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Space weather impacts on aviation: bridging scientific understanding and operational implications

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Space weather, long considered a peripheral concern for aviation, is increasingly recognized as a significant systemic factor influencing global flight operations. While its impact on communication, navigation, and power systems is well-documented, the broader contribution of space weather to flight delays and cancellations has been historically underestimated, with attention largely confined to polar route disruptions. This perspective calls for a paradigm shift, highlighting the systemic effects of space weather on flight delays and cancellations worldwide and stressing the urgent need to integrate space weather considerations into aviation research, operational frameworks, and strategic planning. Building on recent analyses of U.S. airline data (2024) and prior investigations of Chinese hub airports (2015–2019), we reveal how understanding these impacts can transform aviation operations, improving efficiency and resilience in an interconnected global network. By moving beyond a traditionally siloed approach, this perspective uncovers a previously underappreciated global challenge with profound implications for the future of air travel. We advocate for interdisciplinary collaboration, advanced real-time monitoring, and predictive analytics to enhance aviation resilience and operational efficiency amidst escalating space weather activity.

KEYWORDS

space weather, aviation, flight delays, flight cancellation, solar storm

1 Introduction

The term ‘Space Weather’ appeared in the 1960s and 1970s, and became widely used after the United States proposed the ‘National Space Weather Program’ in the mid-1990s (Schwenn, 2006). Early research efforts understandably concentrated on the most immediately apparent and high-consequence risks associated with space weather (Pulkkinen, 2007; Hapgood, 2012). In the realm of aviation, particular focuses are put on the unique challenges posed to aviation operations on polar region and specified routes. These initial investigations primarily addressed concerns radiation exposure for flight crews and passengers at high latitudes and the potential for high frequency (HF) communication outages in regions with limited satellite coverage (Jones et al., 2005; Fisher, 2009; Authority, 2020; Zou and Hansen, 2014; Fiori et al., 2022). This focused approach fostered crucial international collaborations, such as the establishment of the China-Russia Consortium space weather center under the auspices of the International Civil Aviation Organization (ICAO) in 2019 (Aleshin et al., 2021).

However, the broader implications of space weather for general flight operations, including its potential impacts on flight delays, remained largely speculative and outside the primary scope of these investigations (Lyakhov and Kozlov, 2012; Polishchuk et al., 2012; Tobiska et al., 2011). Traditional research on flight delays has predominantly concentrated on factors such as meteorological conditions within the Earth's atmosphere, inefficiencies in air traffic managements, and various airline-specific operational challenges (Chakrabarty et al., 2019; Lambelho et al., 2020; Gui et al., 2020; Gultepe et al., 2019; Borsky and Unterberger, 2019). While these terrestrial factors undoubtedly play a significant role in flight disruptions, the exclusion of space weather from comprehensive delay models has created a significant disciplinary isolation, severely limiting our holistic understanding of the complex dynamics that contribute to them. This limitation is further exacerbated by the inherently difficulty and complexity of space weather's impacts on the Earth's Magnetosphere-Ionosphere-Thermosphere system, which makes it even more challenging to establish a clear logical chain connecting space weather and flight delays (Schwenn, 2006; Pulkkinen, 2007; Wang et al., 2023).

The influence of space weather on flight delays is not a simple, direct relationship, but rather a complex interplay of nonlinear and multi-coupled effects propagating through various technological systems (Wang et al., 2023; Xu et al., 2023). Space weather, manifested through Solar Flares (SFs), Interplanetary Coronal Mass Ejections (ICMEs), and Solar Energetic Particles (SEPs), arising from the dynamic interaction of solar activity with Earth's magnetosphere and ionosphere, can induce global-scale disturbances, including HF radio blackouts, significant errors in Global Navigation Satellite System (GNSS) positioning, and elevated radiation levels at flight altitudes (Cander, 2019; Kauristie and Team, 2020; Bust et al., 2021). The potential for these disruptions to exacerbate flight delays, a systemic and globally interconnected challenge for the aviation industry, has been consistently neglected in mainstream research and policy.

Unlike terrestrial weather, space weather phenomena are not directly perceptible, leading to limited public awareness of their potential effects on aviation. Within the aviation industry, attention has primarily centered on safety concerns, with research focusing on links to accidents, radiation exposure for crew and passengers, and impacts on avionics (Lyakhov and Kozlov, 2012; Polishchuk et al., 2012; Bust et al., 2021; Meier and Matthia, 2014; Meier et al., 2020). For example, studies have demonstrated that solar particle events (SPEs) can increase polar radiation levels and disrupt HF communications. Such disruptions occasionally necessitate route diversions for polar flights, resulting in longer flight times and delays (Bland et al., 2018; Zaalov et al., 2015). However, the relatively small number of affected flights, even with the rise in polar routes, has reinforced the perception that space weather's impact on flight delays is negligible or non-systemic.

Public and scientific awareness of space weather's impact on aviation, particularly on flight delays beyond polar routes, remains limited due to a lack of robust quantitative studies exploring this complex relationship. Within the space weather research community, this gap has led some researchers, perhaps prioritizing scientific rigor, to conclude that no significant relationship exists, while others, relying on conventional understandings of space weather effects on communication and navigation systems (Kauristie and Team, 2020; Bust et al., 2021; Meier and Matthia, 2014), speculate that while impacts might be present in specific regions, the systemic influence on modern commercial flights is negligible. However, these perspectives remain largely conjectural, as peer-reviewed quantitative analyses are scarce (Wang, 2022). In fact, beyond our own work (Wang et al., 2023; Xu et al., 2023), no published journal article has comprehensively investigated the systemic effects of space weather events on flight delays and cancellations, leaving a critical gap in understanding.

Recent studies are providing compelling evidence for the systemic impact of space weather on flight delays, challenging the long-held notion that its effects are primarily confined to polar routes and specific regions. Wang et al. (2023) analyzed comprehensive arrival and departure data (~4 $\times$ 10^6 records) from five major hub airports in China spanning 2015–2019. Examining flight delays during 103 space weather events, and employing the Kolmogorov-Smirnov non-parametric hypothesis test, the study provided the first statistical evidence demonstrating a systemic increase in flight delays (~7.41 min) during these periods. Further strengthening the causal link, Xu et al. (2023) identified a distinct spatiotemporal signature in departure delays during 52 solar flare events. Dayside flares resulted in an additional 8.12-min delay compared with nightside flares, with a latitudinal gradient showing delays decreasing by 0.35 min per degree of latitude. Remarkably, Wang et al. (2023) also discovered a correlation between long-term flight punctuality trends and the 11-year solar cycle, suggesting a pervasive, cyclical influence of solar activities on aviation performance.

These findings also demonstrate a monotonic increase in flight delay time and rate with increasing geomagnetic field fluctuations and ionospheric disturbances. This correlation suggests that disruptions to communication and navigation systems during space weather events are a likely primary driver of the observed increase in flight delays (Wang et al., 2023; Xu et al., 2023). Robust communication and navigation are integral to the civil aviation CNS (communications, navigation, and surveillance) system; consequently, such disruptions directly impact both the safety and efficiency of air travel. These emerging evidences indicate that the influence of space weather on flight delays may be mediated through its effects on communication and navigation infrastructure, as well as on air traffic management system efficiency. Collectively, these studies are prompting a critical re-evaluation of the factors influencing flight delays and highlighting the previously underappreciated role of space weather as a significant driver of systemic disruptions.

2 Preliminary evidence from U.S. data

Flight delays often exhibit localized characteristics, whereas space weather events can produce widespread, even global, impacts on Earth's systems. Consequently, investigating the relationship between space weather and flight delays requires a broad geographical scope and a selection of airports distributed across a wide area (Wang et al., 2023; Campanelli et al., 2016). To ensure data homogeneity, such studies are best conducted within

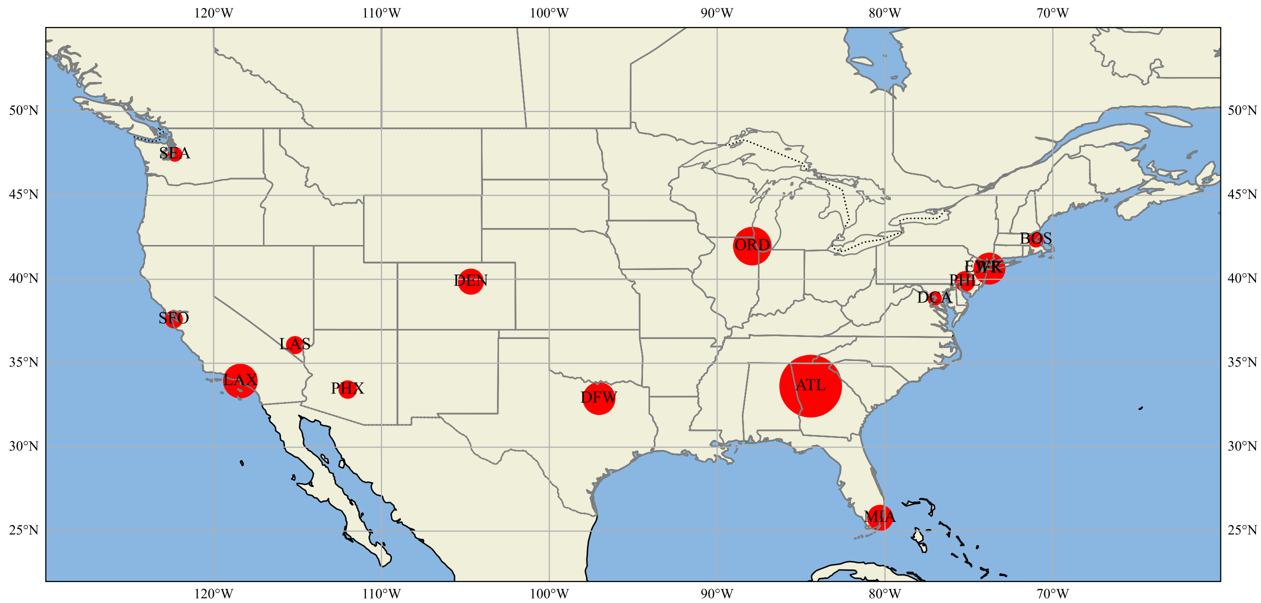

FIGURE 1
The distribution of airports used in this study.

a single country. Among the nations capable of meeting these criteria, China, the United States, Russia, and Canada. While Russia and Canada are less ideal due to lower population density and commercial aviation activity. Prior research has focused on Chinese hub airport data, primarily comparing flight delays during space weather events to those in quiet periods. In this perspective, we extend the scope by presenting a preliminary investigation into the impact of space weather events on flight cancellation rates in the United States. Using superposed epoch analysis, we examine the temporal response of cancellations to space weather events and explore potential differences arising from varying aviation policies.

Flight delays exhibit non-linear propagation across airline networks, with performance in managing delays and cancellations varying significantly among airlines of different scales (AhmadBeygi et al., 2008). These differences are primarily driven by variations in operational models, route network structures, and resource allocation capacities for disruption management. Consistent with established research practices (Bitzan and Peoples, 2016; Avogadro et al., 2021; Bombelli and Sallan, 2023), we categorize airlines into two groups: full-service carriers (FSCs) and low-cost carriers (LCCs). FSCs generally maintain extensive route networks and larger resource reserves, while LCCs, operating under strict cost constraints, are more vulnerable to cascading disruptions. Recognizing these distinctions, our study explicitly incorporates this factor. Among the top ten U.S. airlines by passenger volume in 2024, we selected United Airlines (UA), American Airlines (AA), and Delta Air Lines (DL) as representative FSCs (Group 1) and Frontier Airlines (F9), Southwest Airlines (WN), and Spirit Airlines (NK) as representative LCCs (Group 2). Additionally, we included data from 15 major hub airports distributed across the eastern, central, and western United States, which also include the middle and lower latitude regions, to account for the large-scale impacts of space weather events as shown in Figure 1.

Data for this study were sourced from the U.S. Bureau of Transportation Statistics (BTS) online database, covering the first 8 months of 2024. To minimize confounding factors unrelated to space weather, we excluded data from two major events: the January 2024 North American winter storm and the late July 2024 Microsoft aviation system outage. Our primary focus was the compound Space Weather Event (SWE) period from May 25 to 7 June 2024 (14 days; flight data volume: 238,793), during which no other significant disruptions occurred. Most crucially, the 3 days before and after this period were free of space weather events, allowing us to analyze the temporal evolution of flight cancellation rates in direct response to the space weather activities.

Given the extremely high solar activity in 2024, characterized by frequent events occurring at intervals of only a few days or even hours for SFs, extended quiet periods were scarce. For baseline comparisons, we identified 'Quiet Time Periods 1' (QTP1) with no significant space weather events or major disruptions affecting national flight operations: January 29 to 11 February 2024 (14 days; flight data volume: 221,622), and August 11 to 24 August 2024 (14 days; flight data volume: 247,510) (Bombelli and Sallan, 2023). To further address the scarcity of quiet periods and enhance comparison robustness, we incorporated 'Quiet Time Period 2' (QTP2), which consisted of geomagnetically quiet days (Q1, the quietest days of each month in 2024), as identified from data provided by the Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences (Matzka et al., 2021) (7 days; flight data volume: 112,815). This dual-baseline approach offers a comprehensive framework for assessing flight delays during space weather events, facilitating a deeper understanding of their systemic impacts.

Figures 2a,b present the solar soft X-ray flux from the GOES satellite and the solar wind magnetic field components from the ACE satellite, respectively. Figure 2c illustrates the temporal evolution

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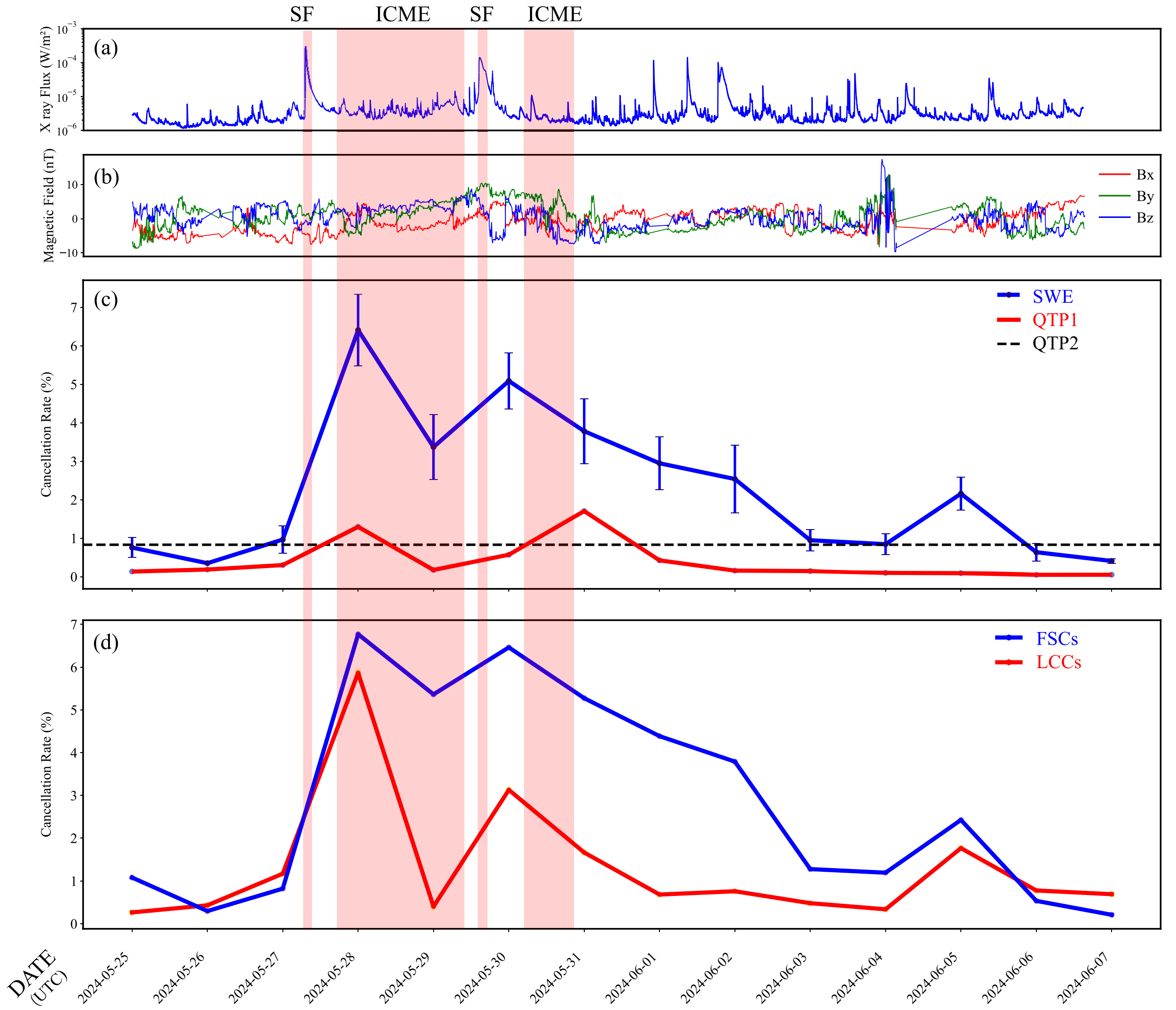

FIGURE 2
(a) Solar soft X-ray flux from the GOES satellite. **(b)** Solar magnetic component flux from the ACE satellite. **(c)** The superposed epoch analysis of flight cancellation rates in response to SWEs (blue), QTP1 (red), and QTP2 (black). **(d)** The superposed epoch analysis of flight cancellation rates for Group 1 (blue) and Group 2 (red) airlines. The light red rectangles mark the durations of space weather events.

of flight cancellation rate in response to space weather events. In the 3 days preceding the onset of the SWE, the cancellation rate remains low and stable at approximately 1%. Following the first SF at 07:14 UTC on May 27, the cancellation rate rises sharply, escalating further with the arrival of an ICME, which significantly perturbs the Earth's magnetosphere-ionosphere system. This disruption causes cancellation rate to surge from approximately 1%–6%. Although cancellation rate begins to decline on May 30, a second X-class SF around 14:23 UTC, significant southward B_z, together with the ICME, contribute another spike, with cancellation rate eventually returning to baseline levels after 3–4 days. Notably, as shown in Figure 2d, the fluctuation of the cancellation rate of Group 2 (LCCs) is more pronounced. This observation seems to align well with previous findings that low-cost carriers are more vulnerable to cascading disruptions due to their strict cost constraints and limited resource buffers (Bitzan and Peoples, 2016; Avogadro et al., 2021). In contrast, during quiet time periods, when no major solar activity is present, the cancellation rate of QTP1 remains relatively constant over time. This stability is also consistent with the rate calculated during the geomagnetically quiet days (QTP2). The high consistency between the two further confirms the systemic impact of solar activity on flight cancellations. Finally, given that previous studies indicate that low-intensity, nighttime, or short-duration SFs are unlikely to significantly impact flight delays (Xu et al., 2023), the minor increase in flight cancellations observed on June 5th is more likely to be attributed to other factors rather than space weather events.

3 Conclusion and discussion

As mentioned before, the influence of space weather on flight delays is not a simple cause-and-effect relationship but rather a complex, multi-faceted interaction mediated through various technological and atmospheric systems. Although challenging to conceptualize intuitively, our prior research utilizing Chinese aviation data (Wang et al., 2023; Xu et al., 2023), alongside the findings presented here based on U.S. data, provides compelling evidence of increased flight disruptions during space weather events. Together, these studies establish a robust foundation supporting a causal framework for understanding the impact of space weather on flight delays and cancellations.

The most likely primary mechanisms through which space weather affects aviation operations involve geomagnetic-ionospheric perturbations caused by space weather events. These disturbances can disrupt communication systems, leading to increased noise, signal degradation, or even complete outages. Similarly, navigation systems may experience delays in satellite signal transmission and heightened positioning errors. As foundational components of the civil aviation CNS framework, reliable communication and navigation are critical for ensuring safe and efficient air travel. Regulatory frameworks in both the U.S. (e-CFR, 2022) (e-CFR, 2022) and China (CCAR-93TM-R5, 2017) (CCAR-93TM-R5, 2017) mandate continuous two-way communication and provide protocols for addressing communication failures. Consequently, space weather-induced disruptions can necessitate flight diversions, impose ground delays for additional inspections, and ultimately lead to significant delays and cancellations. Moreover, interruptions in communication between Air Traffic Control (ATC) and flight crews can cascade operationally, causing delays in takeoff and landing clearances and inaccuracies in flight planning due to disrupted information flow to dispatch centers. These effects can compound, amplifying minor delays into widespread disruptions across the aviation network. Similarly, even small increases in time required to manage navigation interference can accumulate, further exacerbating delays and cancellations (Wang et al., 2023).

Our ongoing analysis of U.S. flight data aims to examine the influence of space weather events on flight operations over an extended timeframe, encompassing an entire solar cycle. This research accounts for geographical variations, temporal dynamics, and event categorizations and is being compared with findings from Chinese aviation data to construct a comprehensive causal chain linking space weather events to operational disruptions. Although our preliminary findings provide new insights, the broader implications of space weather on aviation remain a complex and expansive field, with many unresolved questions and limited theoretical frameworks (Schwenn, 2006; Pulkkinen, 2007; Authority, 2020; Aleshin et al., 2021; Baker, 2002). Addressing these gaps will require sustained, multidisciplinary research efforts over decades, supported by significant resources. This perspective explores only a subset of these issues, presenting preliminary findings and encouraging further exploration to deepen our understanding of the mechanisms linking space weather and aviation operations. Comprehensive insights will require extensive collaboration across disciplines, leveraging global datasets and innovative analytical approaches.

Whether or not one assumes the two are intrinsically connected, the seemingly counterintuitive systemic phenomenon demands rigorous investigation grounded in both inductive and deductive reasoning, supported by robust quantitative analysis. Refusing to acknowledge this emerging phenomenon based on personal experience or intuition is scientifically untenable. Recognizing space weather as a significant systemic contributor to flight delays has profound strategic implications, requiring a paradigm shift in aviation operations and planning. Current delay models must be revisited, as the ambiguous 'other' category often used for unexplained delays likely obscures significant impacts from space weather. Operationally, proactive measures are essential, including integrating space weather forecasts and nowcasts into air traffic management systems beyond the polar regions, developing adaptive routing and scheduling strategies informed by space weather predictions, and enhancing the resilience of critical aviation technologies. For example, the Civil Aviation Administration of China's (CAAC) 2024 revision of the 'Regulations on the Release and Exchange of Civil Aviation Flight Meteorological Information,' which significantly expanded the inclusion of space weather information, exemplifies progress in embedding space weather considerations into operational decision-making frameworks.

Beyond operational efficiency, these findings have broader implications for governments and international organizations, which must develop robust contingency plans to safeguard essential services. Future research should prioritize interdisciplinary collaborations to unravel the intricate interactions between space weather and aviation (Jones et al., 2005; Fisher, 2009), as well as the associated economic impacts (Eastwood et al., 2017; Xue et al., 2023). Additionally, the aviation insurance industry should integrate space weather risk assessments into its frameworks. Bridging the gap between space weather science and aviation operations presents opportunities to enhance efficiency, improve safety, and strengthen the resilience of the global air transportation network.

In conclusion, prioritizing space weather in aviation strategy, research, and planning is critical, particularly as aviation continues to expand. A proactive, integrated approach to understanding and mitigating space weather effects is vital for addressing the challenges of our interconnected world. The future of aviation is inherently linked to space weather dynamics, necessitating coordinated and forward-thinking strategies to ensure safety, efficiency, and predictability in global air travel.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YW: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Project administration, Resources, Validation, Writing – original draft, Writing – review and editing. RL: Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – review and editing, Conceptualization. FS: Conceptualization, Writing – review and editing. XF: Conceptualization, Writing – review and editing. BW: Writing – review and editing. PZ: Writing – review and editing. CJ:

Writing – review and editing. XX: Writing – review and editing. ZZ: Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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