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Panama Canal drought and supply chain disruptions in Asia-United States trade: Evidence from micro-level trade shipments and vessel trajectory data

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PANAMA CANAL DROUGHT AND SUPPLY CHAIN DISRUPTIONS IN ASIA–UNITED STATES TRADE

EVIDENCE FROM MICRO-LEVEL TRADE SHIPMENTS
AND VESSEL TRAJECTORY DATA

Paul H. Jung, Kijin Kim, Ah-Hyun Jo, and Joseph Seong-Hyun Cho

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ABSTRACT

Global chokepoints such as the Panama Canal propagate drought shocks into supply chains, yet disruptions to shipments remain poorly investigated. We examine the impact of supply chain disruptions induced by the 2022–2023 Panama Canal drought on Asia–United States (US) trade flows. We fuse Automatic Identification System vessel trajectories with US Customs Bills-of-Lading, matching 95% of 29.6 million 2022–2023 filings to 48 million hourly vessel positions. Difference-in-differences and event study analysis results present that canal voyages of containerized shipments took 133.8 hours longer, spent 33.6 hours more stopped, and sailed 2.3 kilometers per hour slower, with route distance unchanged, and these disruptions more than reversed normal-time efficiency gains. Shipment times for metallic raw materials and light manufacturing shipments increased markedly, and there was no significant effect on food products. The results provide a robust foundation for valuing delay-induced opportunity costs and designing resilient trade-facilitation policies for export-oriented economies in Asia.

Keywords: Panama Canal drought, maritime chokepoints, global supply-chain disruptions, Asia–US container trade, transaction-level trade data

JEL codes: F14, R41, Q54, C23

1. INTRODUCTION

Global chokepoints are geographically unique passages in global transportation that offer indispensable shortcuts, accelerating voyages and compressing transport costs for a large share of world trade (Haralambides 2024; Rodrigue 2024). For example, the Suez Canal reduces the Rotterdam–Mumbai sea distance by about 41%, and the Panama Canal shortens a New York–Los Angeles all-water route by roughly 60% (Rodrigue 2024). Because these gateways concentrate flows, supply chains reap substantial efficiency gains while becoming more exposed to localized shocks (Rodrigue 2004; Ducruet 2016; Bailey and Wellesley 2017; Pratson 2023). Such dependence is especially pronounced at Suez and Panama, where the former has a significant share of global trade and the latter underpins a large fraction of Asia–US container movements (Ducruet 2016). This concentration creates a clear trade-off between logistic economies and systemic vulnerability. When any of these arteries encounters a physical or operational disruption, carriers must decide between lengthier detours and costly queues, shippers must revise schedules and buffer inventories, and many economies should face the macro-level fallout of higher delivered-goods prices (Pratson 2023; Wan et al. 2023; Verschuur and Hall 2024).

The 2022–2023 Panama Canal drought best exemplifies the extent to which critical trade supply chains are vulnerable to global chokepoints. In late 2022, an El Niño-linked rainfall deficit pushed Gatún Lake, in the middle of the passage along the Panama Canal, to its lowest wet-season level in nearly 3 decades (Panama Canal Authority 2023a). It constrained the Panama Canal’s lock-and-lake system, whose throughput depends on freshwater storage from Gatún Lake (Panama Canal Authority 2025). As the deficit persisted into 2024, effective vessel transits fell to roughly half of normal levels (UNCTAD 2024). This episode was one of the first in the canal’s recent operating history where water shortage forced continuous draft and transit restrictions and heavily disrupted vessel transits. The Panama Canal Authority (*Autoridad del Canal de Panamá*, or ACP) responded to drop in water levels with successive draft reductions and binding slot caps that lowered effective daily vessel passages. This successive operational tightening erased the canal’s normal-time speed advantage and created a clean setting to study how capacity shortfalls propagate through Asia–US trade supply chains.

Previous research has highlighted the macroeconomic significance of the Panama Canal (Huebner 1915; Gibbs 1978; Ungo and Sabonge 2012; Park, Richardson, and Park 2020) and, more recently, the bottleneck effects of temporary closures or accidents in other waterways, like the Suez Ever Given blockage (Fan et al. 2022; Wan et al. 2023). In a wider sense, previous literature consistently quantifies the substantial financial penalties associated with time delays and disruptions along trade supply chains. Gravity model analyses established that delays are costly, demonstrating that an extra day of shipping

time can reduce trade by over 1%, with the tariff-equivalent time cost estimated to range from 0.6% to 2.1% per day in transit (Djankov, Freund, and Pham 2010; Hummels and Schaur 2013). At the macroeconomic level, structural models with input-output linkages and inventory frictions illustrate that increases in shipping times are generally contractionary, raise prices, and increase stockouts, operating functionally as negative productivity shocks across the economy (Rose and Wei 2013; Pant, Baker, and Landers 2015; Alessandria et al. 2023; Bai et al. 2024). Specific chokepoint crises confirm these costs. The 2021 Suez Canal blockage froze an estimated \$10 billion in trade each day (Fan et al. 2022; Pratson 2023; Wan et al. 2023; Haralambides 2024). Conversely, investments like the 2016 Panama Canal boosted trade between connected country pairs by 9%–10%, illustrating the strategic leverage of canal capacity (Park et al. 2020; Heiland et al. 2025). Yet we still lack shipment-level, causal evidence on how a hydrological capacity shock at Panama redistributes time costs across routes and commodities.

Transportation researchers assess system vulnerability of global chokepoints using complex network models to simulate failures and evaluate changes in network connectivity and capacity (Ducruet 2016; Achurra-Gonzalez, Angeloudis et al. 2019; Rousset and Ducruet 2020; Wan et al. 2023). Such models seek to quantify operational consequences like additional handling costs and non-delivery penalties (Achurra-Gonzalez, Angeloudis et al. 2019; Achurra-Gonzalez, Novati et al. 2019). The growing use of high-frequency Automatic Identification System (AIS) data enables empirical analysis, providing metrics to track congestion, speeds, and waiting times (Verschuur et al. 2020; Bai et al. 2024; Chico et al. 2024, 2025; Verschuur and Hall 2024; Fuentes and Munim 2025). AIS analysis of the 2021 Suez Canal blockage confirmed severe consequences, like decreased network accessibility, rerouting around the Cape of Good Hope, and the substantially increased carbon footprint of affected container ships (Wan et al. 2023; Yue et al. 2024). However, while port substitution could be a potential resilience option, empirical analysis suggests it is rarely observed during short-term disturbances because neighboring ports are often simultaneously affected and because specialization limits substitutability (Rousset and Ducruet 2020; Verschuur et al. 2020; Hamano and Vermeulen 2021). Crucially, the literature recognizes that climate change introduces severe hazards; for instance, drought severely restricts the Panama Canal's capacity by limiting water levels, leading to draft restrictions and lower transit numbers (Bailey and Wellesley 2017; Becker et al. 2018; Chico et al. 2024).

Despite the Panama Canal's importance to global trade and high climate sensitivity, empirical investigation into the consequences of disruptions specifically affecting this crucial chokepoint remains limited and requires more extensive work (Ducruet 2016; Chico et al. 2024; Fuentes and Munim 2025). To fill the gap in the literature, using the Panama Drought in 2022–2023 as a natural experiment, we answer the following interrelated questions that have not been explored in previous studies: (i) How important

but vulnerable are the global chokepoints like the Panama Canal in global supply chains, especially for Asia–US trade? (ii) During the 2022–2023 drought, how large are the shipment-level time penalties imposed by the freshwater shortage in the Panama Canal? (iii) Do those penalties fall evenly across commodities, vessel classes, and US coastlines, or are certain trades disproportionately exposed? (iv) Does delay stem primarily from queuing and reduced cruising speeds, or from extended diversions via alternative passages? By answering these questions, we assess the critical importance of the Panama Canal in the Asia–US trade supply chains and examine the impact of the climate-related disruptions at global chokepoints.

We address these questions by leveraging micro-level big data about disaggregated trade shipments and cargo-ship movement trajectories. Given gravity of the event, we consider the Panama Canal Drought as a natural experiment to test the centrality of the chokepoints in trade supply chains, especially Asia–US trade and treat 2022 as a normal baseline and 2023 as drought years. We construct the shipment-level containerized cargo data that combines AIS vessel trajectories of 48 million point locations with transaction-level 29.6 million US Customs Bills-of-Lading (BoL) records. With 95% matching rate, the merged data base covers 28.2 million containerized shipment records and 2.4 million voyage segments between January 2022 and December 2023, matched to 2,501 containerships. We exploit the decrease in Gatún Lake’s water level that commenced in January 2023 as an exogenous supply shock. Based on geospatial analysis on this combined shipment data, we trace each shipment’s fine-level voyage trajectories and identify shipments that transit the Panama Canal and those do not before and after the drought. A difference-in-difference (DiD) estimation approach compares shipments that passed the Panama Canal and those did not and were routed via the Suez Canal or the North-Pacific corridor. An event study model traces the month-by-month time-varying impact of the penalty by the drought. Finally, subgroup analysis with commodity types reveals the distributional footprint of the shock.

Our results present that, relative to the predrought baseline, container voyages that continued to use the canal now take 5.54 days longer, sail 2.32 kilometers per hour (km/h) slower, and spend an additional 33.6 hours in anchorage or lock queues, while average voyage distance remains unchanged. The mechanism is congestion and deliberate speed management, not large-scale rerouting: in the average case, routes stayed the same but took longer. Crucially, the drought offset the canal’s normal-time advantage: in the pre-period, transiting Panama reduced duration by 150.27 hours (12.45%), cut distance by 1,448.42 km (5.73%), and raised speed by 1.53 km/h (7.57%) relative to non-Panama routings. During the drought, those benefits were neutralized by the post-event penalty, leaving the net effect on duration and speed at approximately zero. When looking into shipping patterns by commodity type, the penalty is far from uniform. Delays for shipments of machinery and mechanical products and of metallic raw materials were

about 2–3 percentage points longer than the overall mean, whereas food cargoes and petroleum-oil products show no statistically significant slowdown. As disruption shocks are revealed to eliminate the canal's normal-time advantage, our results directly point to the necessity for trade facilitation policies and climate-risk planning for shipping services incorporating flexible routing optionality.

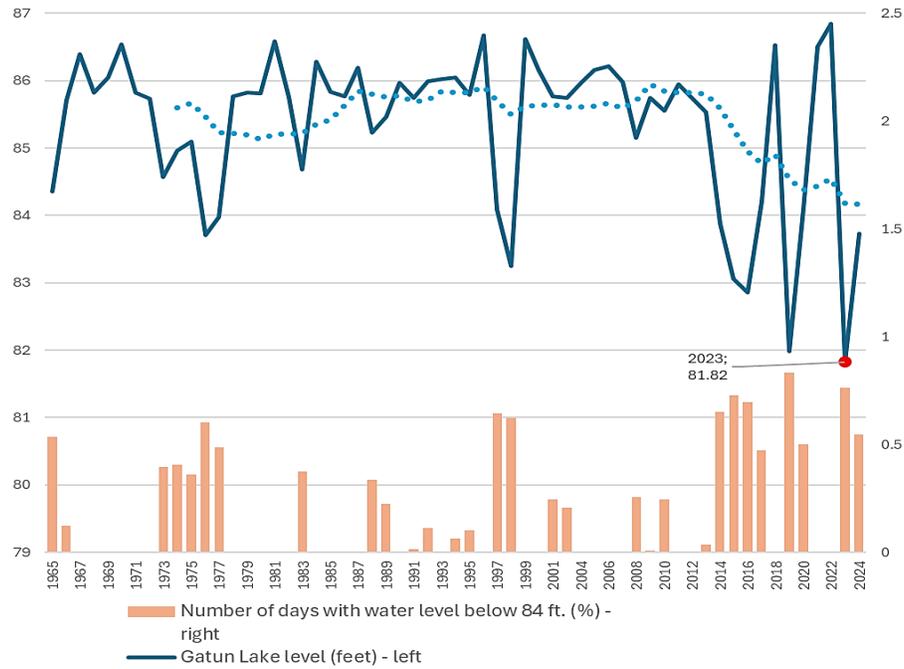
2. BACKGROUND: THE PANAMA CANAL DROUGHT

The Panama Canal is a critical chokepoint for Asia–US trade supply chains. While the canal handles roughly 5% of global seaborne tonnage, 70% of its traffic either originates from or is bounded to the US (UNCTAD 2024). In fiscal year 2023, routes linking Asia, Oceania, and the wider Pacific accounted for more than 53% of all tonnage that traversed the Panama Canal (Panama Canal Authority 2023b). The US remains the dominant counterpart, with nearly 70% of total canal traffic either originating in or destined for US ports, while the People's Republic of China is the single biggest non-US user, representing 22.5% of total cargo volume, followed by Japan, the Republic of Korea, and a cohort of other export-oriented Asian economies. Without the Panama Canal, carriers must choose between a detour via Suez and the Atlantic, adding 10–14 days or costlier transcontinental rail bridges for Asian container traffic headed for the East and Gulf coasts of the US.

For the stable operation of the Panama Canal, freshwater availability is highly essential. The Panama Canal operates as a lock-and-lake system, where each lockage consumes large volumes of freshwater that must be replenished seasonally (Panama Canal Authority 2025a). Gatún Lake is a primary freshwater source for canal operations and keeps vessel traffic flowing (Panama Canal Authority 2016). For this reason, when precipitation falls short, the ACP is forced into trading off the permitted vessel draft against the number of daily transits (Panama Canal Authority 2023c). With a water shortage, the canal can save water either by lowering the allowed draft or limiting the number of daily transits. While a lower draft constrains heavy container ships first, transit caps create slot shortages. Either way, less rain should result in longer queues, slower passages, and schedule delays.

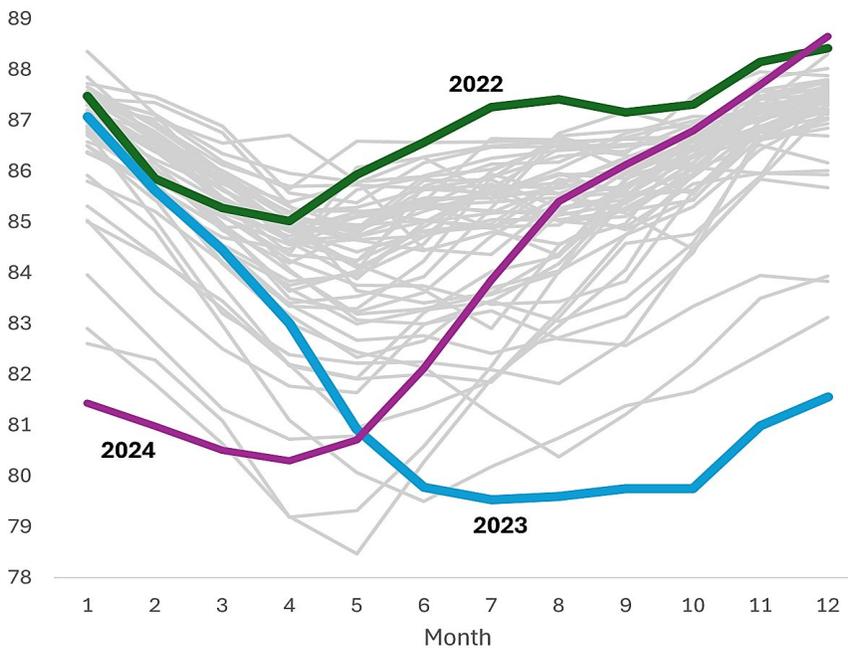
When the Panama Canal faced water shortage and drought beginning in late 2022, its importance in global supply chains was clearly revealed. A severe El Niño-linked rainfall deficit drove Gatún Lake to its lowest wet-season level in almost 3 decades. October 2023 was the driest October since 1950, with rainfall 41% below normal. The frequency and severity of canal-relevant droughts have increased in recent years (Figure 1). Within our study window, 2022 serves as the normal-hydrology baseline, whereas 2023 is the most severe drought year and 2024 remains drought-affected (Figure 2). These idiosyncratic deviations heavily affected canal operations throughout 2023 and 2024.

Figure 1: Annual Average Water Level of Gatún Lake, 1965–2024



Note: 1 ft = 0.3048 meter.
 Source: Panama Canal Authority (2025b).

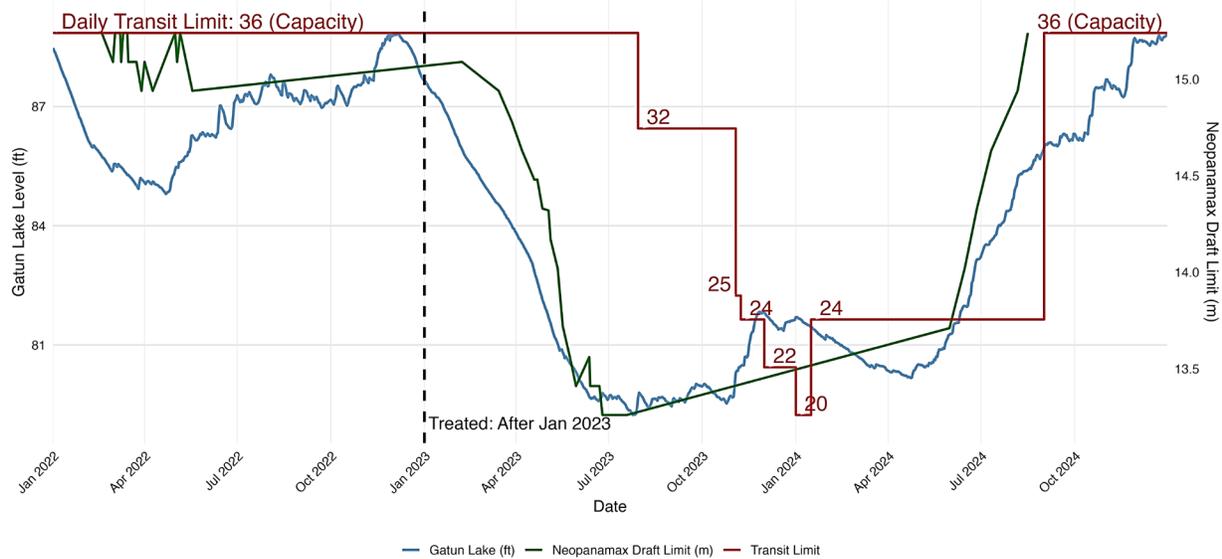
Figure 2: Water Level of Gatun Lake by Month, 1965–2024 (ft.)



Note: 1 ft = 0.3048 meter.
 Source: Panama Canal Authority (2025b).

Within our study window the operational response unfolded in phases. After rainfall fell below the trend from late 2022, the ACP progressively tightened operating parameters during 2023 (Figure 3). Since the water level of Gatún Lake started to decline drastically in January 2023, the maximum permissible drafts for Neopanamax traffic were stepped down from March 2023 (Panama Canal Authority 2023d). From 30 July 2023, total daily transits were capped at 32. As the drought intensified, ACP announced further sequential booking-slot cuts: 25 (3–7 November 2023), 24 (8–30 November 2023), 22 (December 2023), and 20 per day (January 2024) (Panama Canal Authority 2023a, 2023e). With some improvement in conditions and additional measures, ACP increased daily transits to 24 on 16 January 2024 and finalized the transit-cut measure by recovering transit capacity to 36 on 1 September 2024. These measures may have erased the canal’s normal-time speed advantage and turned a longstanding shortcut into a binding bottleneck.

Figure 3: Water Level of Gatun Lake and Draft and Transit Restrictions During the Panama Canal Drought, 2022–2024



Source: Panama Canal Authority (2025); US DOT Bureau of Transportation Statistics (2024).

Recent studies have begun to focus on the Panama Canal drought and assess the disruption mechanism at higher temporal and spatial resolution. Chico et al. (2024) propose an AIS-based indicator framework to monitor passageway performance and apply it to the 2023 drought to track transit operations, voyage delays, and port-call adjustments in near real time and diagnose transit capacity, waiting times draft limitations at the Panama Canal. In a similar vein, Fuentes and Munim (2025) show that “canal water times” are predictable from integrated environmental and operational covariates,

reinforcing the causal link between rainfall-related water shortage and throughput degradations. UNCTAD's rapid assessment situates Panama within a broader network of simultaneous shocks of the Red Sea Crisis and Black Sea rerouting (UNCTAD 2024). It shows how overlapping constraints lengthened routes and amplified schedule risk and cost pass-through even where the canal is not directly used. Together, these views hint that freshwater shortage may be a primary driver of canal reliability rather than a residual shock at the Panama Canal.

3. DATA

3.1 United States Customs Bills-of-Lading Data

In this research, we use the Port Import Export Reporting Service (PIERS) data base for the micro-level trade shipment data that anchor our empirical analysis. The PIERS data base collects the full set of seaborne bills of lading (BoLs) filed with US Customs and Border Protection. Every trade shipment that enters or leaves US territory is recorded in the PIERS, so it gives the data base census-level coverage of seaborne trade. Each BoL records the foreign port of lading, the US port of discharge, carrier and voyage identifiers, the shipper and consignee addresses, the number and size of containers, cargo weight, estimated customs value, and a Harmonized System code at the six-digit level. This detail permits sector, spatial, and temporal disaggregation that few alternative sources can match. Previous research has drawn on these attributes to map port hinterlands (Jung and Thill 2022), measure hub-and-spoke routing economies (Jung and Thill 2023; Ganapati, Wong, and Ziv 2024), and estimate route-choice elasticities amid security or geopolitical shocks (Kashiha, Thrill, and Depken 2016; Ganapati, Wong, and Ziv 2024; Jung, Thill, and Galvis-Aponte 2024).

A distinctive strength of PIERS data is providing the International Maritime Organization (IMO) number of a vessel when the shipment is unloaded on US port of entry for every BoL record. Since the IMO number is a unique identifier for vessels, this allows us to merge BoL records with AIS trajectory logs at the voyage level. The resulting linked dataset makes it possible to reconstruct each shipment's actual maritime path and measure realized sailing speeds. With this merge, it is possible to identify cargoes that genuinely transited the Panama Canal and those that did not transit the canal and were rerouted via Suez or the Pacific during the drought.

From a causal inference standpoint, PIERS offers other advantages. Its continuous time series enables rigorous pre-trend diagnostics and placebo tests on the same micro-unit used during treatment. Also, daily time stamps mean that we can align the event study design exactly with the APC-imposed phased draft and slot restrictions after January 2023.

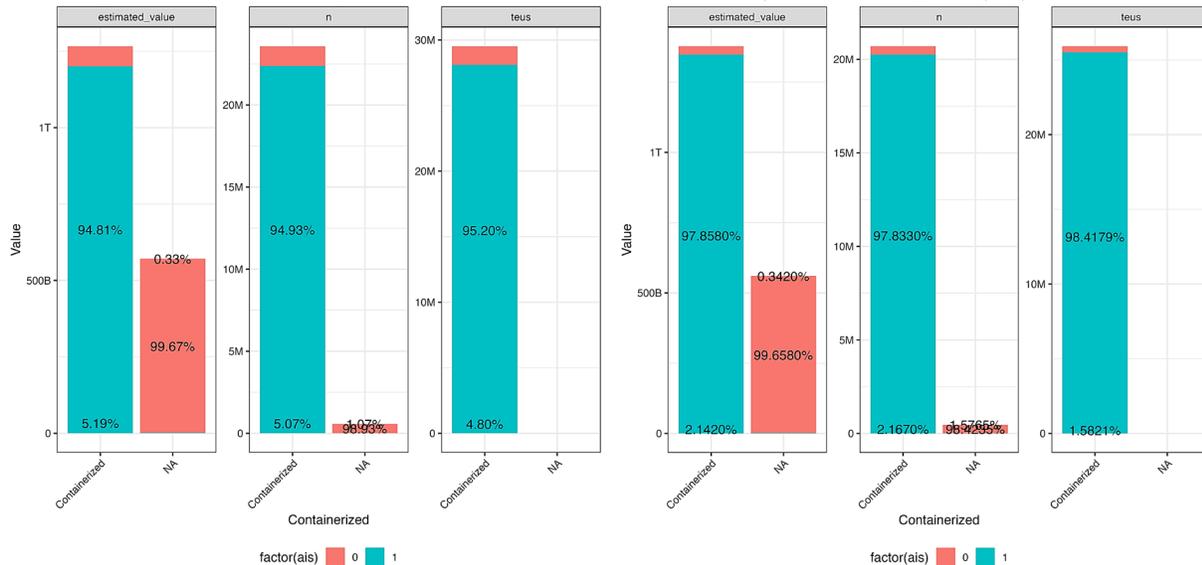
3.2 AIS Vessel Trajectory Data

To track the point-to-point movement of BoL shipments and represent their supply chain performance, we merge shipment records in PIERS with global AIS data. AIS is a satellite and shore-based transponder network that obliges every SOLAS-class vessel above 300 gross tonnages to broadcast its identity, position, speed, and course at intervals of a few seconds to several minutes. We acquired the complete stream of hourly AIS vessel location data for 2022–2023. Each message reports the unique IMO vessel identifier, with which we match to PIERS BoL records. This enables us to follow the exact trajectories of the vessels that carry shipments bound to the US.

We reconstruct voyages by splitting successive AIS trajectories of each ship into continuous series of segments with a speed filter of 1.5 km/h and by port calls. The resulting trajectory segments allow us to calculate voyage distance, total voyage duration, mean speed, and the time spent at anchor or in port (stopping duration). Because AIS provides information about the precise moment a vessel enters and exits the Panama Canal locks, we can measure queuing delays and lockage time directly and distinguish shipment that transit the canal and those that does not.

We combine AIS and PIERS data base for shipments by aligning the BoL filing date with the nearest port-call timestamp and enforcing consistency in the origin–destination pair. This AIS-BoL records’ match rate exceeds 95% for loaded containers (Figure 4). By

Figure 4: Matching Rate of AIS and PIERS Bills-of-Lading Data, 2022–2023



Note: Left: PIERS US import data matched to AIS data for 2022 (Column 1 – by estimated value of shipments, column 2 – by the number of shipments, column 3 – by TEUs [container unit]), Right: same for 2023

Source: Authors’ calculations.

transforming each BoL record into a spatio-temporal observation, we can capture each shipments' documentary attributes (commodity, value, weight) and voyage attributes (distance, duration, stop time). Consequently, with this combined AIS-BoL data, we can implement a DiD design that treats voyage delays as the outcome of interest while considering commodity, vessel, and seasonal fixed effects.

4. EMPIRICAL STRATEGY

4.1 Identification Framework

ACP's Gatún Water Level Indicators data show that Gatún Lake storage began to reduce and be deviated from the usual level in September 2022 (Figure 3). In response to the drought in the Gatún Lake, the ACP imposed the first draft cut of the Neopanamax Locks (from 15.24 m to 14.94 m) on 15 March 2023; then two further reductions followed until July. Furthermore, the ACP imposed a hard limit of 32 southbound transits per day on 30 July. Given the cumulative operational constraints, we mark January 2023 as event time zero of the drought, the point at which all subsequent voyages experience the tighter water-depth constraint.

To identify control and treatment groups as well as pre- and post-treatment periods, we begin by scanning all AIS-BoL records for vessel passages through both the Miraflores and Gatún lock polygons. If a vessel of the AIS-BoL ever passed the Panama Canal, we tag it as a treatment group, *Panama*. For each month in which the vessel arrives at a US port, we set *Panama* = 1 if the voyage physically transits through the Panama Canal; otherwise, *Panama* = 0. Control observations are AIS-BoL shipments that departed from Asia but never crossed the Panama Canal and rerouted via other routes, such as the North-Pacific direct corridor to US West-Coast ports, an cross-Atlantic passage via the Suez Canal or a Cape of Good Hope routes (*Panama* = 0). As we noted that January 2023 can be considered event time zero of the drought at the Panama Canal, we therefore set $Post_t = 1$ for all months after January 2023 and 0 beforehand.

Our DiD treatment variable is the interaction $Panama_i \times Post_t$, which equals one only for AIS-BoL voyages that transit the Panama Canal and do so during the drought regime (after January 2023). This interaction term captures the canal users' response to the drought-related circumstances, such as shallower drafts, longer queues, and higher booking fees by passing the Panama Canal drought. Because the ACP's drought measures did not alter the physical or regulatory conditions on alternative routes, these non-Panama voyages serve as natural counterfactuals.

4.2 Difference-in-Difference Estimation and Dynamic Event Study Approach

To quantify the causal effect of the drought, we adopt a standard DiD causal inference approach. We estimate a shipment-level DiD model that contrasts canal users with otherwise comparable sailings that avoid the waterway. Let y_{ijt} denote the voyage operational outcome, such as total voyage time, voyage distance, voyage grand mean speed, or stopping time, for shipment i on origin-destination route j in calendar month t . The DiD empirical equation is:

$$y_{ijt} = \beta \text{Panama}_i + \gamma \text{Post}_t + \delta \text{Panama}_i \times \text{Post}_t + \alpha_{jt} + \varepsilon_{ijt}$$

where $\text{Panama}_i = 1$ if the AIS trajectory crosses the Panama Canal, $\text{Post}_t = 1$ for t after January 2023 and 0 beforehand, α_{jt} absorbs origin-destination-month route fixed effects, and ε_{ijt} is an idiosyncratic disturbance.

The main coefficient of interest is δ . It measures the incremental delay (or distance penalty, speed loss, stop time) incurred by voyages that transited the canal after the drought-induced draft and slot restrictions, over and above (i) any persistent differences between canal and non-canal sailings captured by β , and (ii) time-varying shocks common to all voyages captured by γ . Because α_{jt} capture origin-destination-time-specific fixed effects, it absorbs γPost_t , so γ is not estimated in the analysis.

The DiD estimate can effectively summarize the drought's effect in a single average, but we should note that carrier responses were unlikely to manifest instantaneously in January 2023 and then remain fixed. In order to track the month-by-month dynamic adjustment path, we also estimate an event study specification to trace how the penalty by the drought evolves month by month around the shock date. Let $\tau_{it} = t - \tau_0$ denote the number of months before or after January 2023, where $\tau_0 = \text{Jan 2023}$. We define a month dummy $\mathbf{1}\{\tau_{it} = k\}$ and include each k as a separate regressor except the reference month, $\tau = -1$ (December 2022). For the distant tails from the event time zero (January 2023), we collapse all pre-period observations with $k \leq -5$ into a single “-5 (*pre*)” bin, and all post-period observations with $k \geq +6$ into a single “+6 (*post*)” bin. Consequently, the coefficient vector $\{\beta_k\}$ contains individual month effects for $k = -5(\text{pre}), -4, -3, -2, 0, +1, \dots, +5, +6(\text{post})$. The event study empirical equation is defined as:

$$y_{ijt} = \beta \text{Panama}_i + \sum_{k \neq -1} \delta_k \times \mathbf{1}\{\tau_{it} = k\} \times \text{Panama}_i + \alpha_{jt} + \varepsilon_{ijt}$$

Plotting the estimated path $\hat{\delta}_k$ with confidence bands can present the adjustment process and also provide support to the parallel trend assumption, which is required for the DiD causal estimation. By checking if all pre-treatment coefficients are statistically

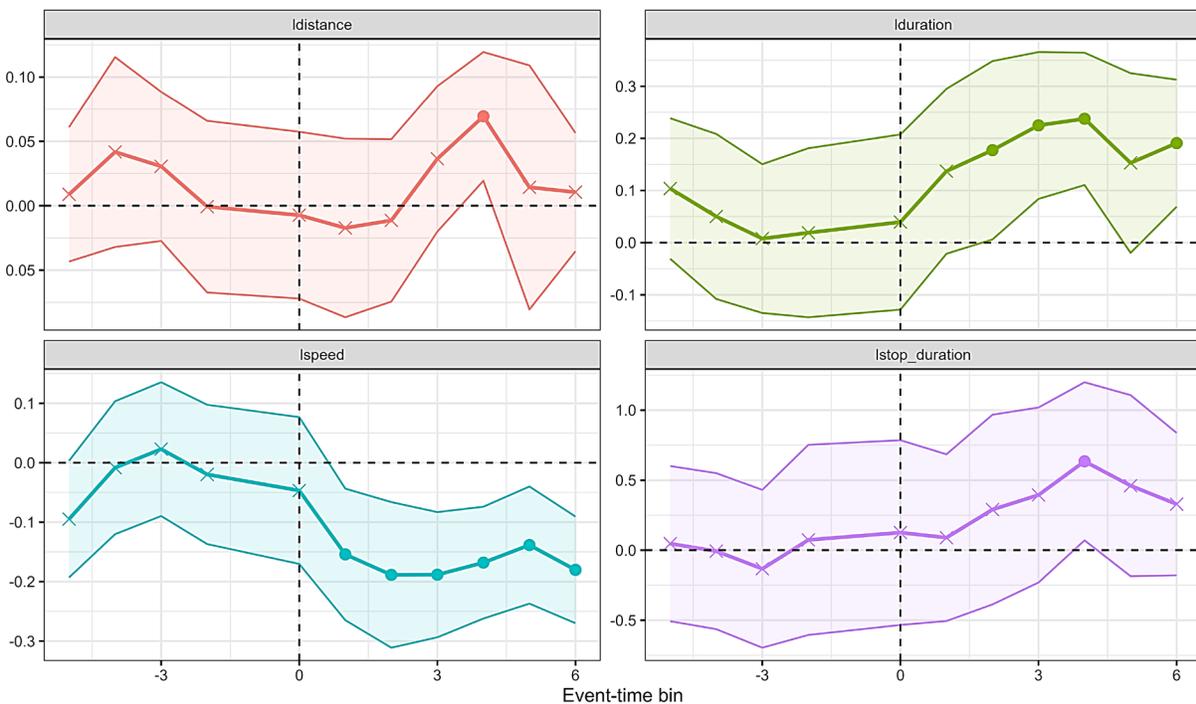
indistinguishable from zero, we can confirm if the parallel trend assumption holds. Standard errors are clustered by origin-destination-month, jt .

5. RESULTS

5.1 Baseline Difference-in-Difference Estimation Results

In order to check whether our empirical setting satisfies the parallel-trend assumption required for DiD estimation, we examine statistical significance of pre-event coefficients in the event study specification. Results for the full sample (Figure 5) show that all pre-event interaction coefficients are statistically insignificant at the 5% level, indicating no difference between the control and treatment groups before the Panama Canal drought began. This insignificance is consistent across all dependent variables, distance, total duration, average speed, and stopping time, confirming that causal inference through the DiD framework is empirically feasible.

Figure 5: Event Study Plot of the Full Sample Results (Log-transformed)



Note: Upper left = voyage distance, upper right = voyage duration, bottom left = mean speed; bottom right = stopping duration. The band shows 5% confidence interval.

Source: Authors' calculations.

The baseline DiD estimates further demonstrate that the drought disrupted container shipping along the canal. Tables A.1 and A.2 report that the average voyage duration for Panama-route shipments increased by 133.78 hours (5.54 days), or 12.19%, relative to the pre-event period. Their average stopping duration rose by 33.59 hours (35.39%),

while average speed declined by 2.32 km/h (10.15%). These results imply that, after the drought, containerships more frequently stopped for anchoring, queuing, or port calls and did so for longer periods, and so explained the overall delay. Because the DiD coefficient for voyage distance is found to be not statistically significant, the penalty seems mainly driven by extended voyage duration, longer stops, and reduced speed, while the route itself remains unchanged. This indicates that the response to drought disruption occurred mainly with delays along routes via the Panama Canal rather than rerouting via Suez or the North-Pacific corridor in average. This implies difficulty in shippers' prompt operational responses to the sudden disruption shock on the critical chokepoints like the Panama Canal. The operational process regarding the shipping route choices usually requires complex corporate contracts among multiple entities, shippers, shipping lines, freight forwarders, and port authorities, they cannot be changed flexibly on short notice (Tongzon 2009). Thus, rerouting via Suez or the North-Pacific corridor may not be promptly done when sudden disruptions like the Panama Canal drought occur, and lack of alternative routes to the canal might compel shippers to keep the existing route and take a longer time rather than reroute.

Notably, the *Panama* dummy also indicates that, under normal conditions, the Panama Canal provides a clear logistic advantage. When origin and destination ports are identical, passing through Panama reduces voyage duration by 150.27 hours (12.45%), lowers voyage distance by 1,448.42 km (5.73%), and increases speed by 1.53 km/h (7.57%) relative to non-Panama routes. Notably, when comparing this coefficient with the magnitude of the post-event interaction term, this benefit is found to vanish during the drought: the post-event interaction terms offset the pre-event effects, so the net impact of using the canal becomes essentially about zero for both duration and speed once the drought begins. This implies that the impact of the Panama Canal drought was devastating enough to cancel out the benefit from transiting through the canal and reveals the significance of such global chokepoints in global supply chains.

5.2 Event Study Model Results

As noted in Section 4.1, the event study model results confirm the parallel-trend assumption: all pre-event interaction coefficients are statistically insignificant at the 5% level (Figure 5). After the onset of the drought, most post-event coefficients become highly significant, positive for voyage duration, and negative for speed (Table A.3). Shipping distance and stopping duration rise only marginally and rarely reach significance, indicating that the penalty manifests mainly through longer total time and lower voyage speed rather than through rerouting. In other words, the drought-induced shock to the Panama Canal continued to slow container traffic month after month, beginning in January 2023.

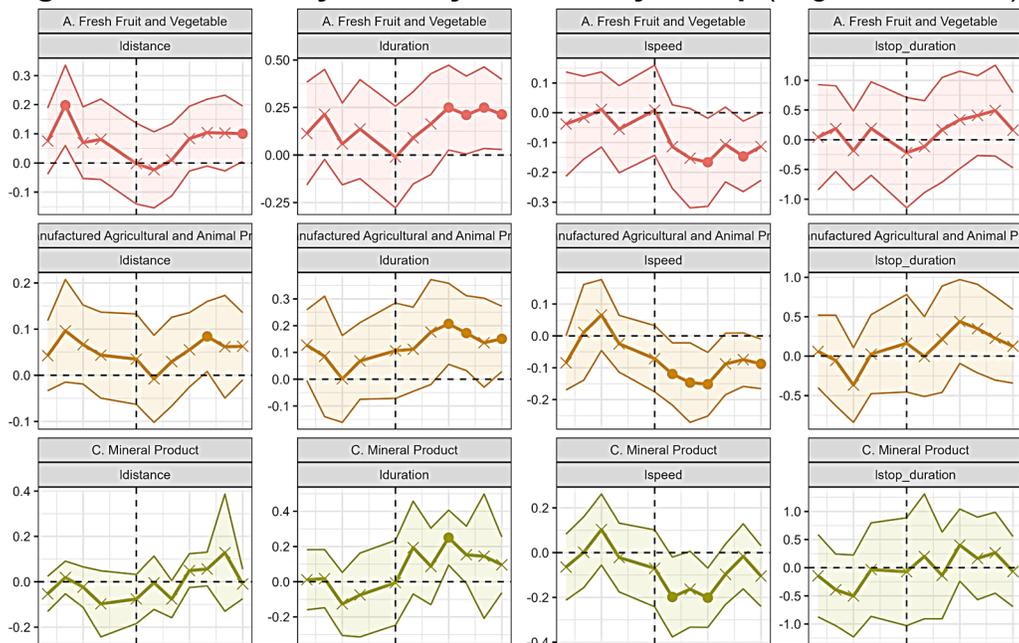
The time profile of the effect is monotonic in the early months: duration increases by 14.68% in February, when the first draft reduction was imposed, and peaks at 26.74% in May 2023, before edging downward. Changes in speed follow the mirror image, ranging from a 12.98% to 17.22% decrease over the same window. This hump-shaped trajectory tracks the phased policy sequence and carrier responses: each additional draft cut or slot cap lifts the curve, while the gradual decline after May likely reflects carriers' increased responses to take alternative routes to transiting through the Panama Canal as the drought had remained a long-term issue.

5.3 Heterogeneity in the Impact of the Drought Disruptions

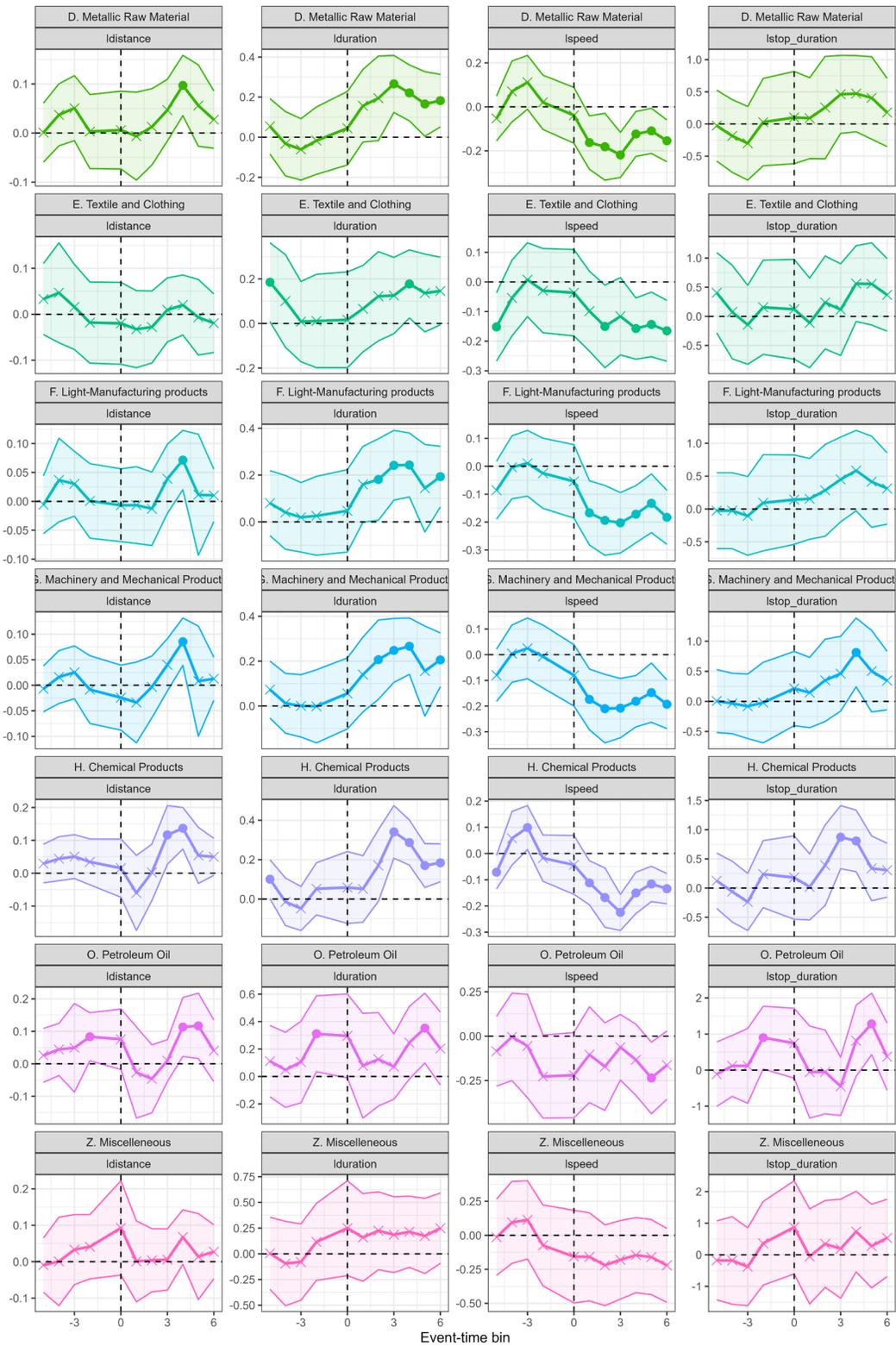
Following the commodity group classification at the HS-2 level proposed by Jung, Thill, and Galvis-Aponte (2024), we estimate the DiD and event study models on subsamples that cluster goods by key logistic attributes presented in Table A.4: time sensitivity, physical fragility, perishability, unit value, and weight.

The event study plots in Figure 6 show that the parallel trend assumption holds within every commodity group: all pre-event interaction coefficients are statistically insignificant at the 5% level. Hence, the DiD framework remains valid for commodity specific inference, as the full sample model does.

Figure 6: Event Study Plots by Commodity Group (Log-transformed)



Continued on the next page



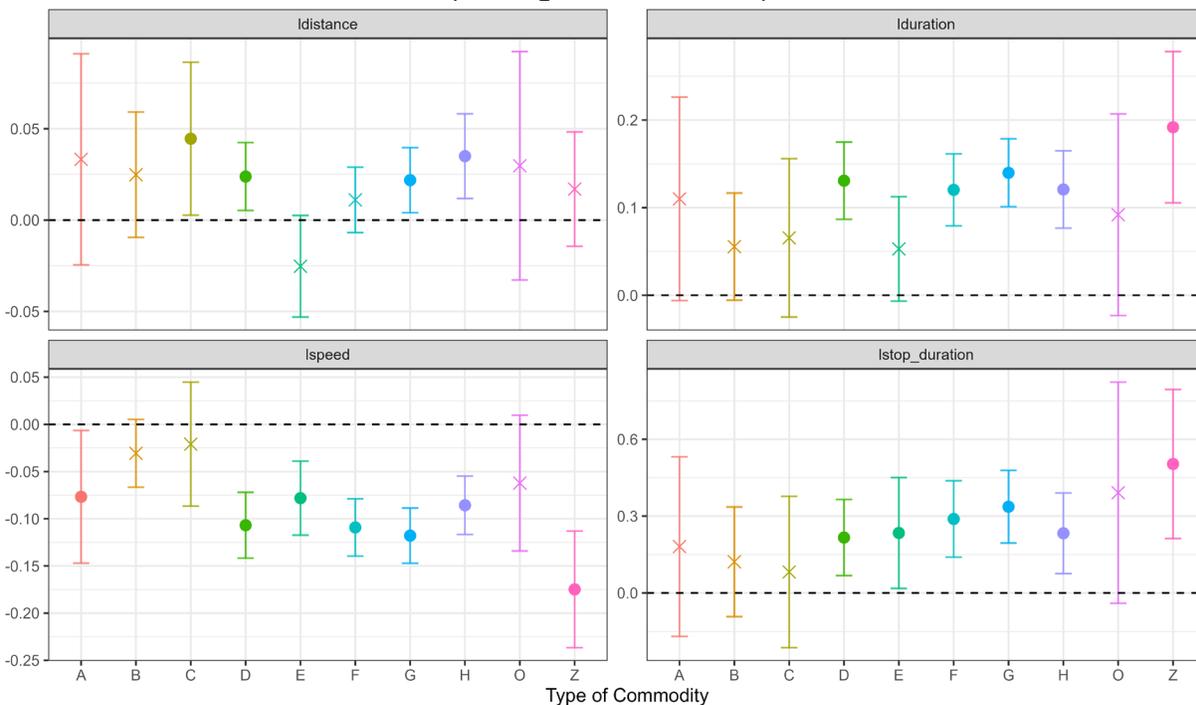
Note: Column 1 = voyage distance, column 2 = voyage duration, column 3 = mean speed; column 4 = stopping duration.

Source: Authors' calculations.

Post-event responses of the Panama-passing shipments unfold differently across commodity groups (Figure 6 and Table A.5). For Fresh Fruit and Vegetables (Group A), Mineral Products (Group C), Petroleum-Oil Products (Group O) and Miscellaneous Goods (Group Z), most post-event coefficients remain insignificant, indicating little or no drought-induced delay. By contrast, Manufactured Agricultural and Animal Products (Group B), Metallic Raw Materials (Group D), Light-Manufacturing Products (Group F), Machinery and Mechanical Products (Group G), and Chemical Products (Group H) display a clear pattern of extended voyage duration and lower cruising speed, mirroring the aggregate results in Section 4.2.

Figure 7 and Table A.6 report varied DiD point estimates across commodity groups. The coefficient on duration is positive and significant for Groups D, F, G, H and Z. Other than Miscellaneous Products (Group Z), the largest effects occur in Machinery and Mechanical Products (Group G, +2.84 percentage points relative to the mean) and Metallic Raw Materials (Group D, +1.81 percentage points). These commodity groups consist mainly of aluminum ingots, semi-finished steel and heavy machinery, loads that impose high draft to containerships but offer relatively low value per ton. Heavier containers leave crews less room to trim ballast or offload to meet reduced drafts, so even modest water-level cuts translate into material time losses.

Figure 7: Difference-in-Difference Estimates by Commodity Group
(5% significance band)



Note: Upper left = voyage distance, upper right = voyage duration, bottom left = mean speed, bottom right = stopping duration.

Source: Authors' calculations.

In contrast, Mineral Products (Group C) and Petroleum Oil Products (Group O) show no significant delay and continue to reap the canal's normal time speed advantage. Two possible reasons account for this exemption. The ACP maintains a pool of "reserved" or "just-in-time" slots for energy and raw material carriers, so tankers and bulkers laden with fuel or ores were able to bypass the longer container queues even at the height of the drought. Food cargoes, including Fresh Fruit and Vegetables (Group A) and Manufactured Agricultural and Animal Products (Group B), also escape measurable delay. Their logistic profile (high perishability, strict cold-chain requirements) makes them natural candidates for rerouting through Suez or direct Pacific services when the canal is congested; the absence of a penalty therefore may reflect preemptive diversion rather than privileged access.

The heterogeneity results reveal that the canal drought imposed its heaviest burden on dense, draft-intensive, and manufactured goods, while leaving containerized bulk commodities and perishables largely unaffected. This implies that resilience measures cannot adopt a one-size-fits-all approach; instead, they must prioritize the specific sectors, particularly metals and machinery, whose supply chains are uniquely exposed to canal-capacity risk.

6. CONCLUSIONS

By fusing hourly AIS trajectories with 28.2 million transaction-level US Customs Bills-of-Lading, this paper provides the first shipment-level account of how the 2022–2023 Panama Canal drought propagated through Asia–US container trade. The difference-in-differences and dynamic event-study results reveal important findings. Canal voyages that persisted through the drought were lengthened by an average of 5.54 days, sailed 2.3 km/h more slowly, and accumulated an additional 33.6 hours in stopping during the entire voyage, while the underlying voyage distance remained unchanged. Also, the benefit from transiting via the Panama Canal during the normal operation was found canceled out during the drought, and the net effect of using the canal becomes zero for duration and speed after the drought. The disruption impact was found to be highly uneven: shipments of machinery, mechanical equipment, and metallic raw materials incurred the largest penalties, whereas food cargoes, mineral products, and petroleum shipments were statistically unaffected, reflecting both ACP slot-allocation priorities and preemptive diversions of sensitive or bulky cargo.

Our research into the disruption caused the Panama Canal drought provides a few important policy implications for more robust global supply chains. One important finding is the rigidity in global supply chains during the unexpected disruption. Shippers could not seek alternative routes and bear all shipping delays and slowdown of voyages. For export-oriented Asian economies, the findings especially argue for a multipronged

resilience strategy for global supply chains to have multiple routing options. Exporting countries should internalize drought-related canal risk when designing port capacity expansions and inland distribution corridors that could provide room for alternative routes for unexpected disruptions. With the collective policy effort with shipping line companies and port authorities, they can consider incentivizing flexible “dual-coast” routing, under which shippers retain contractual access to both East and West-coast gateways to the US, either with or without resorting to transiting the Panama Canal for shipping. In this way, shippers can avoid delay exposure even in a severe canal shock by promptly switching to alternative routes.

The heterogeneity in the effect of the drought disruptions across commodity types underscores the need for emergency customs cooperation that is commodity-specific rather than uniform. In practical terms, customs authorities of exporting or importing countries may consider accelerating trusted-trader lanes for vulnerable sectors to reduce domestic clearance times and offset foreign maritime delays in the event of supply chain disruptions. These measures can be accompanied by pre-arrival processing for low-risk shipments or critical products in affected HS groups to facilitate faster export and import processes. Structured data-sharing that links bills-of-lading to AIS-based delay signals can guide how to streamline customs during the disruptions on both sides of customs authorities. By doing so, delays induced by the drought disruptions can be offset by the shortened customs procedures, and they can ensure that scarce berth time and port capacity are allocated first to the sectors most affected by drought-induced penalties.

Although the Panama Canal drought event is not attributed to the current climate change, it could be seen as a stress test for disruptions driven by the climate change in future. Adopting the analytical approach taken here to track supply chains by combining the BoL and AIS data, policymakers can be better guided by an operational early-warning and planning tool for climate-sensitive chokepoints. Export-oriented Asian economies can use the estimates obtained in this research to assess the impact of potential multiple hazards, such as prolonged drought, typhoon landfalls, or river-stage anomalies. By tracking vessel behavior and shipment composition in near real time, authorities and carriers can conduct scenario exercises and quantify the extent of delays and welfare loss to which those events build. Then they can establish a plan for investment in transshipment hubs and intermediate ports that enables resilient supply chains by preserving optionality when a single corridor binds.

We envisage directions of future studies by noting limitations of this research. First, as the robustness checks are not still exhaustive, future work could estimate fully dynamic models with heterogeneous treatment timings across individual vessels to rule out residual route-specific shocks that coincide with the drought window. Second, our heterogeneity analysis focuses on broad HS-2 commodity groups. More granular

subsample work could uncover additional distributional patterns and refine policy targeting. For example, distinguishing reefer containers from dry boxes or parsing East-coast destination ports could be an interesting expansion. Third, the drought shock enters most regressions as a binary interaction, even though ACP restrictions evolved along a continuous spectrum of draft reductions and transit caps. While the supplemental dose-response exercise using lake-level deficits partly addresses this limitation, a richer design that instruments for each distinct policy step would disentangle the marginal delay attributable to individual draft cuts or slot reductions.

Fourth, the analysis is confined to containerized imports. Extending the framework to bulk, LNG, and outbound empty repositioning legs would provide a fuller accounting of the drought's network-wide impact. Finally, our study follows only inbound containers from Asia to the US. If the drought altered vessel rotations or empty-equipment availability, the delay profile for outbound cargo from the US could differ systematically from that for inbound cargo. Based on the current empirical approach, we could extend our analysis to outbound US cargo to examine the impact on supply chains and their economic implications to both the US and Asian economies.

APPENDIX

Table A.1: Difference-in-Difference Estimation Results (Full sample)

Dependent variable	Duration	Distance	Stopping duration	Speed
Panama	-150.267*** (18.392)	-1,448.419*** (175.286)	10.033 (11.690)	1.528*** (0.295)
Panama × Post	133.779*** (22.302)	245.282 (235.725)	33.588* (13.085)	-2.316*** (0.345)
OD-Year-Month FE	Yes	Yes	Yes	Yes
SE Clustered	OD-Year-Month	OD-Year-Month	OD-Year-Month	OD-Year-Month
Observations	28,189,346	28,189,346	28,189,346	28,189,346
Adjusted R ²	0.62546	0.84361	0.48797	0.54204
Within R ²	0.00739	0.01023	0.00160	0.00234

Notes: *** $p < 0.1\%$; ** $p < 1\%$; * $p < 5\%$; . $p < 10\%$; Clustered standard errors in parentheses.
Source: Authors' calculations.

Table A.2: Difference-in-Difference Estimation Results on Log-Transformed Dependent Variables (Full sample)

Dependent variable (Log transformed)	Duration	Distance	Stopping duration	Speed
Panama	-0.133*** (0.018)	-0.059*** (0.007)	0.013 (0.063)	0.073*** (0.013)
Panama × Post	0.115*** (0.021)	0.008 (0.009)	0.303*** (0.076)	-0.107*** (0.015)
OD-Year-Month FE	Yes	Yes	Yes	Yes
SE Clustered	OD-Year-Month	OD-Year-Month	OD-Year-Month	OD-Year-Month
Observations	28,189,346	28,189,346	28,189,346	28,189,346
Adjusted R ²	0.74569	0.93200	0.63825	0.55901
Within R ²	0.00508	0.01156	0.00074	0.00267

Notes: *** $p < 0.1\%$; ** $p < 1\%$; * $p < 5\%$; . $p < 10\%$; Clustered standard errors in parentheses.
Source: Authors' calculations.

Table A.3: Event Study Model Results (Full sample)

Dependent variable	Duration	Distance	Stopping duration	Speed
Panama	-242.183 ^{***} (64.212)	-1,608.494 ^{**} (521.635)	-16.488 (61.134)	2.877 ^{**} (0.991)
Panama × Event -5(+) month	115.926 (71.864)	112.825 (614.222)	32.429 (64.015)	-1.861. (1.109)
Panama × Event -4 month	66.590 (83.375)	1,022.791 (864.286)	8.870 (63.630)	-0.110 (1.267)
Panama × Event -3 month	26.605 (75.369)	755.324 (666.370)	-8.722 (63.362)	0.534 (1.302)
Panama × Event -2 month	16.182 (88.141)	-138.757 (852.644)	3.698 (72.663)	-0.365 (1.321)
Panama × Event 0 month	52.583 (90.977)	-154.899 (759.354)	47.237 (76.381)	-0.849 (1.381)
Panama × Event +1 mon	161.831. (87.045)	-595.228 (873.584)	49.546 (69.333)	-2.929* (1.254)
Panama × Event +2 month	206.329* (91.268)	-280.793 (750.363)	53.848 (78.457)	-3.869 ^{**} (1.410)
Panama × Event +3 month	261.475 ^{***} (73.336)	909.586 (656.227)	79.973 (66.034)	-3.941 ^{**} (1.210)
Panama × Event +4 month	281.946 ^{***} (67.787)	1,676.995 ^{**} (585.704)	88.012 (62.668)	-3.367 ^{**} (1.075)
Panama × Event +5 month	149.995 (118.388)	-28.414 (1,516.931)	60.047 (70.875)	-2.939 ^{**} (1.115)
Panama × Event +6(+) month	225.927 ^{***} (65.232)	299.708 (538.481)	56.970 (61.444)	-3.762 ^{***} (1.011)
OD-Year-Month FE	Yes	Yes	Yes	Yes
SE Clustered	OD-Year- Month	OD-Year- Month	OD-Year- Month	OD-Year- Month
Observations	28,189,346	28,189,346	28,189,346	28,189,346
Adjusted R ²	0.62612	0.84378	0.48833	0.54277
Within R ²	0.00913	0.01132	0.00230	0.00391

Notes: ^{***} $p < 0.1\%$; ^{**} $p < 1\%$; ^{*} $p < 5\%$; [.] $p < 10\%$; Clustered standard errors in parentheses.

Source: Authors' calculations.

Table A.4: Classification of Commodity Types

Class	Label	First 2-digit HS Code
A	Fresh Fruits and Vegetables	06, 07, 08, 09, 10, 11, 12, 13, 14
B	Manufactured Agricultural and Animal Products	01, 02, 03, 04, 05, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24
C	Mineral Products	25, 26
D	Metallic Raw Material	72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 83
E	Textile and Clothing	41, 42, 43, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67
F	Light Manufacturing Products	39, 40, 44, 45, 46, 47, 48, 49, 68, 69, 70, 71, 82, 94, 95, 96, 97
G	Machinery and Mechanical Products	84, 85, 86, 87, 88, 89, 90, 91, 92, 93
H	Chemical Products	28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38
O	Petroleum Oil	27
Z	Miscellaneous Products	00, 98, 99

Source: Jung, Thill, and Galvis-Aponte (2024).

Table A.5: Event Study Model Results (Full sample)

Dependent variable (Log-transformed)	Duration	Distance	Stopping duration	Speed
Panama	-0.211*** (0.061)	-0.068** (0.023)	-0.052 (0.255)	0.143** (0.045)
Panama × Event -5(+) month	0.104 (0.069)	0.009 (0.027)	0.047 (0.283)	-0.095. (0.050)
Panama × Event -4 month	0.050 (0.081)	0.042 (0.038)	-0.007 (0.284)	-0.008 (0.057)
Panama × Event -3 month	0.008 (0.073)	0.031 (0.030)	-0.132 (0.287)	0.023 (0.057)
Panama × Event -2 month	0.019 (0.083)	-0.001 (0.034)	0.074 (0.346)	-0.020 (0.060)
Panama × Event 0 month	0.040 (0.086)	-0.007 (0.033)	0.126 (0.336)	-0.047 (0.063)
Panama × Event +1 month	0.137. (0.081)	-0.017 (0.035)	0.090 (0.304)	-0.154** (0.056)
Panama × Event +2 month	0.177* (0.087)	-0.011 (0.032)	0.290 (0.345)	-0.189** (0.062)
Panama × Event +3 month	0.225** (0.072)	0.036 (0.029)	0.394 (0.319)	-0.188*** (0.054)
Panama × Event +4 month	0.237*** (0.065)	0.069** (0.026)	0.635* (0.288)	-0.168*** (0.048)
Panama × Event +5 month	0.153. (0.088)	0.014 (0.048)	0.461 (0.330)	-0.139** (0.050)
Panama × Event +6(+) month	0.191** (0.062)	0.011 (0.023)	0.329 (0.259)	-0.180*** (0.046)
OD-Year-Month FE	Yes	Yes	Yes	Yes
SE Clustered			OD-Year-Month	
Observations	OD-Year-Month 28,189,346	OD-Year-Month 28,189,346	Month 28,189,346	OD-Year-Month 28,189,346
Adjusted R ²	0.74598	0.93207	0.63833	0.55986
Within R ²	0.00623	0.01265	0.00095	0.00459

Notes: *** $p < 0.1\%$; ** $p < 1\%$; * $p < 5\%$; . $p < 10\%$; Clustered standard errors in parentheses.

Source: Authors' calculations.

Table A.6: Difference-in-Difference Estimation Results by Commodity Group

Sample	A	B	C	D	E	F	G	H	O	Z
Dependent var. (Log- transformed)	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration
Panama	-0.060 (0.054)	-0.023 (0.021)	-0.138*** (0.033)	-0.177*** (0.019)	-0.045. (0.027)	-0.144*** (0.017)	-0.183*** (0.016)	-0.165*** (0.017)	-0.137*** (0.034)	-0.169*** (0.039)
Panama × Post	0.110. (0.059)	0.055. (0.031)	0.065 (0.046)	0.131*** (0.022)	0.053. (0.030)	0.120*** (0.021)	0.140*** (0.020)	0.121*** (0.023)	0.092 (0.059)	0.192*** (0.044)
OD-Year- Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SE Clustered	OD-Year- Month	OD-Year- Month	OD-Year- Month	OD-Year- Month	OD-Year- Month	OD-Year- Month	OD-Year- Month	OD-Year- Month	OD- Year- Month	OD-Year- Month
Observations	390,247	966,735	67,117	2,038,886	5,540,16 5	11,413,14 3	6,515,13 4	1,018,75 1	26,330	212,838
Adjusted R ²	0.79756	0.79822	0.82881	0.75458	0.74534	0.74490	0.75556	0.75572	0.83339	0.88214
Within R ²	0.00108	0.00029	0.00347	0.00917	0.00058	0.00690	0.00780	0.00544	0.00303	0.00858

Notes: *** $p < 0.1\%$; ** $p < 1\%$; * $p < 5\%$; . $p < 10\%$; Clustered standard errors in parentheses.
Source: Authors' calculations.

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Panama Canal Drought and Supply Chain Disruptions in Asia–United States Trade

Evidence from Micro-Level Trade Shipments and Vessel Trajectory Data

Disruptions at global chokepoints propagate shocks through supply chains. This paper quantifies the 2022–2023 Panama Canal drought’s impact on Asia–United States container trade using matched microdata on shipments and vessel movements. The drought induced significant delays in canal voyages and erased normal-time efficiency gains. Delays were largest for metals and light manufactures, while food shipments saw no significant effect. The study offers critical insights for valuing supply delays and shaping resilient trade policies for Asia’s export-driven economies.

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