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Socioeconomic Impact Analysis of Yellow-dust Storms: An Approach and Case Study for Beijing

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ABSTRACT *Dust storms can extensively disrupt socioeconomic activities and pose hazards to human health and the ecosystem; yet no one has made a systematic analysis of dust storms from an economic perspective. Using a case study for Beijing in 2000, we present a preliminary analysis of socioeconomic impacts of yellow-dust storms, integrating regional economic analysis models with environmental-economic evaluation techniques. Our analyses demonstrate that the costs of delayed effects of yellow-dust storms can be higher than those of the immediate effects, and that the impacts potentially caused by supply effects can be greater than those caused by demand effects. Because this is a preliminary analysis with extremely limited data, our primary purpose is not to produce precise numerical results, but to develop an integrated model that policy analysts can use and further improve in order to evaluate the comprehensive impacts of other phenomena with similar properties more accurately.*

KEY WORDS: Dust storms, input–output analysis, socioeconomic impact analysis, China

1. Introduction

Yellow dust occurs every spring in northern China. It is composed of fine sediments originating in arid and semi-arid regions, mostly from the Gobi Desert and Mongolia, and transported by strong winds. When the concentration of atmospheric particles is so high that visibility decreases to less than one kilometer, the China Meteorological Administration defines it as a dust storm.[1] Severe winds and low visibility during dust storms can extensively disrupt socioeconomic activities, such as construction, tourism, trade, and transportation. Particles in a dust storm hinder sophisticated manufacturing, damage agricultural products and other plant life, and generate risks to human respiratory and cardiovascular systems. Records show that the effects of dust storms have reached 17

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provinces in China; moreover, similar impacts are detected in Japan, Korea, Mongolia, and even North America.[2]

Because of the increasingly severe problems with dust storms in the recent decade, scientists have conducted many studies on their causation, source areas, transportation trajectories, and physical damage (Zhu and Zhang, 1994; Jie, 1999; Gao *et al.*, 2000, 2002; Wang *et al.*, 2000; Kim and Park, 2001; Lin, 2001, 2002; Lu *et al.*, 2001). However, analysts have not undertaken any socioeconomic-impact evaluations to examine dust storms either quantitatively or qualitatively. Such studies are urgently needed, because socioeconomic information on dust storms will help officials to identify the most vulnerable groups and correspondingly enhance preparedness. They will also provide planners with a basis for appropriate investment in disaster mitigation and control. Moreover, a systematic and uniform research approach will enable analysts to conduct further studies to record and track yellow dust, and to compare it with similar problems, such as acid rain, hail, snowstorms, and severe acute respiratory syndrome (SARS), and further, to seek applicable solutions to mitigate the impacts.

Analysts are confronted, however, with many challenges in conducting a socioeconomic-impact evaluation of yellow-dust storms. First, yellow dust may reach every corner of a region and involve almost all industries. In most cases, dust storms actually do not result in mortality or severe infrastructure damage, which are evident in other disasters, such as earthquakes, fires, and floods. Thus, common disaster-assessment techniques may not be applicable to evaluating the socioeconomic impacts of dust storms. Second, in addition to the unknown extent of negative effects, scientists have also suspected possible benefits of yellow dust, such as neutralization of acid rain, absorption of part of the heat from sunshine, and prevention of the occurrence of photochemical smog. This has further complicated any quantitative analysis of dust storms. Third, although yellow-dust storms can cause significant monetary or physical losses to a regional economy, officials in China excluded dust storms from China statistical yearbooks until 2004 (China Meteorological Administration, 2004, 2006). The China Meteorological Administration, State Forestry Administration, State Environmental Protection Agency, Ministry of Internal Affairs, and several newly founded agencies all have the function of analyzing the information regarding dust storms and managing the associated problems. Nevertheless, none of the individual agencies provides a database for yellow-dust storms. Consequently, analysts can gather data only from the limited information published online or in newspapers, or from individual studies in a few regions.

On the basis of such second-hand information, we conduct a case study in Beijing for 2000 with three objectives: (1) integrate economic, environmental, and social impacts of yellow-dust storms into a regional economic framework; (2) measure the impacts of yellow-dust storms in 2000 on Beijing's economy; and (3) discover possible policy implications of the quantitative analysis results. We select Beijing for our case study because scholars have accumulated more information in this capital city than in any other region in China. We believe this could be a good starting place, because Beijing is probably more economically vulnerable to yellow-dust storms and is likely to be affected in more ways than other less-developed regions in China. Furthermore, because one dust storm usually lasts for only a few hours, but several may occur in one day, analysts have difficulty distinguishing successive occurrences, especially for their long-term effects. Consequently, we evaluate the total impacts of all occurrences of dust storms in 2000, instead of any single one. In addition, we ignore those delayed impacts only apparent after one year, because we had access only to a static 1999 input–output table for Beijing.

We discuss in the next section the application of input–output techniques in evaluating the economic impacts of yellow-dust storms, and in the third section we briefly introduce the environmental-economic evaluation techniques that we adopted to integrate the manifold impacts into a regional economic framework. The fourth section presents our data-preparation process for a regional input–output analysis, as we employ these techniques and develop several other approaches to ascribe a monetary value to the direct impacts of yellow-dust storms. Using the results from the fourth section, in the fifth section we use our modified input–output model to measure the total economic impacts of yellow-dust storms on Beijing's economy in 2000, from both demand and supply sides. We conclude with a sensitivity analysis in the sixth section, along with a discussion of our calculation results. Because this is a preliminary analysis with extremely limited data, the primary purpose of our study is to develop a conceptual model applying feasible methodologies, rather than to produce precise numerical results. Policy analysts may use and further improve our research framework to evaluate the comprehensive impacts more accurately, or to measure the economic impacts of other phenomena with similar properties.

2. Application of Input–Output Techniques for Socioeconomic-impact Evaluation of Yellow-dust Storms

The input–output technique is commonly used for economic-impact analyses, because it incorporates detailed information on a sectoral basis, thus showing accurate results in evaluating both tangible and intangible economic impacts on a regional level. We believe that such a sectoral perspective, compared with other available socioeconomic-impact evaluation techniques, may best clarify and systemize the manifold impacts of yellow-dust storms exhaustively and accurately when data are available.

Given that lessened demand from affected sectors (e.g. households) may diminish production in other sectors after dust storms, analysts may trace the demand-driven effects on a region's output by the changes in final demand. This traditional method, however, cannot capture all the economic impacts of dust storms, because some sectors apparently affected by dust storms may not change the demand from other industries. For example, outdoor vendors who sell newspapers or fruits need to make new orders for the next day's sale, instead of selling outdated goods held up due to dust storms; construction activities may be disrupted during a strong storm, but the amount of raw materials and utilities needed may not change for a year-long project; agricultural products may be damaged only after farmers have invested in the seeds, fertilizer, and other farming facilities, or even after the sowing season. In fact, these sectors may provide less to other sectors and, subsequently, less to the whole region. After identifying this aspect, we maintain that it is necessary to distinguish and evaluate the economic impacts caused by dust storms not only by demand-driven effects, but also by supply-constrained effects.

Measurement of supply-constrained effects, however, is still controversial (Giarratani, 1976; Hoover and Giarratani, 1984; Bon, 1986; Oosterhaven, 1988, 1989; Dietzenbacher, 1989, 1997, 2001; Gruver, 1989; Miller, 1989; Rose and Allison, 1989; Dietzenbacher and van der Linden, 1997; de Mesnard, 2002; Cai and Leung, 2004). Mathematically, the counterparts of the row calculations in a demand-driven model are column calculations, as in Ghosh's (1958) allocation model, which was later interpreted as a supply-driven, supply-constrained, or supply-side model (see for example, Augustinovics, 1970; Cartwright *et al.*, 1982; Bon, 1986). However, economists represented by Oosterhaven (1988, 1989) argue that the supply-driven model developed by Ghosh (1958) is 'theoretically implausible' mainly because the model would allow production increases without additional requirements for labor and capital. Some researchers follow this argument and conclude that the Ghosh model cannot be interpreted in a 'physical, causal sense' (Dietzenbacher and van der Linden, 1997; Gallego and Lenzen, 2005) and Dietzenbacher (1997, 2001) proposes an interesting remedy by interpreting Ghosh's model as a price model instead of a quantity model. Despite the debates, researchers tend to agree on a 'descriptive' usage (Gallego and Lenzen, 2005) of the Ghosh model for 'a reasonable approximation' (Gruver, 1989) to cost-minimizing production, and thus interpret the results as 'potential output decreases' or 'vulnerabilities' (Cartwright *et al.*, 1982). With these arguments in mind, we believe that it is still applicable and useful to consider the supply-constrained model in our case study if we interpret the results with caution. Our case study may also serve as an empirical example to elicit improvements by regional economists to supply-side analyses.

The latest Beijing input–output table available during our research is for 1999. Because the industrial structure in Beijing did not change dramatically from 1999 to 2000, we use the 1999 table for conducting regional economic-impact analyses in 2000. It is a single-region table with 49 intermediate sectors and with a final demand sector composed of households and other final-demand components. The table has complete statistical information for intermediate and final demand transactions. Although it can provide us with basic requirements for input–output analysis, we make two important modifications.

First, we aggregate the 49 sectors in the original table to 15, as it is impossible to determine the differences, presumably small, in impacts among 49 sectors, due to limited data and information. Because industries in some broad categories of sectors have similar consumption and production relationships and appear affected by dust storms in similar ways, we assume that such an aggregation (see Table A-1 in the Appendix) does not compromise our calculation results, but it does simplify our analysis.

Second, we transform the open input–output model into a partially closed one, treating households as endogenous to the regional economy. This approach is important because households are affected by dust storms in many ways, such as property loss, health impacts, and corresponding increases in expenses and workday losses. In addition, the household sector plays an important role as the supplier of labor and can consequently induce ripple effects in a regional economy. Therefore, we use the 1999 Beijing 16-sector input–output table, with households as the 16th row and column (see Table A-2 in the Appendix) to quantify the economic impacts of dust storms from both demand and supply sides.[3] To distinguish the matrices that we use in our partially closed model from those of an open model, we mark an asterisk after the symbols, such as $\mathbf{A}^*$ (augmented matrix of direct-input coefficients) and $\mathbf{F}^*$ (augmented matrix of the allocation coefficients).

3. Integration of Environmental-economic Evaluation Techniques

Because traditional input–output models normally do not capture non-economic or environmental aspects of yellow-dust storms, we have also incorporated environmental-economic evaluation methods into our economic analysis, mainly including a dose-response analysis, market-value, and human-capital methods.

A dose-response analysis is 'a component of risk assessment that describes the quantitative relationship between the amount of exposure to a substance and the extent of toxic injury or disease caused by such a substance' (SRA, 2003). We use the findings of the ECON Center for Economic Analysis (2000) on health impacts from pollution, and compile the research results by Aunan and Li (1999), the European Commission (EC, 1998), the World Health Organization (WHO, 1999), and the Asian Development Bank (ADB, 1996). Their results indicate that corresponding to every one-microgram increase in particulate matter of 10 microns or less (PM_{10}) per cubic meter in the atmosphere, in one year, from 0.003% to 0.02% more people exposed to it will make an emergency hospital visit and from 0.2% to 0.6% more workers will incur workday losses. This finding enables us to estimate the number of people affected and corresponding workday losses by examining the change in the concentration of PM_{10} during dust storms.

The market-value method, as its name implies, evaluates economic impacts by multiplying the losses in productivity by the market value. We adopt this approach to quantify the impacts of yellow-dust storms on agriculture, referring to the research findings of Chameides and his team that the high concentration of fine particles is 'currently depressing optimal yields of about 70% of the crops grown in China by at least 5–30%' (Chameides *et al.*, 1999, p. 13626). Using the sectoral output as a substitute for the market value of the crops, we are able to proceed with our estimation.

The human-capital method is used by analysts to ascribe a money value to the health impacts on working people exposed to environmental pollution. Because yellow-dust storms rarely involve mortality, we adopt this method mainly for measuring the economic loss of workdays interrupted during dust storms. We first rely on dose-response functions to estimate the total number of workday losses; then, we multiply the result by the value that the workers would have produced per day if storms had not occurred, using Beijing's Gross Domestic Product (GDP) per capita per day as a substitute.[4]

4. Identification and Evaluation of Direct Impacts of Yellow-dust Storms

In addition to a few transportation statistics recorded in Duan and Zhang (2001, p. 364), we identified direct impacts by exploring second-hand data mainly compiled by NFBC (2000) and Zheng *et al.* (2000). The single occurrence of a dust storm with at least a skeleton of information for socioeconomic analysis was on April 6, 2000. All the records largely show immediately visible impacts that occurred on the day of the dust storms; we thus call them 'immediate impacts.' We define those impacts that are revealed or even strengthened only after a certain period after the dust storms as 'delayed impacts.' By this categorization, immediate and delayed impacts together add up to the direct impacts of yellow-dust storms.

Although we have the basis to measure immediate impacts of a single event (on April 6, 2000), we need to estimate immediate impacts of other occurrences of dust storms and all delayed impacts. To capture the comprehensive impacts of dust storms without limiting the analysis to those with concrete statistics, we have explored the following three methods to make the estimations.

First, connecting impacts of yellow-dust storms with meteorological records. Because socioeconomic data on the other dust storms (aside from the one on April 6) in Beijing in 2000 are incomplete, we connect the impacts of yellow-dust storms with meteorological records. Scientific studies show that dust storms can only occur with the coexistence of three factors – strong winds, source of sand (such as dust and sand from bare land), and thermally unstable air (see, for example, Gao *et al.*, 2000; Zhu and Zhou, 2002). We accordingly assume that the higher the speed of wind velocity and the higher the concentration of particles (PM_{10}) during a dust storm, the more severe the socioeconomic impacts would be. With reference to our evaluation of the dust storm on April 6, 2000, on the basis of actual socioeconomic records, we can estimate the economic impacts of other dust-storm occurrences by comparing the environmental conditions recorded by Beijing Meteorological Bureau.

Second, balancing positive impacts with negative ones. In addition to the negative impacts caused by the high concentration of particulates and strong winds accompanying yellow-dust storms, scientists have suspected that there could be positive effects, such as decreases in pollutants of ozone (O_3), nitrogen oxide (NO_x), and sulfur dioxide (SO_2), which are absorbed by dust particles to an unspecified extent. Without adequate scientific support, we assume on the basis of field observations that the positive impacts of dust storms are not apparent in the immediate term; in the long run, negative impacts of PM_{10} play a dominant role,[5] but they may be offset slightly by positive impacts. Given that the coefficients of dose-response functions are designed for evaluating the severity of pollution – that is, the higher the coefficient, the more severe the negative impacts – we have selected the mid value for the indicator of emergency visits and the lowest value for the indicator of workday losses. That is, we assume a 0.011% increase in emergency visits of all population in one year and a 0.2% increase in workday losses per microgram increase of PM_{10} per cubic meter atmosphere.

Third, incorporation of long-term effects of yellow-dust storms. From the scientific literature, we find that, in the long run, the dust particles primarily affect three sectors: agriculture, manufacturing, and households. To incorporate the impacts of the damage in agriculture, defects of sophisticated-equipment manufacturing, and workday losses of households, we locate some general findings on particulate pollution from the environmental literature and make some adjustments to take into account the positive impacts. We further adopt the market-value method and dose-response analysis to ascribe a monetary value to these environmental impacts. Because many environmental impacts are not significant in one year and the input–output table available is only for a one-year period, we exclude the impacts existing after one year. In Table 1, we summarize the immediate and the delayed long-term impacts that we evaluate in our case study in Beijing. Our estimated results show that dust storms in Beijing in 2000 may have resulted in a considerable decrease in the output of Agriculture, Manufacturing, Construction, Transportation, Trade and Catering Services, accompanied by a fall in household expenditure for that year.

In total, these direct impacts add up to 2,195.1 million renminbi (RMB), or US$264.5 million, one-quarter of which are caused by immediate impacts, while three-quarters are caused by delayed impacts (see Table 2). Regarding each individual sector examined, the manufacturing sector appears to have lost the most (855.3 million RMB), with the agriculture sector close behind (788.4 million RMB). In absolute percentage terms (75% of the total direct impacts), these sectors show greatest losses from delayed impacts gradually generated throughout the year. Although being affected only during dust storms, trade and catering services along with construction sectors also undergo significant impacts (295.8 million RMB and 227.2 million RMB, respectively). The direct impacts on the

Table 1. Economic impacts of yellow-dust storms in Beijing in 2000 to be evaluated

Sub-categorization	Affected sectors	Recorded/estimated impacts	Evidence/source	Evaluation method
Immediate impacts	Construction	Nearly 60 million square meters of construction sites shut down.	Zheng *et al.* (2000)	Market-value approach
	Transportation	1. Air Transportation: 48 flights were cancelled, 9 flights returned, 52 landing flights were transferred, and altogether 129 flights delayed. 2. Road Transportation: An increase in road accidents of 20-30% over normal conditions.	Duan and Zhang (2001, p. 364)	
	Trade	Outdoor vendors closed business much earlier than usual.	*China Youth Daily*, April 7, 2000. Quoted from NFBC (2000, p. 16)	
	Households	Emergency hospital visits increased for eye infections.	*China Economic Daily*, April 7, 2000. Quoted from NFBC (2000, pp. 12–13)	Dose-response analyses
Delayed Impacts	Agriculture	High concentrations of particulates depressed optimal yields of about 70% of the crops grown in Beijing by 5%.	Adjusted based on the findings of Chameides *et al.* (1999).	Market-value approach
	Manufacturing	Particulates may have caused a 1% decrease in product yield of sophisticated-equipment manufacturing.	Only one article (Peng, 2000) presented a numerical analysis, which briefly mentioned that less than 5% of product defects are caused by human and environmental effects. Taking account of possible positive effects caused by decreases in O_3, NO_x, and SO_2 after dust storms, we assume that particulates do not significantly increase product defects and only lead to a 1% decrease in product yield.	Market-value approach
	Households	There was a 0.2% increase in workday losses per $\mu g/m^3$ of PM_{10}.	Lower value selected from dose-response functions.	Dose-response analyses

Source: Ai (2003).

Table 2. Summary of direct impacts of yellow-dust storms in Beijing in 2000

Affected sectors	Immediate impacts	Delayed impacts	Total direct impacts	Percentage of total direct impacts (%)
	Thousand RMB			
Agriculture	N.A.	788,412	788,412	35.9
Manufacturing	N.A.	855,268	855,268	39.0
Construction	227,174	N.A.	227,174	10.4
Transportation	26,898	N.A.	26,898	1.2
Trade and Catering Services	295,802	N.A.	295,802	13.5
Households	460	1,185	1,645	0.0
Total	550,334 ($66.3 million)	1,644,865 ($198.2 million)	2,195,119 ($264.5 million)	100.0

N.A.: not applicable.
Source: Ai (2003).

transport sector (26.9 million RMB) are less significant compared with other affected sectors. In terms of the household sector, our estimation of both immediate impacts (0.5 million RMB) and delayed impacts (1.2 million RMB) in a one-year period appears to be small, because they comprise only part of many aspects of human health that cannot be evaluated with currently available data and methodology. These numerical results of direct economic impacts on an individual sector basis enable us to examine the inter-sectoral interactions by using the modified input–output model.

5. Input–Output Calculations and Analyses

5.1. Calculations of Total Impacts Caused by Demand-driven Effects

With an initial decrease in affected sectors' output caused by yellow-dust storms, less input would be required (and thus needs to be produced). This paper measures the subsequent (direct and indirect) effects after the initial effect has occurred, following the common practice of evaluating total economic impacts by demand-driven analysis.[6] We multiply the Leontief inverse of the direct requirement matrix, $(\mathbf{I}-\mathbf{A}^*)^{-1}$, by direct economic impacts, which has the same effect as an exogenous decrease in the exports (one component in final demand). In absolute value, the manufacturing, agriculture, trade and catering services, household, and construction sectors are the sectors that experience the greatest total impacts in Beijing (Table 3), comprising nearly 90% of the total in the region as a whole. As a proportion of a sector's total output, however, the agriculture sector is the most severely affected (with a loss of 5.2% of its total output). Although our estimation of the impacts on the mining sector (61.9 million RMB) is not among the top ones, it is equivalent to 2.2% of its sectoral output – the second largest percentage rate among all sectors. The third largest share (1.8%) is for the trade and catering services sector. The other sectors, almost evenly affected, show much less evident losses through demand-driven effects (0.1–0.4% of their sectoral output).

Table 3. Approximated impacts of yellow-dust storms on each sector of Beijing in 2000

No.	Sector	Sectoral output in 1999 (Million)	Impacts caused by demand-driven effects (DDE): Total sectoral impacts (Million)	DDE: Sectoral impacts/ Total DDE (%)	DDE: Impacts/ sectoral output (%)	Impacts potentially caused by supply-constrained effects (SCE): Total sectoral impacts (Million)	SCE: Sectoral impacts/ Total SCE (%)	SCE: Impacts/ sectoral output (%)
1	Agriculture	18,208.9	946.8	23.5	5.2	1,136.7	8.1	6.2
2	Mining	2,844.3	61.9	1.5	2.2	29.4	0.2	1.0
3	Manufacturing	246,847.4	1,681.7	41.7	0.7	5,317.8	38.0	2.2
4	ElecGasWater	11,224.9	34.4	0.9	0.3	96.3	0.7	0.9
5	Construction	66,445.0	230.7	5.7	0.3	1,404.9	10.0	2.1
6	TranSPT	27,306.6	114.5	2.8	0.4	407.5	2.9	1.5
7	Trade	25,153.5	445.8	11.1	1.8	711.6	5.1	2.8
8	Finance	62,022.3	86.3	2.1	0.1	695.9	5.0	1.1
9	Real Estate	6,032.3	7.3	0.2	0.1	112.0	0.8	1.9
10	Service	34,408.7	62.2	1.5	0.2	616.1	4.4	1.8
11	HealthSW	6,677.6	1.2	0.0	0.0	156.2	1.1	2.3
12	EduCulture	16,491.5	9.7	0.2	0.1	311.7	2.2	1.9
13	Science	24,682.2	38.4	1.0	0.2	278.9	2.0	1.1
14	Geology	636.7	0.6	0.0	0.1	11.4	0.1	1.8
15	GovOthers	12,690.3	24.6	0.6	0.2	282.0	2.0	2.2
16	Household	137,118.4	286.1	7.1	0.2	2,424.3	17.3	1.8
	Total	698,790.5 ($84,191.6)	4,032.3 ($485.8)	100.0	1.6*	13,992.7 ($1,685.9)	100.0	5.7*

Source: Ai (2003).

Notes: (1) US $/RMB = 8.3, in 2000 value. (2) Numbers with '*' are percentage of total economic impacts/gross domestic product (GDP) in Beijing in 2000, which was 246 billion RMB, or $29.6 billion (BMSB, 2001b). (3) The currency in this table is in RMB, unless otherwise noted.

Overall, our calculations show that the total economic impacts caused by demand-driven effects are 4,032.3 million RMB ($485.8 million, 1.6% of Beijing's GDP in 2000), which includes direct impacts, indirect impacts on other sectors due to decreases in demand during and after production disruption, and induced impacts, as shown in the household sector.

5.2. *Calculation of Total Impacts Potentially Caused by Supply Effects*

As discussed earlier, supply effects can be approximated by multiplying the Leontief inverse of the transpose of the direct-output allocation coefficients, i.e. $[\mathbf{I}-(\mathbf{F}^*)^{\mathrm{T}}]^{-1}$, by changes in value added of each sector.[7] Our calculations (Table 3) show that the total economic impacts caused by supply effects would be potentially 13,992.7 million RMB ($1,685.9 million), which is equal to 5.7% of Beijing's GDP in 2000. Compared with the impacts caused by demand-driven effects, Beijing's regional economy may have been affected more seriously through supply effects, in both absolute and percentage terms.

In absolute value, manufacturing and households are the top two sectors affected by dust storms, showing 5,317.8 million RMB and 2,424.3 million RMB (38.0% and 17.3% of the total economic impacts, respectively). When we examine the comparative value of each sector, the agriculture sector still shows the most serious internal economic impacts – 6.2% of its sector's output; the trade and catering services sector incurs the second-greatest economic impacts caused by supply effects, while the mining sector does not show an impact ranking as high as with impacts caused by demand-driven effects.

Although current techniques to measure supply-side effects do not provide us with accurate results to compare the economic impacts on each sector caused by demand-driven effects and supply effects, we find that the agriculture sector tends to bear the most serious impacts, far exceeding those of other sectors. Other sectors could be affected through inter-sector interaction very differently: some show larger losses through demand-driven effects, and some show the opposite. To study the underlying reasons for the differences in allocation of the indirect impacts among sectors, we conduct further linkage analyses below.

5.3. *Linkage Analysis*

On the basis of our modified Beijing 1999 input–output table, we calculate both backward and forward linkages for 16 sectors. We derive the total backward linkages (TBL) for each sector as the row of the column sums of the $(\mathbf{I}-\mathbf{A}^*)^{-1}$ (Leontief Inverse), and the total forward linkages (TFL) for each sector as the column of the row sums of the $(\mathbf{I}-\mathbf{F}^*)^{-1}$ (Ghosh Inverse). With only one exception, the forward linkages of each sector are all higher than its backward linkages. We also calculate the weighted average of both linkages, with the weights of both linkages as the share of each sector's input/output out of total input/output. We find that the average of the forward linkages is 5.451, about 3.5 times the average of the backward linkage (1.565). This shows that dust storms may affect the regional economy more heavily through forward linkages than through backward linkages. Furthermore, almost all sectors with high forward linkages (namely, agriculture, manufacturing, transportation, trade and catering services, and households) are all directly affected by dust storms. This causes the total economic impacts on Beijing's regional economy to be significantly higher than direct economic impacts.

We find that the two sectors with the highest backward linkages are the manufacturing sector (2.136) and the construction sector (2.022). They are also the only two sectors with backward linkages above 2.0, being 1.4 and 1.3 times the average, respectively. This implies that decreases in demand in the manufacturing and construction sectors, compared with all the other sectors, may result in the greatest losses to Beijing's regional economy; in contrast, increases in investment in these sectors may have the greatest potential power to augment the regional economy by requiring large quantities of goods and services from other sectors. Because yellow-dust storms do not involve large-scale remediation and mitigation activities afterwards, we infer that their impacts would not create a new round of investment activities on the manufacturing or the construction sectors, as generally happens after earthquakes and tornados. Thus, all the losses may be permanent, and the regional economy may not easily recover to its original level. From this perspective, the most effective and critical means to reduce the negative impacts of yellow-dust storms would be by focusing on prevention, in order to mitigate the impacts before they happen.

6. Sensitivity Analysis and Further Discussion

Acknowledging that our quantitative analyses involve a considerable number of estimates, we conduct a sensitivity analysis in order to determine a range of the total economic impacts. With different estimates, we find that the delayed impacts are always more serious than the immediate impacts: the lowest estimate of delayed impacts is still higher than the upper estimate of immediate impacts. Moreover, the range of delayed impacts is much broader than is that of immediate impacts, presenting the vast uncertainties for delayed impacts of dust storms. Through inter-sector analyses, we estimate that the total economic impacts caused by demand-driven effects range from 1.0% to 2.3% of Beijing's GDP in 2000, while the total economic impacts caused by supply effects range from 2.9% to 8.4%. This suggests that changes of input variables produce a much larger range of effects through the supply side than through the demand side.

Because demand-driven effects and supply effects are substantially intertwined, the total economic impacts on Beijing's regional economy are not the sum of these two. Although we acknowledge that additional studies are necessary to determine the upper bound, we can safely infer that the total economic impacts of the yellow-dust storm in Beijing in 2000 are greater than 2.9% of Beijing's GDP that year (the higher value of the lower estimates of economic impacts caused by demand and potentially by supply effects).

Although economic sectors are affected by dust storms differently through different mechanisms and at different temporal magnitude, we demonstrate in our analysis that the economic impacts on agriculture, construction, and manufacturing, as well as other sectors, can be very costly, although they may not be immediately apparent. Accordingly, we suggest that billions of dollars of annual investment in dust storm control should not be limited to reforestation, as is the current situation in China. The Chinese government should also encourage research on prevention measures, such as how to improve the technology to protect crops and sophisticated equipment from particulates, and how to depress the elevated dust from open construction sites. Such prevention measures may help avoid potentially high costs.

To conclude, we stress that the goal of this study is not to provide precise figures for policymakers' investment decisions, and we acknowledge that our study may incorporate some biases, such as the constraints of a single-region, one-year study, and the narrow perspective on human economic activities. We regard it as a starting point for an integrated economic-impact analysis across disciplines and a reference for other analysts to verify and improve, and have demonstrated in our case study the current knowledge gap in measuring the socioeconomic impacts of environmental events with similar characteristics to yellow-dust storms. With a sound research framework and additional data, analysts can subsequently improve both the research methodology and the data inputs, thereby enhancing the accuracy of the numerical results.

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Notes

[1]Because the origin of dust particles in China is mainly yellow-sand covered deserts, scientists interchangeably use the terms of 'yellow-dust storms' and 'dust storms' in the case of China.

[2]Source: China Dust Storm Net. http://www.duststorm.com.cn/script/ReadNews.asp?NewsID=204&BigClassID=23&SmallClassID=72.

[3]Although the Household Consumption column is presented in the 1999 Beijing input–output table we were provided, the information in the row of Labor Compensation is missing. We thus follow four steps in filling such information. First, we locate the statistical information necessary for the wage adjustment, including (1) the household consumption, (2) the savings of residents in Beijing in 1999, and (3) 1999 Beijing statistical data of household wages and salaries by sector. Second, we calculate the sum of household consumption spent on every sector (denoted by TC) and add TC to household savings (HS) and denote the sum as TCHS. We also calculate the sum of wages and salaries from all sectors (TW). Third, we compare the difference between TCHS and TW. We split the difference in each sector according to their weights, which we calculate by dividing each sector's wages by TW. Fourth, we add the split difference to the value of household wages and salaries. We take the values of adjusted wages and salaries as the proxy for Labor Compensation that we enter into the 1999 Beijing input–output table.

[4]Source: BMSB (2001a).

[5]This assumption is supported by World Bank (1997), which indicates that health costs of PM_{10} emissions make up 83% of environmental costs in China.

[6]Given that most regional input–output tables in the United States use region-to-region inputs for the intermediate transactions, we originally assumed that the Beijing table was constructed in the same way. A comment by one of the reviewers caused us to inquire more deeply into this issue, and we discovered that the Beijing intermediate inputs represent both regional inputs and inputs from outside the region. Given that the method to remove the imports and the available data would be only an extremely rough

approximation, we decided not to make any adjustment to the table. Given that a considerable portion of inputs in Beijing may be imported from other regions, some of the estimates, therefore, are probably larger than they would be if the inputs represented only local Beijing inputs.
[7]Source: BMSB (2001b).

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Appendix

Table A-1. Aggregation of sectors in the 1999 Beijing input–output table

No.	15-Sector aggregation	Abbreviation	Corresponding 49-sector aggregation
1	Farming, Forestry, Animal Husbandry and Fishery	Agriculture	1. Agriculture, 2. Forestry, 3. Fishery, 47. Services for farming, forestry, animal husbandry and fishery
2	Mining	Mining	4. Coal-selection, 5. Gasoline and natural gas extraction, 6. Metal mineral mining, 7. Non-metal ore extraction
3	Manufacturing	Manufacturing	8. Food production and cigarettes, 9. Textiles, 10. Clothing, leather, fur and other fiber production, 11. Wood processing and furniture manufacturing, 12. Papermaking and education-equipment manufacturing, 13. Petroleum and coke-making, 14. Chemistry, 15. Non-metal mineral products manufacturing, 16. Metal smelting and manufacturing, 17. Metal-products manufacturing, 18. Machinery, 19. Transportation-utility manufacturing, 20. Electric-equipment manufacturing, 21. Electronic and communications manufacturing, 22. Equipment and meter manufacturing, 23. Machinery repairing, 24. Other manufacturing, 25. Waste materials
4	Electricity, Gas, Water Production and Supply	ElecGasWater	26. Electric power supply, 27. Steam and hot water supply, 28. Gas supply, 29. Water supply
5	Construction	Construction	30. Construction
6	Transportation, Storage, Post and Telecommunications	TranSPT	31. Water transportation, 32. Other transportation and warehouse, 33. Post and telecommunications, 36. Water passenger transportation, 37. Other passenger transportation
7	Wholesale, Retail Trade and Catering Services	Trade	34. Commerical, 35. Catering trade
8	Finance and Insurance	Finance	38. Finance and insurance
9	Real Estate Trade	Real Estate	39. Real estate trade

(*continued*)

Table A-1. Continued

No.	15-Sector aggregation	Abbreviation	Corresponding 49-sector aggregation
10	Social Services	Service	40. Public utilities, 41. Residential services, 42. Other social services
11	Health Care, Sports and Social Welfare	HealthSW	43. Health care, sports and social welfare
12	Education, Culture, Art, Radio, Film and Television	EduCulture	44. Education, culture, arts, radio, film and television
13	Scientific Research and Polytechnical Services	Science	45. Scientific research, 46. Polytechnic services
14	Geological Prospecting and Water Conservancy	Geology	48. Geological prospecting and water conservancy
15	Government Agencies, Party Agencies, Social Organizations and Others	GovOthers	49. Administrative agencies and others

Source: The list of 49 sectors is presented in the 1999 Beijing 49-sector input–output table, provided by Professor Xikang Chen at the Institute of System Science at the Chinese Academy of Sciences in Beijing, in March 2002. The abbreviation and aggregation of sectors are determined by the authors.

Table A-2. 1999 Beijing 16-sector input–output table, including households

	Purchasing Sectors															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
No	Agri-culture	Mining	Manufac turing	ElecGas Water	Cons-truction	Tran SPT	Trade	Finance	Real Estate	Service	Health SW	Edu Culture	Science	Geology	Gov Others	House-hold
Producing sectors																
1	3,540	1	7,163	0	0	0	565	0	10	22	18	0	2	0	0	6,063
2	53	340	10,802	559	1,094	21	38	0	79	168	15	33	42	5	24	547
3	2,510	360	121,482	1,554	32,925	7,382	4,075	8,846	696	6,411	2,751	1,460	2,820	76	1,794	35,526
4	285	97	3,110	199	300	306	540	690	193	764	66	135	299	10	165	3,926
5	5	2	113	30	9	83	109	261	73	1,590	46	23	62	2	131	0
6	282	73	10,242	461	3,177	2,504	1,168	2,068	225	1,376	146	1,681	658	18	1,412	1,731
7	1,440	80	15,592	507	4,380	1,260	714	1,962	214	1,109	605	251	341	17	477	10,996
8	111	98	9,674	419	657	2,746	1,276	10,729	2,090	761	15	543	213	69	1,749	9,928
9	0	5	223	0	12	43	388	2,830	59	212	14	8	32	0	66	568
10	39	166	5,505	99	2,887	709	1,536	8,120	345	4,058	46	394	690	42	545	2,277
11	2	1	34	2	17	44	16	11	6	201	116	68	127	0	66	1,028
12	17	9	365	41	186	173	287	1,579	17	252	31	2,158	1,203	19	368	2,892
13	39	15	4,937	428	1,517	154	875	145	55	485	3	812	1,960	35	115	0
14	3	38	0	0	0	0	0	0	0	19	0	0	0	16	0	0
15	592	0	28	1	987	288	0	247	31	1,921	105	20	152	19	110	56
16	520	491	21,954	1,208	10,224	4,929	10,356	2,940	2,855	13,562	3,842	10,224	7,220	332	9,136	37,326

Source: The 1999 Beijing 49-sector input–output table was provided by Professor Xikang Chen at the Institute of System Science at the Chinese Academy of Sciences in Beijing, in March 2002. The 16th row and column are modified by the authors. Endnote No. 3 provides the methods of modification. Unit: Million RMB.