Source Area Analysis and Immigration Pathways of the White-backed Planthopper in the Sichuan Region: Postprint

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Abstract

To determine the distribution of source regions and migration pathways of immigrant white-backed planthopper populations in the Sichuan rice region, trajectory simulation and source region analysis were conducted for light trap peak days of white-backed planthopper at 17 stations in Sichuan from May to July 2012 using the HYSPLIT 4.8 platform and ArcGIS, and wind field analysis of source regions on major immigration peak days was performed using the meteorological graphics processing software GrADS. The results indicated that: (1) White-backed planthoppers immigrating into the Sichuan Basin during the early period (May-June) primarily settled in southern and eastern Sichuan. The early source populations in southern Sichuan mainly originated from northern Vietnam and Laos, as well as southern, eastern, and northeastern Yunnan, while those in eastern Sichuan were concentrated in southern Chongqing, western Hunan, and the border region of Hunan, Hubei, and Chongqing, with a small proportion from northwestern Guangxi. The July migration of white-backed planthoppers, influenced by southwesterly, southerly, and southeasterly airflows, exhibited source populations widely distributed across Yunnan, Guizhou, Chongqing, Guangxi, Hunan, and Hubei. (2) Four main migration pathways for white-backed planthoppers entering the Sichuan Basin were identified. The first pathway: white-backed planthoppers migrated from Yunnan through western Guizhou into southern Sichuan via southwesterly or southerly airflows, or subsequently through northeastern Guizhou and Chongqing into eastern Sichuan. The second pathway: white-backed planthoppers migrated from Guangxi through central Guizhou into southern Sichuan via southerly airflows, or through northeastern Guizhou and Chongqing into eastern Sichuan. The third pathway: migration from Hunan through Chongqing into eastern Sichuan via southeasterly or southerly airflows. The fourth pathway: migration from Yunnan into western Sichuan via southerly airflows. (3) Due to the influence of unique terrain and topography, the initial immigration period and main immigration period of white-backed planthoppers in the Sichuan Basin developed from southeast to northwest. The primary immigration peaks of white-backed planthoppers in the Sichuan rice region were concentrated in July, with fewer peaks during the early period (May-June) that were concentrated in southern and eastern Sichuan. Overall, the variation in immigration peaks demonstrated a sequential decrease from southeast to northwest. These findings are of significant importance for monitoring and early warning of white-backed planthoppers in the Sichuan rice region.

Full Text

Preamble

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Origins and Migration Pathways of the White-backed Planthopper (*Sogatella furcifera* Horváth) in Sichuan

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Abstract

To clarify the distribution of source areas and migration pathways of white-backed planthopper (WBPH) populations immigrating into Sichuan rice regions, we analyzed daily light-trap data collected from seventeen stations between May and July 2012. Trajectories and distributions of source areas during peak WBPH migration days were simulated and analyzed using HYSPLIT 4.8 (Hybrid Single-Particle Lagrangian Integrated Trajectory) and ArcGIS. Additionally, meteorological backgrounds of these source areas were analyzed using GrADS (Grid Analysis and Display System).

During the early migratory stage (May–June), WBPHs congregated in the southern and eastern areas of Sichuan. WBPHs in southern Sichuan originated primarily from northern Vietnam and Laos, as well as southern and eastern Yunnan. Meanwhile, WBPHs in eastern Sichuan came mainly from southern Chongqing, western Hunan, and the border junction of Hunan, Hubei, and Chongqing, with small contributions from northwestern Guangxi. In July, influenced by southwesterly, southerly, and southeasterly winds, WBPH sources were widely distributed across Yunnan, Guizhou, Chongqing, Guangxi, Hunan, and Hubei. The main sources in early July were Yunnan, parts of mid-western

Guangxi, and western Guizhou. In mid-July, sources shifted northeastward to northeastern Yunnan and central Guizhou. Meanwhile, WBPHs originating from southern Sichuan may have migrated to central and eastern Sichuan. In late July, WBPHs may have traveled from western to northern Sichuan.

We identified four main WBPH migration pathways in Sichuan: (1) from western Guizhou to southern Sichuan, continuing through northeastern Guizhou and Chongqing to eastern Sichuan under southwest and southerly airflows; (2) from central Guizhou to southern Sichuan, or through northeastern Guizhou and Chongqing to eastern Sichuan aided by southerly winds; (3) from Hunan through Chongqing to eastern Sichuan, facilitated by southeast and southerly airflows; and (4) from Yunnan to western Sichuan under southerly airflow. Due to the unique topography, WBPHs tended to migrate from southeast to northwest during the beginning and mid-period of immigration. Migration peaks varied across stations and periods, generally peaking in July, with lesser peaks in May and June in southern and eastern Sichuan. Overall, major migration peaks decreased from southeast to northwest. Accurate monitoring and prediction of WBPH in Sichuan is crucial for effective pest management.

Keywords: white-backed planthopper; source area; migration pathway; wind field analysis

Introduction

The white-backed planthopper (*Sogatella furcifera*) is a typical migratory pest species [1-2], and its migratory behavior represents the primary challenge for effective control. Following the landmark discovery in 1967 by Asahina & Tsuruka of large-scale trans-oceanic migration of rice planthoppers at a Pacific ocean weather station approximately 500 km southwest of Japan' s Honshu Island [3], research on planthopper migration began in earnest. Through nationwide collaborative efforts, Chinese scientists have elucidated the overwintering boundaries of WBPH in China, confirmed its seasonal north-south migration patterns across eastern China [1,4-5], delineated regional occurrence zones [6], and developed predictive methods based on meteorological conditions during migration. WBPH populations in China originate mainly from the Indo-China Peninsula, entering through Yunnan Province, with some populations subsequently migrating to the Jiangnan, middle-lower Yangtze, and Jianghuai rice regions [1,7]. WBPH cannot overwinter in Sichuan [6], and its long-distance migratory capacity makes outbreaks sudden and explosive, greatly increasing the difficulty of forecasting and control. Consequently, accurate prediction, particularly long-range forecasting, is essential, making precise identification of source areas and their population dynamics critically important [8].

While extensive research has been conducted on WBPH in eastern China, studies on migration patterns and source areas in Sichuan and Chongqing remain very limited. Although research in Yunnan has yielded substantial results [9-12], the specific source areas for WBPH immigrating into Sichuan rice regions at different times remain controversial. While some studies have mentioned WBPH migration patterns in Sichuan [7,13], no clear answers exist regarding its immigration pathways into Sichuan rice regions, with discussions of source areas focusing only on individual localities [14-16]. The overall migration pattern remains largely unknown. Sichuan’ s complex terrain and limited research on population ecology, migration patterns, and outbreak mechanisms have left monitoring and early warning systems inadequate, contributing to long-term passive management of WBPH. Given the severity of WBPH occurrences in Sichuan, the unique migration environment, future development trends of hybrid rice in China, and the urgent need to address these research gaps, a macro-level understanding of WBPH spatiotemporal dynamics in Sichuan is urgently needed. Clarifying the precise distribution of source areas, migration pathways, and population exchange with other regions is theoretically and practically significant for accurate early warning and effective control in Sichuan and nationwide. Trajectory analysis is one of the most common and effective methods for identifying source and landing areas [8]. Currently, the HYSPLIT trajectory simulation platform combined with GrADS weather analysis systems and ArcGIS geographic information systems is widely used to simulate migration pathways, analyze landing mechanisms, and investigate source areas during WBPH immigration peaks. The accuracy of the HYSPLIT model has been validated through release-recapture experiments [8]. Therefore, this study employed HYSPLIT 4.8 and ArcGIS software to conduct backward trajectory simulations for WBPH immigration peaks during different periods and at different stations in Sichuan rice regions in 2012—a year of major WBPH outbreaks in Sichuan—to elucidate the precise distribution of source areas and migration pathways, thereby providing scientific basis and technical support for accurate early warning and effective control.

1. Data Sources

Historical light-trap data for WBPH in 2012 were provided by county-level plant protection and quarantine stations across Sichuan Province. Based on geographic location, stations were categorized into southern Sichuan, eastern Sichuan, western Sichuan, northern Sichuan, and central Sichuan (Figure 1 [Figure 1: see original paper]). Specific time periods for light-trap data at each station are detailed in Table 1 . Rice growth stage data for May-July in Chongqing and Sichuan were obtained from the China Meteorological Data Sharing Network (http://cdc.cma.gov.cn). Provincial administrative maps and national geographic data were sourced from the National Geomatics Center of China (http://ngcc.sbsm.gov.cn).

Upper-air meteorological data were acquired from the National Centers for Environmental Prediction (NCEP) Final Operational Global Analysis (FNL) reanalysis dataset with 1° × 1° horizontal resolution (http://rda.ucar.edu/datasets/ds083.2/index.html#description).

2. Methods

2.1 Identification of Immigration Peaks

Annual WBPH immigration peaks were identified as follows: a peak period was defined from the day of sudden increase in light-trap catches to the day of sudden decrease after the peak, with the date of maximum catch designated as the peak day. If the interval between the sudden decrease day of the previous peak and the sudden increase day of the subsequent peak was less than 5 days, they were counted as a single peak.

2.2 Trajectory Analysis and Parameter Settings

Trajectory analysis was conducted using the HYSPLIT 4.8 atmospheric particle trajectory analysis platform jointly developed by the U.S. National Oceanic and Atmospheric Administration (NOAA) and the Australian Bureau of Meteorology (http://www.arl.noaa.gov/HYSPLIT.php). Backward trajectories were calculated from light-trap locations.

Biological parameters for trajectory analysis were set as follows: WBPH migrates with the wind at optimal temperatures of 17-22°C [4,17-18]. Summer migration heights can reach 1500–2000 m [5,7]. Considering regional topography and temperature differences at various altitudes, initial trajectory heights were set at 800, 1000, 1500, and 2000 m above ground. WBPH takes off within 1-2 hours after sunset and before sunrise [1,4,19]. Backward trajectories started from landing areas at twilight and were traced back to takeoff times in source areas [17,20-21]. The peak catch day served as the start date, with whole-hour time points within the day as start times. Flight duration was set at 24–33 hours.

Valid trajectory criteria: (1) The trajectory endpoint time must conform to WBPH takeoff rhythms [20,24]; (2) The endpoint must be located in rice-growing areas that could provide emigrant populations and be in the peak emigration period [25-26]; (3) All three conditions must be met simultaneously. Based on these criteria, valid trajectory endpoints were selected or adjusted. Qualified trajectory endpoints from Excel were imported into ArcGIS 10.0 and overlaid on base maps. Point density was calculated, with numbers representing endpoint counts and color intensity indicating endpoint density (darker colors represent more endpoints).

Wind field analysis: Using GrADS software, wind directions at 850 hPa from meteorological data at various source areas were compiled and summarized. Wind direction frequencies for each ten-day period or month were calculated, and eight-direction wind roses were generated. These roses were inserted into ArcGIS to create final wind direction maps. Wind direction standards followed meteorological classification: N, NE, E, SE, S, SW, W, and NW correspond to angle ranges of 337.5°-22.5°, 22.5°-67.5°, 67.5°-112.5°, 112.5°-157.5°, 157.5°-202.5°, 202.5°-247.5°, 247.5°-292.5°, and 292.5°-337.5°, respectively.

3. Results

3.1 Temporal Dynamics of WBPH Light-Trap Catches

Analysis of light-trap data from Sichuan stations in 2012 revealed significant variation in first appearance dates and catch amounts across stations (Figure 2 [Figure 2: see original paper]). The earliest WBPH appearances occurred in southern Sichuan stations, with Xingwen being the earliest, followed by Xuyong. Eastern Sichuan stations showed intermediate first appearance dates, while northern and central Sichuan stations appeared later. The latest first appearance was recorded in western Sichuan' s Hanyuan station, followed by eastern Sichuan. Thus, WBPH first appears in southern Sichuan, then eastern Sichuan, with northern, central, and western Sichuan following sequentially.

Based on first appearance dates and temporal patterns of light-trap catches, WBPH immigration in Sichuan exhibits a clear pattern of sequential delay from southeast to northwest. Average catch amounts were relatively low in northern and western Sichuan stations, while southern Sichuan showed the highest catches, followed by central and eastern Sichuan. The severity of infestations consequently decreased from southeast to northwest.

3.2 Main Immigration Peak Periods and Frequency in Sichuan

Based on 2012 monitoring data, WBPH immigration peak periods across Sichuan regions were summarized as follows: Southern Sichuan' s main immigration periods were May 26-28, June 7-12, June 20-22, June 27-29, and July 16-17. Eastern Sichuan' s main peaks were June 15-17, June 20-21, June 24-25, July 20-21, and July 27-28. Western Sichuan' s main immigration period was July 20-21. Central Sichuan' s main periods were June 22-23, June 30-July 1, July 26-28, and July 30-31. Northern Sichuan' s main periods were July 16-17, July 22-23, and July 28-29.

WBPH immigration peaks in Sichuan were concentrated primarily in July, with relatively fewer peaks in May and June. The main immigration peaks showed a temporal pattern of decreasing frequency from southeast to northwest, with concentrations in southern and eastern Sichuan.

3.3 Source Area Analysis

Backward trajectory analysis was conducted using HYSPLIT 4.8 for WBPH immigration peak days at various stations, combined with rice growth stage data at trajectory endpoints to obtain valid trajectory endpoints. Since immigration peak days differed across Sichuan regions, source area distributions are described chronologically.

In May, WBPH immigration peaks were concentrated in southern Sichuan, particularly in Xuyong and Xingwen. Source areas for southern Sichuan were located in southern Yunnan, northern Vietnam, and Laos, as well as eastern and northeastern Yunnan. Eastern Sichuan sources differed markedly, concentrated in southern Chongqing, western Hunan, and the Hunan-Hubei-Chongqing border junction, with small contributions from northwestern Guangxi.

In June, WBPH immigration peaks occurred across all Sichuan rice regions, representing a period of substantial immigration. Source distributions were complex, varying among southern, northern, and central rice regions, and also varying across different time periods within June. To enable more precise analysis, June was divided into early, middle, and late ten-day periods. In early June, source areas for southern, eastern, and central Sichuan were distributed in Yunnan, with small contributions from mid-western Guangxi and western Guizhou. In mid-June, sources for southern Sichuan shifted to northeastern Yunnan and western Guizhou; sources for eastern Sichuan were mainly in southern Sichuan, central Sichuan, and western Chongqing; and sources for central Sichuan were in mid-western Yunnan. In late June, southern Sichuan sources comprised two parts: one in Yunnan and another in central Guizhou; eastern Sichuan sources were complex, concentrated in Guizhou with small contributions from Yunnan; and central Sichuan sources were in southwestern Sichuan.

In July, WBPH immigration peaks were observed at all stations, representing the period of mass immigration. Source distributions were most complex in July. Western Sichuan sources were located in western and northern Yunnan and the Panxi region, indicating that more southerly rice areas in Panxi could provide sources for northern regions. Northern Sichuan sources were complex, with eastern Guizhou, central Sichuan, and parts of Chongqing all serving as potential source areas. Western Sichuan sources were distributed in Yunnan, with additional contributions from eastern Guizhou and central-western Chongqing.

3.4 Relationship Between Source Area Distribution and Upper-Air Wind Frequency

Source area analysis revealed that May sources originated from Guangdong, Guangxi, Chongqing, and Jiangxi. Analysis of 850 hPa wind directions at source areas showed that from southern to central Yunnan, southwest or southerly winds were absolutely dominant. Northeastern Guizhou was dominated by easterly and southeasterly winds, preventing southwest or southerly winds from Yunnan from reaching eastern Sichuan. Western Hunan and other source areas showed similar frequencies of southeasterly and southerly winds. Chongqing was dominated by southerly and southeasterly winds, with early source areas in eastern Sichuan located to its southeast.

Further statistical analysis of wind directions in early June showed that from northeastern Guizhou to southwestern Chongqing, southerly winds increased while easterly or southeasterly winds decreased. Southerly or southwesterly winds became absolutely dominant in western Guizhou, causing source areas in eastern Sichuan to shift southwestward to the area from northeastern Guizhou to northwestern Guangxi. In mid-June, southerly wind frequency increased in Guangxi, while western Hunan remained under the influence of southerly and southwesterly winds. Northwestern Guangxi experienced reduced easterly winds and increased southerly winds, causing source areas to shift to central Guizhou and south-central Sichuan. In late June, southwesterly and southerly winds weakened across Yunnan, Guizhou, and Guangxi, with more balanced wind direction frequencies. In western Hunan, southwesterly and southerly winds weakened while southeasterly and easterly winds strengthened. Eastern Sichuan was simultaneously influenced by southwesterly and southeasterly winds, with source areas located partly in northeastern Yunnan and partly from western Guizhou to western Hunan, resulting in more dispersed endpoints.

Northern Sichuan first observed WBPH in early July, with obvious immigration peaks in mid-to-late July. Source area distributions showed that Hubei, Guizhou, and parts of eastern and southern Sichuan could all serve as source areas. Analysis of 850 hPa wind directions at source areas revealed that northern Sichuan was mainly influenced by easterly, southeasterly, and southerly winds, while western Sichuan' s Hanyuan station experienced minimal influence from southwesterly or southerly winds, making it unable to provide WBPH sources for northern Sichuan.

3.5 Timing and Main Pathways of WBPH Immigration into the Sichuan Basin

Due to surrounding mountains mostly exceeding 1000 m, the Sichuan Basin experiences blocked airflow, creating unique WBPH landing and occurrence characteristics [13]. Based on light-trap data and source area analysis, WBPH primarily immigrates into the basin from three directions, concentrating in southern and eastern Sichuan.

In 2012, the main timing and pathways of WBPH immigration into the Sichuan Basin were as follows: In May, the immigration pathway was simplest, with WBPH moving from the Indo-China Peninsula north to southern Yunnan, then entering western Sichuan via northern Yunnan across the Hengduan Mountains under southwesterly or southerly winds (Figure 5A [Figure 5: see original paper]).

In June, WBPH immigration into southern Sichuan followed two routes: one moving from the Indo-China Peninsula north to southern Yunnan, then through northeastern Yunnan and western Guizhou into southern Sichuan; the other moving from Yunnan through its northeastern part and northwestern Guizhou, or from Guangxi through central Guizhou under southerly winds. In June, WBPH immigration into eastern Sichuan also had two pathways: one from Guangxi through northeastern Guizhou and Chongqing under southerly winds; the other from Yunnan through western and northeastern Guizhou under southwesterly or southerly winds (Figure 5B [Figure 5: see original paper]).

In July, WBPH immigration pathways were more diverse and complex, with immigration occurring in early, middle, and late periods. Pathways included: (1) from Guangdong and Hunan through Chongqing under southeasterly winds;

(2) from Yunnan through Guizhou under southwesterly or southerly winds; and (3) other complex routes.

4. Discussion

WBPH occurrence severity is directly influenced by conditions in source areas, immigration timing, and meteorological factors [10]. Migration and landing are also affected by meteorological conditions and topography at landing sites. The direction of initial and main immigration periods in the Sichuan Basin differs from the general south-to-north pattern in most regions of China, primarily due to the basin's unique topography. WBPH initially immigrates mainly into southern and western Sichuan. Western Sichuan stations, located west of the Qionglai Mountains and surrounded by high mountains on the west and northwest, are mainly influenced by southerly winds from Yunnan and northerly winds from the plateau. The Qionglai Mountains block southerly winds, resulting in fewer WBPH migrating from western Sichuan stations to other basin areas. In contrast, southern and eastern Sichuan lack significant mountain barriers, allowing southerly winds from the south and easterly or southeasterly winds from the east to create a migration pattern from southeast to northwest across the basin [7].

Factors affecting the timing of WBPH immigration differ among eastern, southern, and western Sichuan stations. Before late May, most rice regions in the Sichuan Basin were still in the sowing stage and could not provide WBPH sources. Only southern Yunnan, Hainan, Laos, and Vietnam could provide sources. The 17-22°C isotherm lingered at the Yunnan-Guizhou border, only expanding into the Sichuan Basin in late May. We hypothesize that sources for late May appearances in southern Sichuan originated from Laos, northern Vietnam, and southern Yunnan. By early June, southwestern winds controlled the area from central Guizhou to southern Sichuan, allowing WBPH to appear in southern Sichuan, while eastern Sichuan remained under the control of southeasterly and northerly winds, preventing Yunnan-origin WBPH from reaching eastern Sichuan. WBPH appeared in eastern Sichuan in early June, likely arriving from southern Guangxi with southerly winds. When southwestern winds were strong enough to affect eastern Sichuan in certain years, the first appearance date could be advanced. Therefore, the strength of southwestern winds and the 17-22°C isotherm are important factors affecting immigration timing in southern and eastern Sichuan.

Although western Sichuan is also influenced by southwesterly or southerly winds, the lower migration altitude of WBPH in spring prevents them from crossing high mountains into western Sichuan [7,13]. Only when migration altitude increases can WBPH cross mountains into western regions. Consequently, the first WBPH appearance in western Sichuan occurs in June, with more northern stations not recording WBPH until July, while frequent immigration is already underway in eastern and southern Sichuan.

Because WBPH has a high proportion of long-winged adults in each generation and a certain proportion exhibits outward migration [1], and its relationship with rice growth stages is less close than that of the brown planthopper [27], each generation can emigrate when weather conditions are suitable (with a rate up to 80%). As rice in source areas enters mid-to-late growth stages and WBPH has reproduced for at least one generation, the range of areas that can provide WBPH sources greatly expands, making migration pathways more complex and variable. Different meteorological backgrounds lead to different WBPH migration pathways and source area distributions. In different months, May represents the initial immigration period with relatively simple source area distribution, while July is more complex. Before June, rice development is in early stages and fewer rice areas can provide WBPH sources, and wind directions show more obvious dominant directions, resulting in relatively simple source area distributions and concentrated trajectory endpoints in southern and eastern Sichuan. Among different regions, western Sichuan shows the simplest source area distribution, confined to western and northern Yunnan, while eastern Sichuan shows the most complex distribution, spanning Yunnan, Guizhou, Chongqing, and parts of southern and central Sichuan. This difference arises from vastly different airflow influences: western Sichuan, surrounded by mountains at the Yunnan border, receives only southerly winds from Yunnan, while eastern Sichuan simultaneously receives southwesterly winds from Yunnan, southerly winds from Guangxi, and southeasterly winds from Hunan, resulting in a vast source area range and complex source composition.

Long-distance immigration is closely related to the distribution and movement of large-scale weather systems. However, due to the presence of mesoscale and small-scale systems along migration pathways and the influence of geographic conditions, spatial differences in weather systems and source area distributions create spatiotemporal variations in WBPH landing patterns [28]. Horizontal transport volumes differ across regions, with even adjacent areas showing completely different phenomena [13]. For example, when low-vortex weather systems appear at 850 hPa in eastern Sichuan, southerly winds from Guangxi meet northerly winds, creating large-scale heavy rainfall that forces WBPH to land. Meanwhile, stations in northerly and westerly directions under northerly wind control receive no WBPH immigration peaks. Therefore, Daxian and Linshui stations in eastern Sichuan experienced immigration peaks while other stations did not.

This study analyzed only one year of data. To clarify the regular patterns of WBPH occurrence and development in the Sichuan Basin, multi-year data analysis is needed.

References

[1] National White-backed Planthopper Research Collaboration Group. Preliminary studies on the migration patterns of white-backed planthopper. *Scientia Agricultura Sinica*, 1981, 14(5): 25-31.

[2] [Reference content appears incomplete in original]

[3] Asahina S, Tsuruka Y. Records of the insects visited a weather-ship located at the ocean weather station 'Tango' on the Pacific, II. *The Entomological Society of Japan*, 1969, 37(3): 290-304.

[4] [Reference content appears incomplete in original]

[5] [Reference content appears incomplete in original]

[6] [Reference content appears incomplete in original]

[7] [Reference content appears incomplete in original]

[8] [Reference content appears incomplete in original]

[9] [Reference content appears incomplete in original]

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[13] [Reference content appears incomplete in original]

[14] [Reference content appears incomplete in original]

[15] [Reference content appears incomplete in original]

[16] [Reference content appears incomplete in original]

[17] [Reference content appears incomplete in original]

[18] Furuno A, Chino M, Otuka A, Watanabe T, Matsumura M, Suzuki Y. Development of a numerical simulation model for long-range migration of rice planthoppers. *Agricultural and Forest Meteorology*, 2005, 133(1/4): 197-209.

[19] [Reference content appears incomplete in original]

[20] [Reference content appears incomplete in original]

[21] [Reference content appears incomplete in original]

[22] [Reference content appears incomplete in original]

[23] [Reference content appears incomplete in original]

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