   | -16.0  | 3.9    | 6.4    |
| Qinghai      | Northwest| 42.6      | 9.4    | 3.4    | -27.5  | 8.2    | 14.2   | 15.4   | 14.4   | 14.5   | 12.0   | 4.7    |
| East         | East     | 5408.1    | 12.2   | 20.4   | -21.3  | 6.0    | 3.6    | 1.4    | 8.1    | 4.7    | 4.6    | 5.7    |
| South-central| South-central| 3961.7 | 9.2    | 10.5   | -30.9  | -6.4   | 3.7    | 2.9    | 10.6   | 8.1    | 6.4    | 6.3    |
| North        | North    | 1718.1    | 4.5    | 7.2    | -21.9  | 1.8    | 6.4    | 6.6    | 11.2   | 9.5    | 8.0    | 8.0    |
| Southwest    | Southwest| 1592.3    | 5.4    | 6.2    | -26.2  | 6.9    | 8.9    | 12.8   | 16.9   | 14.3   | 10.4   | 9.9    |
| Northeast    | Northeast| 1275.9    | 6.1    | 8.7    | -21.1  | -6.3   | 7.0    | 10.1   | 11.3   | 7.6    | 8.4    | 10.3   |
| Northwest    | Northwest| 793.5     | 8.3    | 6.1    | -23.3  | 3.8    | 16.4   | 20.2   | 17.8   | 10.7   | 12.4   | 10.8   |
| Average      |          | 473.3     | 8.2    | 10.6   | -25.9  | 0.2    | 7.5    | 8.5    | 13.1   | 9.6    | 8.3    | 8.2    |

Note: This table presents calculated welfare changes across 30 provinces from November 2019 to September 2020 using both value-added and trade series in the modeling. The provinces and regions are ordered based on their GDP in 2019 ($US). Please note that the China’s National Bureau of Statistics does not report growth rate of value-added in January, and the productivity shocks in February denote the productivity shocks from January to February. Welfare shocks in regions are population weighted average welfare shocks across provinces in a region.