PERSPECTIVE

Elephant Early-warning System in China: Leveraging Information Superiority to Mitigate Human-elephant Conflict

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Abstract: Human-elephant conflict (HEC) poses a major socio-ecological challenge across elephant range states. Since 2015, the National Forest Ecosystem Research Station of China based in Xishuangbanna has developed the Elephant Early-warning System (EEWS), a novel approach that has demonstrably reduced the risk of HEC incidents—particularly those involving direct encounters between people and elephants. By dynamically maintaining safety buffers, this system safeguards endangered elephants while mitigating human safety risks during livelihood activities and ensuring uninterrupted elephant movement. Building upon the C4ISR framework (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance), EEWS integrates key technological and institutional innovations—including the widespread adoption of mobile internet, deployment of camera traps, use of drones, and cross-sectoral governance reforms. The EEWS's conceptual framework and technical architecture have been already recognized by local government and are now being scaled up from Xishuangbanna to the entire Asian elephant range in China, establishing a replicable "China model" for achieving harmonious human-elephant coexistence. This study reviews the conceptual foundations, development, and field implementation of EEWS, and offers recommendations to guide future refinement and broader application.

Keywords: human-elephant conflict, Elephant Early-warning System, C4ISR framework, social governance

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Human-elephant Conflict in China

Conserving large and potentially dangerous wildlife is a daunting task in the Anthropocene (Ripple et al., 2016). As the largest terrestrial animals in Asia, Asian elephants (*Elephas maximus*) are an umbrella species with important roles in ecosystem processes across tropical Asia (Campos-Arceiz & Blake, 2011; Terborgh et al., 2025). Despite their endangered conservation status (Williams et al., 2020), human-elephant conflict (HEC) has become a major social and conservation concern in elephant range countries (Shaffer et al., 2019).

In China, the remaining population of approximately 300 wild Asian elephants is restricted to Yunnan Province (Wang et al., 2025). Over 70% of these elephants were found in the candidate area of the Asian Elephant National Park, across the prefectures of Xishuangbanna, Pu'er, and Lincang (Yang et al., 2024). From 2013 to 2019, HEC in China resulted in over 40 human deaths, more than 30 injuries, and direct property losses exceeding 210 million yuan (Hu et al., 2021; Yang et al., 2024), with over 80% of which gone for compensation of crop damage (Su et al., 2020; Li et al., 2023). HEC has become the most prominent form of wildlife-related damage in China (Li et al., 2018) (Fig. 1).

Fig. 1. Human-elephant conflict in Xishuangbanna, China.

Concept Proposal for an Elephant Early-warning System

Asian elephants are habitat generalists with a preference for a combination of natural forest and secondary vegetation (English et al., 2014; Evans et al., 2018; Wadey et al., 2018; Huang et al., 2020). In the Anthropocene, moderately disturbed, human-dominated landscapes near large forest patches have become prime habitats for elephants (de la Torre et al., 2021, 2022). In China, their suitable habitats are increasingly shifting toward such human-dominated areas (Yu et al., 2024), increasing the likelihood of contact with people, and making HEC inevitable (Campos-Arceiz, 2013; de la Torre et al., 2021).

For decades, China has been committed to mitigating HEC and has introduced a range of targeted conservation policies. Illegal hunting of Asian elephants carries severe legal penalties (Wang et al., 2020), and the domestic ivory trade has been completely banned since 2018 (Chen et al., 2023), drastically reducing incentives for poaching and illegal trade. While wildlife insurance schemes provide partial compensation for crop losses (Wang et al., 2024), the central challenge now lies in preventing human injuries and maintaining public safety in areas where elephants and people coexist.

Reducing HEC-related safety risks fundamentally depends on preventing unintentional encounters between people and elephants. Such unexpected interactions can elicit unpredictable stress responses in both species, potentially resulting in unnecessary mutual harm. Traditional methods for separating the two species rely primarily on passive barriers such as electric fences and trenches. However, given the wide-ranging movements of Asian elephants across diverse habitats (Sukumar, 2003; Chen et al., 2021), fencing entire conflict areas is both costly and inefficient. Moreover, given their intelligence, elephants often circumvent barriers (Huang et al., 2025) or shift to new habitats in unprotected areas (Campos-Arceiz et al., 2022).

Active strategies to maintain human-elephant separation rely on monitoring systems and coordinated responses, commonly referred to as elephant early-warning systems (EEWS). These systems track real-time elephant activity patterns and enable timely management of human activities in communities. By leveraging their informational advantage, EEWS proactively establish and maintain dynamic safety buffers between humans and elephants—mitigating risks to human safety during livelihood activities while ensuring uninterrupted elephant movement free from accidental human interference. At the organizational level, such systems can be framed as a C4ISR (Command, Control, Communication, Computer, Intelligence, Surveillance, and Reconnaissance) structure (Russell & Abdelzaher, 2018; Ahmad et al., 2023) (Fig. 2). Effective EEWS implementation requires the following components:

(1) Intelligence, Surveillance and Reconnaissance: Advanced technological solutions for real-time information collection of elephant activity, all-weather detection capabilities, and continuous monitoring;

(2) Communication: Reliable infrastructure for rapid dissemination of alerts to at-risk populations;

(3) Computer: Sophisticated computing capabilities to process complex data, deliver actionable information to administrators, and prevent misinformation that could trigger false alarms and unnecessary panic;

(4) Command and Control: Clearly defined decision-making structures to coordinate and implement responses efficiently.

The core principle of the C4ISR framework is to maintain a low-latency Observation-Orientation-Decision-Action (OODA) loop capable of rapidly adapting to real-time information (Angerman, 2004; Sun et al., 2020; Bai et al., 2024). Although originally developed for high-stake domains such as military missions and search-and-rescue operations, the framework is increasingly applied to the management of sudden-onset incidents (Yang, 2022), where timely data transmission and rapid execution of response plans are critical. In both contexts, C4ISR systems achieve information superiority, operational effectiveness, and enhanced situational awareness by generating actionable intelligence through the collection and processing of critical data during tactical operations (Ah-

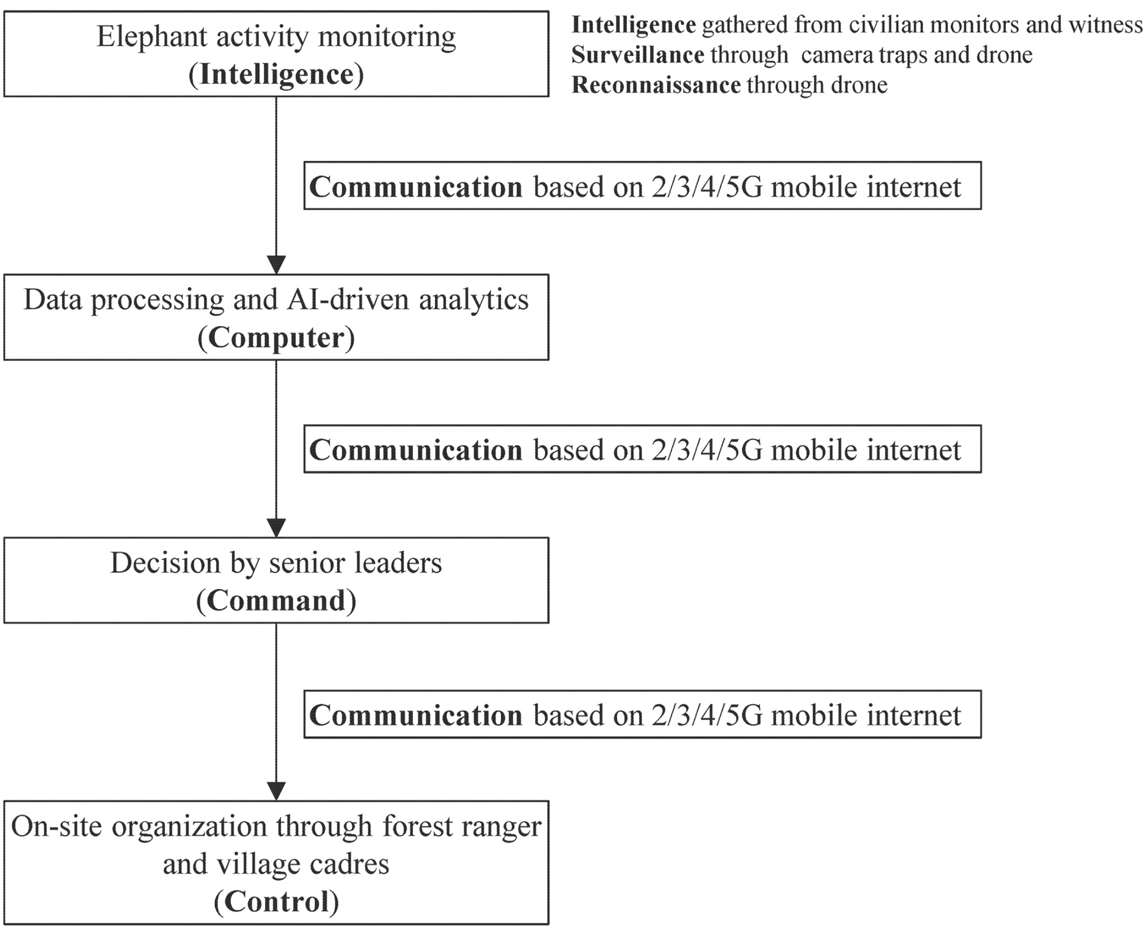

Fig. 2. The C4ISR framework of EEWS.

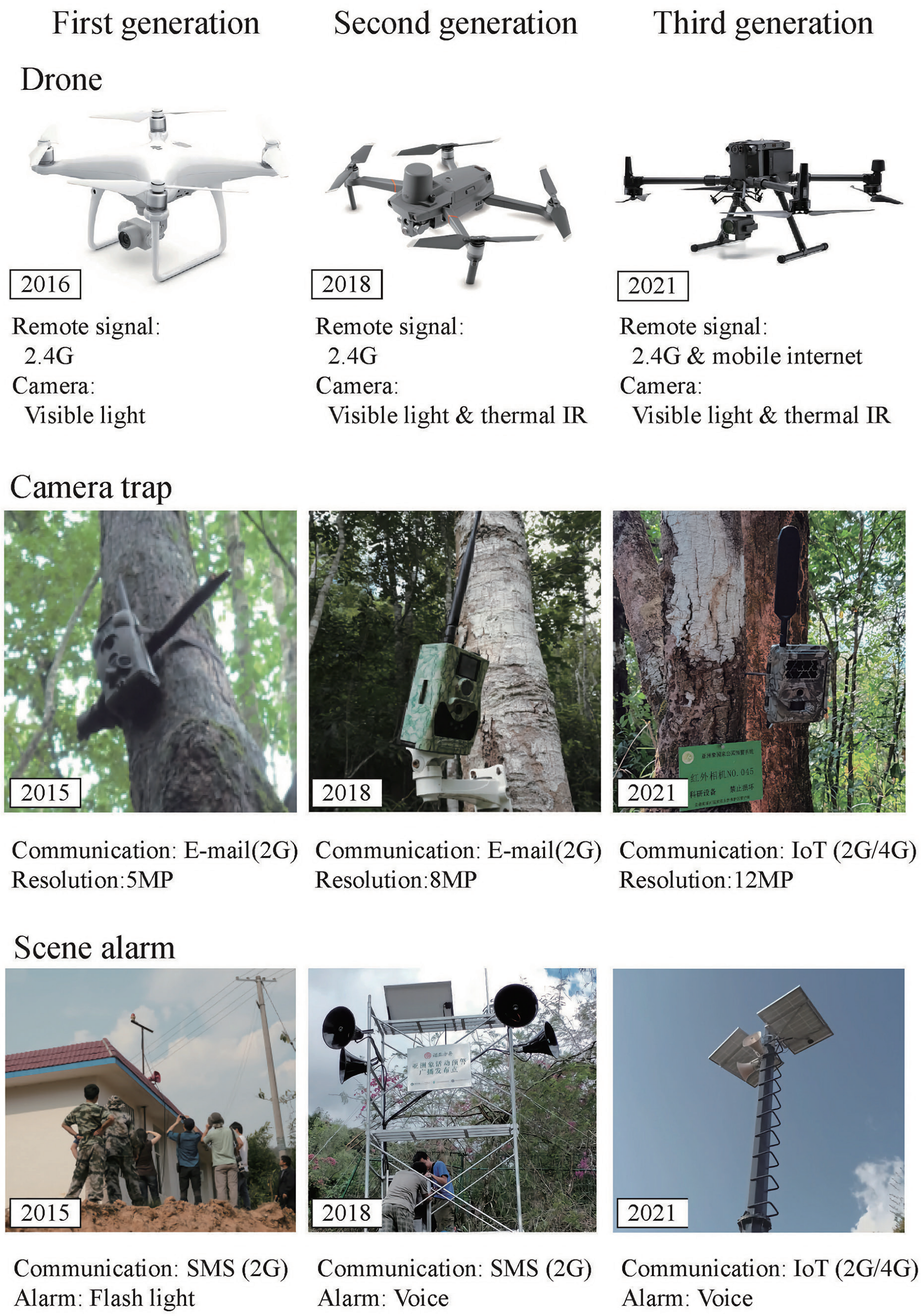

Fig. 3. The equipment upgrade of EEWS from 2015 to the present.

mad et al., 2023). This capability aligns closely with the technical demands of dynamic human-elephant separation management.

Translating conceptual frameworks into effective practice is inherently challenging. While frameworks like C4ISR and the OODA loop have been successfully implemented in military operations for decades, their adoption in civilian contexts remains limited. Civilian implementation requires cost-effectiveness, long-term sustainability, and operational safety. Yet in rural areas and nature reserves, where HEC events commonly occur, continuous close-range tracking of elephants poses significant risks, and poor communication infrastructure often hinders real-time intelligence collection and targeted alert dissemination. The absence of a centralized information-processing system further complicates data filtering and management. Without robust surveillance and communication capabilities, command and control efforts inevitably become ineffective. These limitations delayed the development of effective EEWS until the 2010s.

Practice of EEWS in China

In 2015, the National Forest Ecosystem Research Station at Xishuangbanna (affiliated to the Xishuangbanna Tropical Botanical Garden, XTBG, an institution under the Chinese Academy of Sciences, CAS) has been piloting wide-area network (WAN) camera traps for elephant detection and early-warning purposes (Yuan et al., 2019). This initiative marked the first development of the conceptual framework and technical architecture of the EEWS in China (Jiang, 2015).

A prototype system has been operational since then (http://elephant.noahsark.org.cn/#/), continuously transmitting real-time alerts of elephant presence near human settlements and ecologically sensitive areas to a dedicated web server. Through an AI-assisted manual verification process, validated information is disseminated via point-to-point SMS alerts to local administrators, or through online-controlled loudspeakers to at-risk villagers (Deng et al., 2018a; Deng et al., 2018b). Notably, 83.6% of warning messages reached villagers within 20 minutes, and 93.1% of community residents reported satisfaction with EEWS's functionality (Yuan et al., 2019).

Simultaneously, the Menghai County Forestry and Grassland Bureau, in Xishuangbanna, developed a complementary drone-based monitoring system in 2016. This system shares real-time elephant location data through a dedicated mobile application and provides proximity alerts to users, indicating whether they are entering or approaching elephant activity zones. This drone-based monitoring service has operated continuously to the present day (Wang et al., 2019; Yang et al., 2023), and intelligence on elephant activities derived from drone monitoring has been integrated into the latest version of the EEWS (Fig. 3).

These pioneering initiatives significantly reduced HEC incidents, effectively demonstrating the system's feasibility, sustainability, and cost-effectiveness to local authorities. In 2019, the Xishuangbanna Nature Reserve made substantial investments in enhancing and upgrading the EEWS (Tan et al., 2024). By the first half of 2021 alone, the upgraded system recorded 4,666 elephant activity events in Xishuangbanna; 83.6% (3,901 incidents) triggered successful community warnings, and 94.9% of local residents responded promptly (Wang et al., 2023).

The EEWS proved highly effective in mitigating HEC risks through early intervention, enhancing safety for both humans and elephants while reducing the operational risks and workload of field monitors. Following the success of Xishuangbanna National Nature Reserve, other Asian elephant habitats in China, such as Pu'er (Dao, 2022), Mengla (also part of Xishuangbanna) (Mengla County Forestry and Grassland Bureau, 2024), and Nangunhe Nature Reserve (part of Lincang) (Yang, 2025), began deploying similar EEWS systems in 2022, 2023 and 2025, respectively. This expansion demonstrates local governments' growing recognition of EEWS's practical value.

The Role of Technological and Institutional Innovation

The development of China's EEWS is not accidental but the outcome of a sequence of key technological and institutional innovations. First, the development of information and communication technologies (ICTs) and mobile internet established a robust foundation for large-scale monitoring since the 2000s. This digital infrastructure was further strengthened by the "Internet plus" initiative in the 2010s (Yang et al., 2021b; Yin et al., 2021), which greatly expanded rural internet access, developed critical infrastructure around nature reserves, and significantly lowered the cost of Internet of Things (IoT) services. For field operations, wireless infrared cameras, widely deployed since 2010, provided durable equipment for real-time tracking of elephant movements near protected-zone access points (Rowcliffe & Carbone, 2008; Caravaggi et al., 2017). From 2015 onward, drones enabled safe and effective monitoring over broader areas (Wang et al., 2019). Finally, advances in web-based platforms and database systems, developed since the 2000s, enabled scalable, real-time filtering of data and targeted dissemination of alerts (Willi et al., 2019; Yang et al., 2021a). Together, these mutually reinforcing developments created the conditions for successful design and implementation of EEWS in China.

Experience and Challenges

The EEWS in China represents a technological and managerial breakthrough. Ecologically, it has effectively reduced direct HECs and protected endangered elephants; for local livelihoods, early warnings enable villagers to plan travel and work activities, minimizing accidental injury risks; and technologically, it integrates camera traps, UAVs, and network systems, establishing a scalable model for managing human–large animal conflicts.

Nevertheless, as an emerging system, the EEWS faces notable challenges. First, as a life-critical information management system, it must balance the high efficiency of AI-based recognition with the high accuracy required for human identification. Second, as an online platform storing vast volumes of monitoring data, the EEWS necessitates robust cybersecurity and information security measures. Third, regarding social management, there is a lack of clear and standardized cross-sectoral collaboration mechanisms, which are essential for ensuring sustained and efficient operation. Fourth, further trade-offs are needed to determine the appropriate depth of community involvement in disseminating sensitive alert information. Fifth, for broader application and scaling, the system requires more targeted adaptive modifications to address conflicts involving species other than Asian elephants or those in ecological-social contexts differing from its current operational environment. Sixth, the long-term maintenance and upgrading of equipment demand more stable financial support. In summary, the EEWS is not merely a conservation tool but, more importantly, a complex socio-ecological management system that requires long-term, collaborative input from technology developers, policymakers, and local communities.

Furthermore, since EEWS is fundamentally built on long-term ecosystem monitoring, rigorous data protocols—such as those employed by national field stations—are vital for ensuring data accuracy and reliability. Moreover, regular evaluations, drawing on governance models from government or enterprise sectors, are also required to maintain management effectiveness. By integrating the monitoring of key environmental factors influencing elephant behavior—such as land-use change, food plant phenology, and climate change—the EEWS may achieve dual objectives: short-term early warning and long-term forecasting. These efforts will collectively establish a scientific, standardized, and efficient management framework, ensuring the system's long-term stable operation and supporting harmonious human–elephant coexistence.

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AUTHOR CONTRIBUTIONS

DENG Yun, YUAN Shengdong, DENG Xiaobao & CHEN Hui jointly conceived the study; LI Zhongyuan, GUO Xianming, and WANG Bin promoted the framework and applied it to practical implementation. DENG Yun drafted the manuscript; Ahimsa Campos-Arceiz and LIN Luxiang contributed to improving the manuscript text. All authors critically reviewed, revised, and approved the final version of the manuscript.

DECLARATION OF COMPETING INTEREST

The authors have no conflicts of interest to declare.

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