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REVIEW

RESEARCH AND APPLICATION OF CROP PEST MONITORING AND EARLY WARNING TECHNOLOGY IN CHINA

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KEYWORDS

China, law, early warning system and national crop pest monitoring, pest management, regulation and sustainable agricultural development

HIGHLIGHTS

- Crop pests are a major factor restricting agricultural production in China.
- The National Monitoring and Early Warning System (NMEWS) was established > 40 years ago.
- Application of NMEWS has increased national capability to tackle pests.

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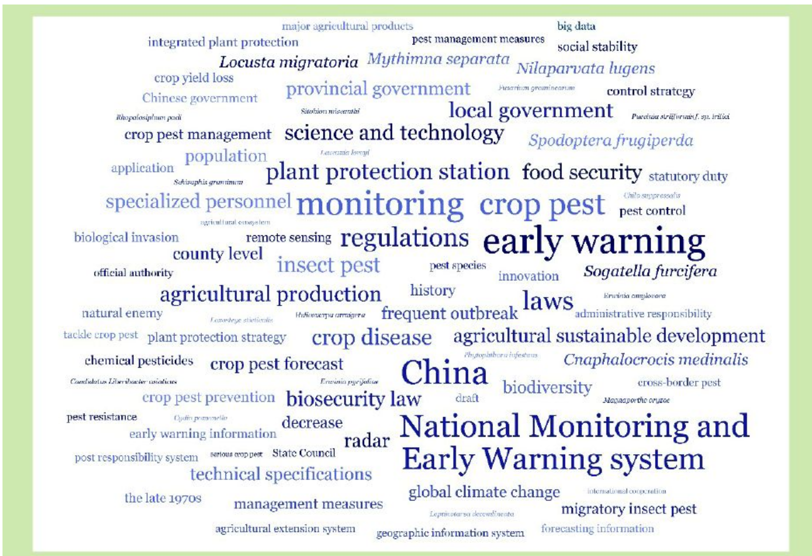
GRAPHICAL ABSTRACT



ABSTRACT

The importance of food security, especially in combating the problem of acute hunger, has been underscored as a key component of sustainable development. Considering the major challenge of rapidly increasing demands for both food security and safety, the management and control of major pests is urged to secure supplies of major agricultural products. However, owing to global climate change, biological invasion (e.g., fall armyworm), decreasing agricultural biodiversity, and other factors, a wide range of crop pest outbreaks are becoming more frequent and serious, making China, one of the world's largest country in terms of agricultural production, one of the primary victims of crop yield loss and the largest pesticide consumer in the world. Nevertheless, the use of science and technology in monitoring and early warning of major crop pests provides better pest management and acts as a fundamental part of an integrated plant protection strategy to achieve the goal of sustainable development of agriculture. This review summarizes the most fundamental information on pest monitoring and early warning in China by documenting the developmental history of research and application, Chinese laws and regulations related to plant protection, and the National Monitoring and Early Warning System, with the purpose of presenting the Chinese model as an example of how to promote regional management of crop pests, especially of cross border pests such as fall armyworm and locust, by international cooperation across pest-related countries.

1 INTRODUCTION

Food security is a major prerequisite of, and is essential for, human well-being, national prosperity, world peace, and development. China is one of the largest agricultural countries with > 1.4 billion people and 110 Mha of grain crops and has prioritized food security with the establishment of a national plant protection strategy. China once suffered widespread hunger and shortage of fiber and owns < 9% of the global arable land area but has now achieved great success in agricultural production[1]. According to the Information Office, Ministry of Agriculture and Rural Affairs of China (MARA), the area sown with grain was 117 Mha in 2020 and the total grain output reached 670 Mt[2] which now feeds nearly a fifth of the global human population[3].

China is the largest agricultural producer in the world and also one of the countries facing very serious annual damage by crop pests (referred to as crop diseases and insect pests in this review)[4]. In recent years, global climate change, biological invasion by pests such as fall armyworm, decreasing agricultural biodiversity and other factors have triggered more intense outbreaks of pests[4,5]. Also, evolution of pest resistance to pesticides, excessive use of chemical pesticides, a wide range of yield losses and pesticide-related environmental pollution pose an overwhelmingly negative drag on agricultural sustainable development[1,6]. Recognizing such serious challenges, countries such as Japan, Turkey, Australia and the United States have developed their monitoring, forecasting and warning systems for crop pests and the Chinese government has also promoted the development of the National Monitoring and Early Warning System (NMEWS)[7–11]. The aim of this review is to provide an overview of Chinese long-term efforts in the fight against major pests and to present the country's experience in crop pest monitoring and early warning technology to the world.

2 NECESSITY OF CROP PEST MONITORING AND EARLY WARNING IN CHINA

Pest control in China has developed greatly since the 1970s as the saved crop yield loss (i.e., the yield difference between natural loss and actual loss, where the natural yield loss is theoretically calculated in natural farming systems without human-directed pest management and control) caused by crop pests has increased by 24% and 51% in the past two decades, respectively, being 51 Mt in the 1990s (Fig. 1). The devastating pests of the most important food crops in China, i.e., maize, rice and wheat, account for over 65% of all agricultural production losses. Compared with 580 Mt yield of these three major crops in the 2010s, only 12 Mt grain was actually lost. Over time, it has been noted that China's success in achieving consecutive bumper harvests is particularly due to its capability to combat crop pests. However, the risk of crop pests continues to rise (Fig. 2)[12,13]. Between 1990 and 2019 the total area where impacts caused by pests of these three major food crops occurred increased by 24%, and consequently, the actual yield loss in 2010–2019 increased by 1.5 Mt.

Severe damage inflicted by regional pest outbreaks also occurs frequently[14]. In 2012, an outbreak of rice planthoppers (*Sogatella furcifera* and *Nilaparvata lugens*), the most important pests of rice in east Asia, occurred in most parts of south China[15]. A destructive epidemic of rice blast disease in in 2014 in which the total affected area was at least 5.1 Mha, was the most severe infestation since 2006[16]. In mid-December 2018 the fall armyworm (*Spodoptera frugiperda*) invaded Yunnan Province, south-west China[17] and has since quickly dispersed across east and south-east Asia, causing substantial damage to maize production[18]. Aside from the direct damage caused by the invasions of non-native crop pests, invasions incite the overuse and frequent sprays of pesticides[18]. Unfortunately, Chinese farmers have prioritized pesticides for pest control because of a lack of knowledge on pest management and the scientific application of pesticides[19]. Consequently, China has become the largest user of pesticides globally[20,21]. The effectiveness of some pesticides has also fallen over time due to rising pesticide resistance which in turn increases the possibility of pesticide abuse in small-scale agriculture[6,19]. In addition, wide-spectrum pesticide applications can decimate natural enemies and other beneficial organisms that provide ecosystem services for pest

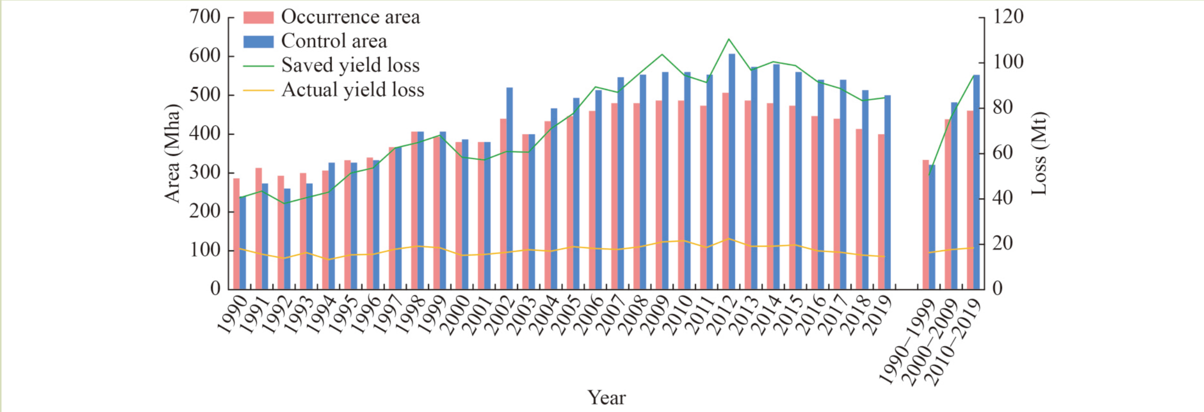


Fig. 1 Occurrence and control areas of pests and yield loss of crop production in China from 1990 to 2019. All data obtained from National Bureau of Statistics of China (NBSC) and National Agro-Tech Extension and Service Center (NATESC)[12,13].

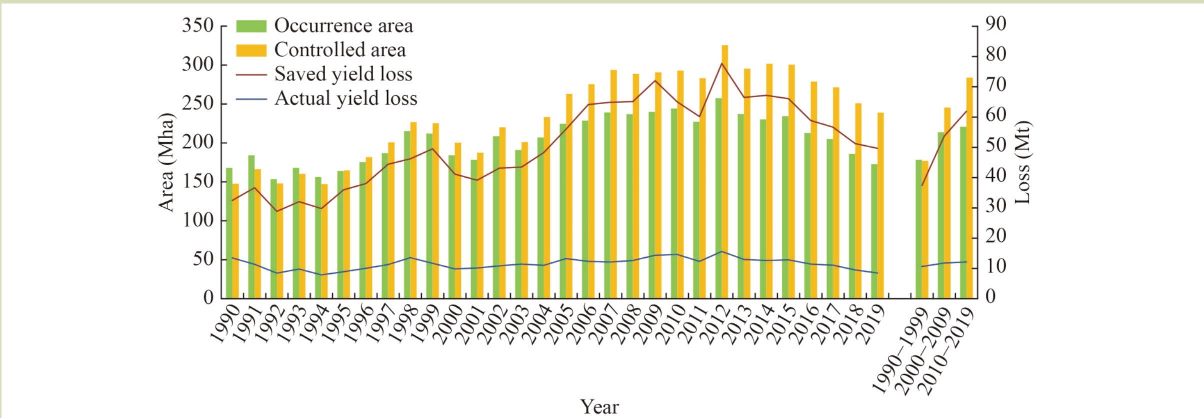


Fig. 2 Occurrence and control areas of pests and yield loss of maize, rice and wheat production in China from 1990 to 2019. All data obtained from National Bureau of Statistics of China (NBSC) and National Agro-Tech Extension and Service Center (NATESC)[12,13].

control[22,23]. Under such a critical situation the steady increase in agricultural production largely depends on the use of pesticide-based plant protection measures at the expense of the conservation of natural enemies, human health, the natural environment, and the sustainable development of agriculture in the future[1,24]. The world has also made impressive progress in global economic integration, bringing in a rich diversity of pests due to the circulation of agricultural products through trade and transport[25]. In the meantime, the threat from the invasion of exotic species, driven by socioeconomic factors, has been greatly aggravated[26]. Furthermore, biological invasions associated with global climate change are likely to occur more frequently[27]. For example, the possible response of invasive crop pests to global warming is leading to an increase in annual generations of pests and their population size, expanding the latitudinal ranges of both tropical crop hosts and pest species and changing trophic interactions that exacerbate damage caused by pests, any of which can represent major risks to agriculture[28–30]. The strategic adjustment of crop planting structure and modern intensive agriculture in China have reduced biodiversity in agricultural ecosystems and brought dramatic decreases in ecological services[31–33]. Consequently, this has also shaped the occurrence of pests and sometimes has markedly exacerbated the agricultural crisis[34]. Thus, agricultural productivity remains at risk[35]. The dispersal of major crop pests in China is also accelerated by the stepwise movement of the east Asian summer (or winter) monsoon which generates long-term south-westerly-southerly (or north-easterly-northerly) air currents that penetrate the major cropping regions throughout east China[36]. This further increases difficulties in monitoring and forecasting Chinese crop pests.

The use of science and technology in monitoring and early warning of major pests is therefore a fundamental part of an integrated plant protection strategy and is developing rapidly in China, driven by the rising demand for the sustainable development of agriculture. This effectively prepares local governments at all levels to cope with crop pests and also increases crop yields and reduces the danger of exposure to pesticides. This helps the nation to promote its 'green' revolution and sustainable development strategy to meet the needs of high-quality growth of agricultural production.

3 LEGAL REQUIREMENT FOR CROP PEST MONITORING AND EARLY WARNING

Accurate monitoring and forecasting of crop pests are the basis for effective management and control. China has formulated laws and regulations to further improve crop pest monitoring and early warning. In January 1993 the Chinese Ministry of Agriculture introduced the *Interim Regulation on Control of Monitoring and Early Warning of Crop Pests in China* and supplemented the management system of forecast issuing to strengthen the management and operation of crop pest monitoring and early warning work with legal guarantees and services. Over recent decades the accuracy and effectiveness of the application of crop pest monitoring and early warning technology have substantially improved.

3.1 Biosecurity Law

In October 2020, the *Biosecurity Law of the People's Republic of China* (abbreviated to the *Biosecurity Law*) was approved at a regular legislative session of the Standing Committee of the National People's Congress. This law came into force on April 15, 2021. It stipulates that biosecurity is a key component of national security and part of a holistic approach to safeguard national security. More specifically, biosecurity refers to the country's effective prevention and response to the threat of dangerous biological factors and related issues; to the steady and healthy development of biotechnology and human health and the ecosystem in a relative state of no danger and threat; to the biological field that can maintain national security and sustainable development.

The *Biosecurity Law* is a basic, comprehensive, systematic and dominant law in the field of biological security. It has a total of 10 chapters and 88 articles focusing on the main risks in the field of biosafety, improving the working mechanism of biosafety risk prevention and control, and striving to increase the national biosafety governance capability. The law specifies the responsibilities of the national network of the biosecurity coordination mechanism, which encompasses authorities of the health, agriculture and rural areas, and others, and the relevant military headquarters of the State Council.

In terms of prevention and control of high-risk newly emerging pests and sudden pest outbreaks threatening crop production, the law stresses the pressing need for establishing the NMEWS to comprehensively increase capacity to tackle major epidemics and outbreaks. Specifically, it requires professional institutes to voluntarily undertake monitoring work, comprising the collection, analysis, evaluation, and reporting of monitoring information, and predicting the dynamics of newly emerging pests and major pest epidemics. Additionally, governments at or above the county level are asked to release pest forecasts and early warnings in a timely, open, and transparent fashion and to respond swiftly to major epidemics as required by law.

3.2 Regulation on the Prevention and Control of Crop Pests

The State Council of China issued the *Regulation on the Prevention and Control of Crop Pests* on March 26, 2020 (abbreviated to the *Regulation* below). The *Regulation* stipulates that the prevention and control of crop pests shall be protected legally, representing an important milestone in opening a new era in the history of plant protection in China. It also clearly specifies the prevention and control principles, placement of prevention and control responsibilities, organization and management system of relevant agricultural departments of local governments at all levels, monitoring and control mechanisms, financial guarantees, the building of plant protection stations and standardized professional services. Thus, it forms a government-led whole-chain regulatory system that tackles crop pests with reasonable decision making, accurate policy implementation, and unified and scientific prevention and control measures to ensure that Chinese agricultural products are safe and of high quality, providing new opportunities for strengthening capacity building in scientific biosecurity governance.

Practical experiences and lessons in responding to major crop pest risks have also been drawn in the *Regulation* to reinforce the NMEWS. Firstly, the management system of the monitoring network should be improved by competent agricultural administrative departments of local governments at or above the county level; secondly, major pest monitoring, risk analysis, evaluation, decision making and forecasting need to be conducted according to industrial standards; finally, only competent agricultural administrative departments of local governments at or above the county level should have corresponding duties and authority to report and release forecasts and warning information.

3.3 Other regulations and rules for the management of crop pest monitoring and early warning

The *Interim Regulation on Control of Monitoring and Early Warning of Crop Pests in China* issued by the MARA in early 1993 has emphasized that crop pest forecasts are an important reference for agricultural administrative departments to make decisions on prevention and is the basis for guiding farmers to control pests safely, economically, and effectively. In accordance with the provisions of Article 2, issuing channels and platforms for crop pest forecasting or early warning information were prescribed, comprising radio, television, newspapers and other means of public transmission. The agricultural administrative departments at different levels hold the authority to release the forecasts or early warnings to the public, strictly classified into short-term (10 days prior to control), medium-term (10–30 days prior), long-term (> 30 days prior), very long-term (interannual or even several years prior to control) forecasts, and early warning of sudden outbreaks of crop pests. As introduced in Chapter 5, both the MARA and provincial governments must focus on issuing medium- to very long-term forecasts, while the prefectural and county level governments mainly announce short- to medium-term forecasts and early warnings, and the township governments submit short-term supplementary forecasts based on the forecasts of local governments.

The MARA released the draft *Management Measures for Crop Pest Monitoring and Forecasting* on November 5, 2020 which encourages provincial governments to propose suggestions and advice. This is the first time that the country has provided detailed clarification on the responsibilities of governments at all levels to implement the NMEWS for crop pests. The country will secure fiscal investment for monitoring and forecasting work and protect the rights and interests of the specialized personnel who undertake field surveys. In Chapter 2 of the draft, more rules emphasizing the construction of national, provincial, prefectural and county level monitoring networks, including the location of monitory and field scouting, provision of necessary infrastructure and supporting facilities for monitoring, a minimum number of specialized personnel, the performance of duties and responsibilities, corresponding analysis and assessment of monitoring information, and equipping of a computing platform are listed. The mechanisms of investigation and submission of monitoring information are defined in Chapter 3. Also, the mechanism of preparing detailed monitoring information reports is described. The draft also calls on monitoring data analysis, information prediction, and forecast issuing. In addition to the three main categories of short-, medium-, and long-term forecasts, early warning is supplemented and alerts are to be issued if any crop diseases or insect pests show the possibility of a future outbreak.

Local governments at prefectural and higher levels, including Tai'an City, Shanghai Municipality, Zhejiang Province, Sichuan Province, and Ningxia Hui Autonomous Region, have issued regulations or rules to fulfil their responsibilities for safeguarding local food security more efficiently. More importantly, publicity and education on the laws, regulations, and rules have been strengthened nationwide to promote the development of monitoring and early warning technology for tackling crop pests.

4 SCIENTIFIC RESEARCH AND TECHNOLOGICAL SUPPORT FOR CROP PEST MONITORING AND EARLY WARNING

Science and technology in China are well placed to provide powerful support for the construction and efficient implementation of NMEWS. Both the *Biosecurity Law* and the *Regulation* emphasize the crucial role of scientific advances and technological innovation which in return have become the main forces to put the laws and regulations into practice, enable the modernization of monitoring and forecasting technology, enhance the capabilities of biosecurity defense, and provide strong support for maintaining food security.

4.1 Scientific research and technological systems for crop pest monitoring and early warning

To meet the requirements of the development of monitoring and early warning technology for crop plant protection and biosecurity regulation, China has prioritized the strengthening of professional teams by providing enormous financial support to launch a range of research projects. Agricultural research platforms and bases, including the Institute of Plant Protection (IPP) under the Chinese Academy of Agricultural Sciences (CAAS), Nanjing Agricultural University (NAU), and other scientific research organizations, institutions, universities and colleges, sustainably promote the application of crop pest monitoring and early warning technology and support the fight against major crop pests.

Over recent years, impressive research processes in monitoring and early warning of crop pests by Chinese research organizations have been integrated. Specifically, the cooperation of the IPP, CAAS with Henan Academy of Agricultural Sciences and NAU, have established entomological radar monitoring networks in six jurisdictions, namely, Guangxi, Shandong, Inner Mongolia, Henan, Jiangsu, and Beijing, to conduct regional real-time monitoring and early warning of major agricultural migratory insect pests. In conjunction, simultaneous searchlight trapping, large-scale field survey, laboratory ovarian dissection, pollen grain detection and identification, stable carbon isotope analysis, atmospheric model-based trajectory simulation, remote sensing, geographic information systems (GIS), global positioning systems, ecological modeling and computer information techniques that are less labor-intensive and widely applied are also employed[37].

In addition to numerous studies on the biological characteristics and mechanisms of a wide diversity of crop pests, China has established education and training involving institutions of higher learning, research institutes, and enterprises. These organizations are responsible for professional training and cultivating specialized personnel, engineers, researchers, and experts in fields related to crop pest monitoring and early warning technology. Concurrently, to enhance technical competence and biosecurity awareness, these organizations incorporate graduate schools covering a broad range of curricula including plant protection, agricultural information and economics, and enrol students in master’s, PhD, and postdoctoral research programs. The *Biosecurity Law* also highlights the promotion of discipline and the growth of scientific research by nurturing talented researchers in basic sciences and specialized personnel.

4.2 Developmental history of scientific research and technology sustaining crop pest monitoring and early warning

China started improving its original agronomic measures to integrate management control strategies for agricultural pests in the 1950s to help ensure the supply of agricultural products and to combat poverty[38]. Chinese scientists started to study the morphology, geographical distribution, behavior and population dynamics of locusts by field observation and statistical analysis at the beginning of the 1950s[39,40]. Entomologists sought to gain a clear understanding of the overwintering distribution and migratory movement of armyworms during the late 1950s and 1960s. Winter breeding and overwintering areas were investigated throughout southern China and seasonal migration across China was proposed based on field population dynamics, for example, larval density and number of trapped moths[41]. In addition to mark–release–recapture experiments, net-catching and light-trapping on ships and mountain peaks were used to clarify the cross-sea, particularly long-distance, migration patterns of insect pests[41,42]. Importantly, the relationship between the population dynamics of aerial insects and weather (especially, humidity, temperature wind direction and wind speed) was also investigated.

Several national coordinated research groups have been formed since the late 1970s with cooperation between national agricultural organizations and universities to study migratory insects such as white-backed planthopper (*Sogatella furcifera*)[43], brown planthopper (*Nilaparvata lugens)*[44] and rice leaf roller (*Cnaphalocrocis medinalis)*[45]. Since 1977, a nationwide aerial insect monitoring network constructed with insect nets at > 40 monitoring sites on small islands and mountain peaks at heights of tens to thousands of meters was deployed to identify the following: (1) community structure and population dynamics of aerial insects in China, (2) potential source areas in early spring, (3) nationwide seasonal migration patterns, and (4) biological characteristics associated with migration, including swarming, flight gesture, development status of the ovary, and remigration behavior[46]. In addition, changes in the number of rice planthoppers caught using high-mounted insect nets were closely tied to population dynamics in local mountainous paddies, greatly contributing to the prediction and prevention of rice planthoppers[46].

During the 1980s, there was also rapid progress in migratory pest studies, especially studies on the biochemical and physiologic mechanisms that induce seasonal migration, the evolution of pest resistance, the influence of atmospheric conditions on insect pest mesoscale take-off and landing, simulation of migration trajectory, and radar detection of insect flight behavior[47,48]. Based on local to national field investigations over recent decades, numerous short-, medium-, and long-term prediction models for the population dynamics of major migratory insect pests have been developed which have provided the scientific basis for constructing the national computer network for crop pest monitoring and forecasting. Additionally, the practical application of optical remote sensing techniques for crop damage detection and pest monitoring started to be explored in the early 1980s when Lin[49] investigated the population density of wheat aphids and their damage by employing spectrometers and cameras.

Research since the 1990s on wind-assisted transport, aerial concentration and layers, and common orientation of migratory insect pests has been greatly stimulated by the increasing use of entomological radars for observing insect flight[48]. Benefiting from the early entomological radar observations and the known flight behavior parameters, the migration trajectory model has been extensively improved based on atmospheric variables to determine possible source regions and flight pathways[50]. Subsequently, Zhou et al.[51] built a stepwise regression model to make a medium-term prediction of the peak immigration of rice leaf roller and the corresponding numbers with a basic understanding of their origin. Also, a forecasting expert system for rice leaf roller was developed to provide early warnings of outbreaks for the subsequent two months[52].

Based on modern technology, a series of crop pest monitoring and forecasting information platforms have been established and substantially updated since 2002. A geographic information system of crop pest distribution was developed in 2005 to map and analyze the occurrence and distribution of major pest targets[53]. In 2006 an improved crop pest monitoring and forecasting information system was established to provide an integrative platform for monitoring, forecasting, early warning, and management[54]. It is also impressive that after > 20 years of research and practice the first monograph of *Agricultural Crop Pest Prediction in China* was published, comprehensively and systematically summarizing the theory and practical experience of pest forecasting in China and filling the knowledge gap of agricultural pest forecasting[55]. In 2008 the Immigratory Peak Forecast of Migratory Insect System was designed and operated based on the theory of atmospheric dynamics, to both construct the three-dimensional trajectories and landing areas of migratory insects and provide timely early warnings of their immigratory peaks[56]. The latest national dynamic monitoring and early forecasting system incorporating remote sensing information, forecasting algorithms and models, and a web GIS platform has been established to predict the infected areas of wheat stripe rust (*Puccinia striiformis* f. sp. *tritici*) and oriental migratory locust (*Locusta migratoria manilensis*) and to support decision making in pest management and control[57]. Other key technologies, especially in automatic data collection (either in the field or under light traps), computer network data transmission and management, real-time monitoring of microclimate and crop pests in the field and real-time remote monitoring systems, have been increasingly modernized to provide essential scientific support for the effective control of pests. Scientific professionals also research genetic differentiation and variation, frequent outbreaks and devastating epidemics related to global climate change, invasion and development mechanisms of high-risk exotic agricultural pests, as well as developing new technologies for risk assessment and early warning, information processing and remote analysis, rapid detection, testing and field monitoring.

Pest monitoring and early warning is being revolutionized with the advent of modern agricultural information technology. The accurate identification of a wide range of crop pests is a prerequisite for the routine implementation of monitoring work[38]. However, the diversity and complexity of the morphology and pathology of pests, especially highly mobile insects, in natural environments make automatic identification difficult. To identify crop pests in such uncontrolled conditions effectively and efficiently, recent digital technological advances in imaging, machine learning, deep learning, optical remote sensing observing, radar monitoring, Internet of Things, change detection in multi-temporal remote sensing, and computer information, especially artificial intelligence (AI), are used to increase the accuracy of the identification of major agricultural pests[58–61]. To enhance the role of AI in the monitoring and early warning of major crop pests, agricultural big data (especially the big earth data, which are derived from ground sensor records and satellite signals) analysis at multiple spatio-temporal scales is rapidly becoming a tool that can both extract valuable information from very large volumes of various data and analyze patterns and provide the predictive likelihood of outbreaks[62,63]. Moreover, the application of cloud computing has been encouraged in areas such as pest monitoring, tracing sources, outbreak prevention and control, and resource allocation.

Given that all crop insect pests (10 in total) of crops in China defined in Category 1 are migratory (described in Section 5) and their migratory flights typically occur at high altitudes beyond the reach of even powerful optical facilities[64], noticeable improvements have been made in insect monitoring studies through the application of radars comprising centimeter-wavelength scanning radar, millimeter-wavelength scanning radar, centimeter-wavelength vertical-looking radar, Doppler radar, and harmonic radar, since the first X-band entomological radar was built in 1981[47]. Long-term experience indicates that radar development and technological innovation are critical in increasing the ability to ensure national food security[65]. It has been invaluable in documenting migrations and identifying flight behaviors of several serious crop insect pest species including brown planthopper (*Nilaparvata lugens*)[66,67], beet armyworm

(*Spodoptera exigua*)[68], cotton bollworm (*Helicoverpa armigera*)[69–71], meadow moth (*Loxostege sticticalis*)[72], clover cutworm (*Scotogramma trifolii*)[73], rice leaf roller (*Cnaphalocrocis medinalis*)[74], oriental armyworm (*Mythimna separata*)[75,76] and other pests of public concern. The standard entomological radars have identification uncertainties which are usually tackled by a variety of supplementary aerial sampling measures including searchlight trapping, or occasionally with balloon- or plane-tethered netting[77–79]. In recent years, fully polarimetric radar has been used for its automatic applications in the direct observation and accurate measurement of biological parameters of insect targets including flight speed, orientation, body mass, body length and wingbeat frequency to meet the rising demand for precise detection and identification of flying pests[80,81]. This inspiring progress in entomological radar has greatly enhanced the observational capabilities of both high-altitude migration and low-altitude foraging flights of small insects.

Relatively cheap food attractants and pheromone traps have also been designed and widely used to monitor and trap target insect species to deal with adult insect pests dispersed in the field. However, the great diversity of insect pests and consequent disturbance from mixed odors in field conditions has made food luring difficult. This has been overcome by the use of new types of food attractants developed by assembling the volatile composition of host crops with synthetic volatile organic compounds[82].

Global climate change and increasing international trade and transportation have great impacts on the occurrence and distribution of crop pests, increasing concerns about the threat of exotic species invading Chinese sustainable agricultural production and long-term food security. Specific molecular markers and their corresponding test kits for quick detection have been successfully developed based on the molecular characteristics of important crop pests[83]. The accuracy and speed of quarantine inspection and identification of species and genetic characteristics of diseases or insect pests have also added to the effectiveness of their management and control.

5 ESTABLISHMENT AND DEVELOPMENT OF THE NMEWS IN CHINA

China has continually improved its NMEWS since the late 1970s to manage pest threats to national agricultural productivity and security. Taking advantage of the nation’s policies and government-led agricultural extension system has ensured the supply of grain and major agricultural products through the long-term development and application of the NMEWS.

5.1 Forty years of NMEWS history

The *Prevention-oriented Integrated Control* principle and policy were put forward in 1975 by the Chinese Ministry of Agriculture and Forestry (MAF) to mitigate the limitations and problems induced by chemical pesticides. This underlines the need to stress forecasting and prevention of crop pests[7,84]. In August 1978, the MAF set up the National Crop Pest Monitoring and Forecasting Center with the approval of the State Council of China, which marks a milestone in the establishment of the NMEWS and sets the stage for the NMEWS to be rolled out nationwide. Since then, provincial and regional stations have been established successively by the joint investment of the central and local governments, which preluded the building of a nationwide monitoring network for insect pests and epidemic diseases. Thus, a national monitoring and forecasting network has been established along the primary outbreak and migratory routes of major crop pests.

In 1983, the Ministry of Agriculture promulgated the *Post Responsibility System of monitoring and forecasting stations for crop pests in China* which further clarified the statutory duties, rules, and regulations of the stations at all levels and ensured that the network was implemented by both the official authorities and the national system. By 1984, the number of stations had increased dramatically to just over 1700 and the number of monitoring and forecasting specialized personnel was nearly 8700.

In 1995, the National Agro-Tech Extension and Service Center (NATESC, Fig. 3) under MARA was established by incorporating the National Crop Pest Monitoring and Forecasting Center. By 1999, with the rapid development of agricultural science and technology there were 32, 180 and 1800 provincial, municipal, and county level stations, respectively. At the same time, numbers of full-time and part-time specialized personnel and forecasters were over 7000 and 10,000, respectively.

Previous literature has also documented a series of agricultural extension system (AES) reforms implemented by the national government from 2003 and the latest study indicates that AES reforms have significantly improved the public service of agricultural extension stations to farmers[85]. In 2019, the total number of specialized personnel reached 49,000 and over 1030 monitoring and early warning stations were constructed throughout the nation of which over 450 stations are specifically responsible for rice pest monitoring and early

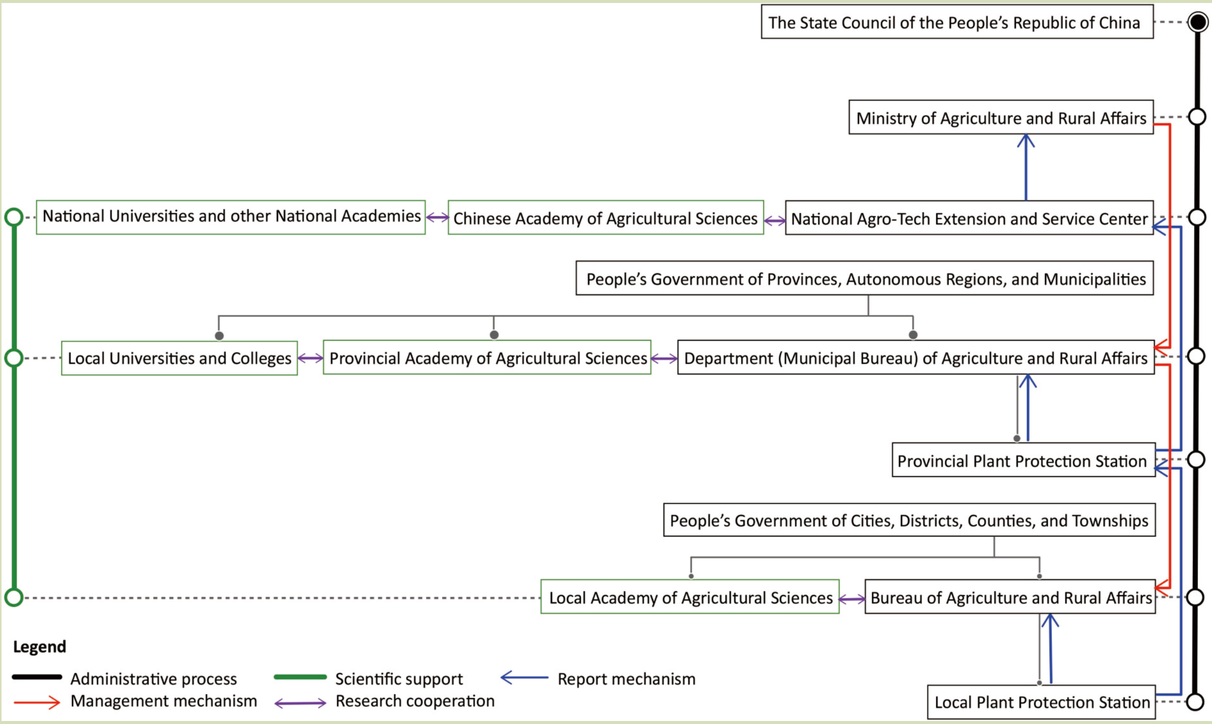


Fig. 3 The administrative governance system and technical support for monitoring and early warning of crop pests in China.

warning[86]. It has been a remarkable era that has led to the establishment of increasingly sophisticated monitoring and early warning system for crop pests at the national, provincial (including provinces, autonomous regions and municipalities), prefectural, county, and township levels.

5.2 The administrative governance system

The objective of the administrative system of the NMEWS is to enable local governments at the county level and above to manage and perform their statutory duties for crop pest monitoring and early warning. In 1983 the *Post Responsibility System of monitoring and forecasting stations for crop pests in China* was introduced to define the duties and responsibilities of local governments; establish rules for investigating, recording, and forecasting; implement a regular inspection mechanism; and launch a system of information coordination, reporting and sharing. Over recent years it has clarified statutory duties, rules and regulations for the stations at all levels and ensured that the network was implemented by both the official authorities and the national system.

5.2.1 Administrative responsibility and management

The responsibility system of provincial governors for monitoring and early warning of crop pests was implemented in May 2020 to accelerate the NMEWS legislation with the enforcement of the *Regulation*. The second chapter of the *Regulation* defines the powers and responsibilities of governments at all levels in safeguarding national food security in terms of monitoring and forecasting (Fig. 3, Table 1). Particularly, the Central Government is responsible for providing policy guidance and supervision and takes overall responsibility for establishing the NMEWS. The administrative department of MARA is responsible for compiling the construction plan of the national crop pest monitoring network and organizing its implementation and the agricultural and rural administrative departments of the provincial governments bear the primary responsibilities of their corresponding administrative regions of provinces, autonomous regions and municipalities. Also, all local governments strengthen the regulation and management of their crop pest monitoring networks, including repair and reconstruction.

Additionally, all regional monitoring stations and specialized personnel conduct systematic field surveys on crop pests under the supervision and governance of their local governments according to the technical specifications formulated by the provincial governments or above for monitoring and

Table 1 Current administrative governance and working mechanism of the National Monitoring and Early Warning System of crop pests (NMEWS) in China

Governments at all levels/agricultural administrative departments/organizations	Duties and responsibilities
The State Council of the People’s Republic of China*	①To construct a national system ②To implement the Biosecurity Law ③To promulgate the Regulation on the Prevention and Control of Crop Pests
Ministry of Agriculture and Rural Affairs§	①To implement the guiding principles, policies, and decisions related to agriculture ②To draft regulations on agriculture and formulate related norms and rules ③To direct the related law enforcement ④To propose the construction plan for the NMEWS ⑤To clarify the crop pests of Catalogue I in China
National Agro-Tech Extension and Service Center¶	①To draft national and agriculture industry standards for forecasting crop pests ②To issue national forecast and early warning of crop pests ③To direct national monitoring and provincial construction for the NMEWS ④To build national monitoring network linking regional key monitoring stations
Department (Municipal Bureau) of Agriculture and Rural Affairs+	①To implement NMEWS in corresponding administrative region ②To propose a regional construction plan for the NMEWS ③To clarify the crop pests of Catalogue II in China ④To build provincial monitoring network linking key monitoring stations ⑤To issue provincial forecast and early warning of crop pests
Provincial Plant Protection Station	①To draft provincial forecasting standards for local crop pests ②To conduct provincial field investigations periodically and seasonally ③To collect and manage the monitoring data from local plant protection stations ④To regularly analyze and report provincial monitoring information, forecast, or early warning ⑤To help local government make decisions on regional management and control strategy
Bureau of Agriculture and Rural Affairs¤	①To implement the NMEWS in the corresponding administrative regions ②To clarify the crop pests in Catalogue III in China ③To build county-level monitoring network with standardized field sites and necessary monitoring facilities and equipment ④To issue local forecast and early warning of crop pests
Local Plant Protection Station	①To implement the NMEWS locally ②To set up monitoring sites with necessary facilities and equipment ③To issue local forecast and early warning of crop pests ④To conduct systematic field surveys ⑤To regularly analyze and report monitoring information, forecast, or early warning ⑥To help local government make decisions on regional management and control strategy ⑦To guide farmers to carry out timely preventive actions
National or regional scientific research and education institutions, universities, and non-government organizations	①To conduct basic and applied research related to the NMEWS ②To develop new technologies affecting agriculture ③To provide scientific support to NATESC for the development of the NMEWS ④To exchange technologies and conduct cooperative research with other agricultural research institutions, domestic and international universities, and global non-government organizations ⑤To educate and foster graduate students, postdocs, technical personnel, engineers, etc.

Note: *, The Central Government. §, A ministerial-level component of the State Council. ¶, Directed by the MARA. +, The Provincial Government. ¤, The Local government at prefectural, county, and township levels.

forecasting of crop pests (Table 1). The main tasks that are part of monitoring crop pests are described in the *Regulation* and include: (1) the name and species of crop diseases or insect pests, and the time, area and extent of occurrence; (2) the name and species of the main natural enemies, and the distribution and development of insect pest populations; (3) field climatic conditions affecting the occurrence of crop pests; and (4) other monitoring activities. Monitoring data such as growth stage of crop plants, infestation ratio, field population density, daily searchlight/light trap catch, control area etc. for major pests on important crops including cotton, maize, potato, rapeseed, rice and wheat, are uploaded to the China Crop Pest Management

Information System, constructed and supervised by the NATESC since 2009. This national platform has two subsystems designed for domestic crop pests and invasive fall armyworm, namely, the National Web-based Monitoring and Early Warning System for Crop Pests and the Occurrence and Control Information Management System for fall armyworm, respectively. Both subsystems are composed of six key modules designed for data collection, data management and submission, data processing and analysis, display of outbreak situations and trends, expert consultation, and release of forecast and early warning information[87]. This has been deployed in 31 provinces (autonomous regions and municipalities) and > 1000 regional plant protection stations which have an essential role in increasing the monitoring and early warning capacity of major crop diseases and insect pests.

Meanwhile, all local governments need to report pertinent, and unified, monitoring information to a higher authority (Fig. 3). Also, crop pests forecast based on a comprehensive analysis of field observations must be announced in a timely manner as per the provisions of the laws and regulations, and no organizations or individuals are given the authority to publicly issue early warning information to society.

5.2.2 Category-wise monitoring of target pests

The category-based management of crop pests is a critical requirement for clarifying and implementing the responsibilities of governments at all levels to monitor, forecast, manage and control. There are well over 2,000 pest species (including mites and mollusks) and 820 plant diseases challenging Chinese agricultural production, primarily in 15 predominant crops in seven categories, including grain (maize, potato, rice, soybean and wheat), fiber (cotton, flax and ramie), oil (peanut and rapeseed), sugar (sugar beet and sugarcane), fruit (apple, citrus and pear), and camellia (tea tree)[88]. According to the characteristics of crop pests and their damage to agricultural production, three categories (Category 1, 2, and 3) have been defined by the *Regulation*. In particular, the major migratory, epidemic, frequent outbreak-causing, and quarantine crop pests that cannot be managed by one region (such as province, autonomous region, or municipality) alone and must be controlled by adopting unified and coordinated measures at the national level are defined in Category 1; those that need to be coordinated and controlled at the provincial level belong to Category 2; and those that can be supervised by the county-level government belong to Category 3.

Also, according to the *Regulation*, the crop pests in Category 1 have been formulated and announced by the MARA (Fig. 3). The list contains 16 major pest species that threaten major crops in China. In rice production, rice leaf roller (*Cnaphalocrocis medinalis*), rice planthopper (including brown planthopper, *Nilaparvata lugens* and white-backed planthopper, *Sogatella furcifera*), rice stem borer (*Chilo suppressalis*), rice blast (*Magnaporthe oryzae*), and southern rice black-streaked dwarf virus are included. In wheat production, two epidemic diseases are wheat scab (*Fusarium graminearum*) and wheat stripe rust (*Puccinia striiformis* f. sp. *tritici*), and pest species of wheat aphids (*Rhopalosiphum padi, Schizaphis graminum* and *Sitobion miscanth*) are included. In maize production, oriental armyworm (*Mythimna separata*), armyworm (*Leucania loreyi*) and invasive fall armyworm (*Spodoptera frugiperda*) are listed. In potato production, potato late blight caused by *Phytophthora infestans* takes first place in occurrence and damage followed by Colorado potato beetle (*Leptinotarsa decemlineata*). In addition, other polyphagous, migratory and fulminant pests including locust (*Locusta migratoria*), meadow moth (*Loxostege sticticalis*), codling moth (*Cydia pomonella*), *Candidatus Liberibacter asiaticus* (causing haunglongbing in citrus) and *Erwinia amylovora* and *Erwinia pyrifoliae* (causing fire blight in pears) are included.

5.2.3 Technical specifications

China is now highly experienced in establishing and implementing the NMEWS, especially in the construction of monitoring facilities and regional stations, exploration and formulation of technical specifications for forecasting crop pests, and training specialized personnel by running national training courses on monitoring and forecasting of crop pests in which over 3000 specialized personnel have been enrolled. In addition, consultations and discussions are held through annual and seasonal conferences, both nationally and locally.

For technical specifications (i.e., industrial standards) for forecasting crop pests, monitoring tools, field survey methods, data collection, processing and transmission, prediction modeling, occurrence intensity classification and prediction accuracy evaluation have been standardized according to the characteristics and occurrence of the targets (Table 2). The national prediction standardization, data- or information-transmission-network building, forecast visualization, and intelligent technology development has driven rapid progress in the NMEWS. The *Forecast Measure of Locust* was the first standardized scheme formulated by the MARA implemented in 1952. Between 1987 and 1990 the MARA approved 15 technical specifications for forecasting major crop pests including *Helicoverpa armigera*, *Leucania loreyi*, *Locusta migratoria*, *Magnaporthe oryzae*, *Mythimna separata*, *Nilaparvata lugens*, *Puccinia striiformis* f. sp. *tritici* and

Table 2 List of standards for monitoring and forecasting of main crop pests in China since 2002

No.	Title	Standard No.	Issuing date	Implementation date
1	Rules for the investigation and forecast of wheat aphides	NY/T 612-2002	2002.12.30	2003.3.1
2	Rules for the investigation and forecast of wheat powdery mildew [*Blumeria graminis* (DC.) Speer]	NY/T 613-2002	2002.12.30	2003.3.1
3	Rules for the investigation and forecast of wheat sharp eyespot (*Rhizoctonia* spp.)	NY/T 614-2002	2002.12.30	2003.3.1
4	Rules for the investigation and forecast of wheat spider	NY/T 615-2002	2002.12.30	2003.3.1
5	Rules for the investigation and forecast of wheat blossom midge	NY/T 616-2002	2002.12.30	2003.3.1
6	Rules for the investigation and forecast of wheat leaf rust (*Puccinia recondite* Rob.*et* Desm.)	NY/T 617-2002	2002.12.30	2003.3.1
7	Rules for forecast technology of the peach fruit moth (*Carposina sasakii* Matsumura)	NY/T 1610-2008	2008.5.16	2008.7.1
8	Rules for programing technology of the crop pest TV-forecasting	NY/T 1612-2008	2008.5.16	2008.7.1
9	Rules for forecast technology of the meadow moth [*Loxostege sticticalls* (Linnaeus)] in agricultural area	NY/T 1675-2008	2008.8.28	2008.10.1
10	Rules for investigation and forecast technology of the Potato Late Blight [*Phytophthora infestans* (Mont.) de Bary]	NY/T 1854-2010	2010.5.20	2010.9.1
11	Rules for investigation and forecast technology of the Tibetan Locust (*Locusta migratoria tibetensis* Chen)	NY/T 1855-2010	2010.5.20	2010.9.1
12	Rules for investigation and forecast technology of rape sclerotiniose [*Sclerotinia sclerotiorium* (Lib.) de Bary]	NY/T 2038-2011	2011.9.1	2011.12.1
13	Rules for investigation and forecast technology of the pear fruit moth (*Grapholitha molesta* Busck)	NY/T 2039-2011	2011.9.1	2011.12.1
14	Rules for investigation and forecast technology of Wheat Yellow Mosaic	NY/T 2040-2011	2011.9.1	2011.12.1
15	Rules for investigation and forecast technology of the rice gall midge [*Orseolio oryzae* (Wood-Maspn)]	NY/T 2041-2011	2011.9.1	2011.12.1
16	Rules for forecast technology of cotton mirid bugs	NY/T 2163-2012	2012.6.6	2012.9.1
17	Rules for investigation and forecast technology of Asian migratory locust (*Locusta migratoria migratoria* Linnaeus)	NY/T 2358-2013	2013.5.20	2013.8.1
18	Rules for investigation and forecast technology of the paddy stem borer [*Tryporyza incertulas* (Walker)]	NY/T 2359-2013	2013.5.20	2013.8.1
19	Technical specification for investigation and forecast of maize rough dwarf disease	NY/T 2621-2014	2014.10.17	2015.1.1
20	Rules for investigation and forecast of southern rice black-streaked dwarf virus	NY/T 2631-2014	2014.10.17	2015.1.1
21	Rules for investigation and forecast of disease caused by rice black-streaked dwarf virus	NY/T 2730-2015	2015.5.21	2015.8.1
22	Rules for investigation and forecast of *Agrotis ipsilon* (Rottemberg)	NY/T 2731-2015	2015.5.21	2015.8.1
23	Rules for population monitoring of crop insect pests by sex pheromone traps (for Pyraloidea and flying-behavior liked moths)	NY/T 2732-2015	2015.5.21	2015.8.1
24	Rules for forecast technology of mirid bugs—Part 1: Cotton	NY/T 2163.1-2016	2016.10.26	2017.4.1
25	Rules for forecast technology of mirid bugs—Part 2: Fruit trees	NY/T 2163.2-2016	2016.10.26	2017.4.1
26	Rules for forecast technology of mirid bugs—Part 3: Tea plant	NY/T 2163.3-2016	2016.10.26	2017.4.1
27	Rules for forecast technology of mirid bugs—Part 4: Alfalfa	NY/T 2163.4-2016	2016.10.26	2017.4.1
28	Rules for forecast technology of *Bemisia tabaci* Gennadius—Cotton	NY/T 2950-2016	2016.10.26	2017.4.1
29	Technical specification for forecast technology of the corn borer	NY/T 1611-2017	2017.12.22	2018.6.1
30	Technical specification for forecast technology of *Athetis lepigone* (Mŏschler)	NY/T 3158-2017	2017.12.22	2018.6.1
31	Rules for the investigation and forecast of the rice stripe virus	NY/T 1609-2018	2018.7.27	2018.12.1
32	Technical specification for population monitoring of crop insect pests by sex pheromone traps (for Noctuidae and flying-behavior liked moths)	NY/T 3253-2018	2018.7.27	2018.12.1

(Continued)

No.	Title	Standard No.	Issuing date	Implementation date
33	Technical specification for forecast technology of sweet potato whitefly—Vegetables on open fields	NY/T 3544-2020	2020.3.20	2020.7.1
34	Technical specification for forecast of cotton thrips	NY/T 3545-2020	2020.3.20	2020.7.1
35	Technical specification for forecast of corn leaf blight	NY/T 3546-2020	2020.3.20	2020.7.1
36	Technical specification for forecast of Cotton bollworm in corn field	NY/T 3547-2020	2020.3.20	2020.7.1
37	Construction specification of observation field for crop diseases and insect pests	NY/T 3698-2020	2020.8.26	2021.1.1
38	Technical specification for forecast technology of corn aphides	NY/T 3699-2020	2020.8.26	2021.1.1
39	Technical specification for forecast technology of cotton *Verticillium* wilt	NY/T 3700-2020	2020.8.26	2021.1.1
40	Technical specification for forecast of fall armyworm	NY/T 3866-2021	2021.5.7	2021.6.1
41	Technical specification for investigation and forecast of *Locusta migratoria manilensis* (Meyen)	GB/T 15803-2007	2007.10.16	2008.4.1
42	Rules of investigation and forecast for the Asiatic rice striped borer [*Chilo suppressalis* (Walker)]	GB/T 15792-2009	2009.3.27	2009.10.1
43	Rules of investigation and forecast for the rice planthopper (*Nilaparvata lugens* stål and *Sogatalla furcifera* Horváth)	GB/T 15794-2009	2009.3.27	2009.10.1
44	Rules for investigation and forecast of the armyworm [*Pseudaletia* (Mythimna) *separate* Walker]	GB/T 15798-2009	2009.3.27	2009.10.1
45	Rules for investigation and forecast of the cotton bollworm (*Helicoverpa armigera* (Hübner))	GB /T 15800-2009	2009.3.27	2009.10.1
46	Technical specification for the forecast of diseases and insects on cruciferous plants—Part 3: *Plutella xylostella* Linnaeus	GB/T 23392.3-2009	2009.3.27	2009.10.1
47	Technical specification for the forecast of diseases and insects on cruciferous plants—Part 4: *Spodoptera exigua* (Hübner)	GB/T 23392.4-2009	2009.3.27	2009.10.1
48	Rules of investigation and forecast for the rice leaf-roller (*Cnaphalocrocis medinalis* Guenée)	GB/T 15793-2011	2011.9.29	1996.6.1
49	Rules for monitoring and forecast of the cotton aphid (*Aphis gossypii* Glover)	GB/T 15799-2011	2011.9.29	2011.12.1
50	Rules for monitoring and forecast of the cotton pink bollworm (*Pectinophora gossypiella* (Saunders))	GB/T 15801-2011	2011.9.29	2011.12.1
51	Rules for monitoring and forecast of the cotton spider mites (*Tetranychus* spp.)	GB/T 15802-2011	2011.9.29	2011.12.1
52	Rules for monitoring and forecast of the sorghum aphid (*Melanaphis sacchai* Zehnter)	GB/T 15804-2011	2011.9.29	2011.12.1

Note: The standards for monitoring and forecasting of main crop pests in China from No. 1 to No. 41 were introduced by the Ministry of Agricultural and Rural Affairs of the People's Republic of China and the standards Nos. 42–53 were introduced by the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China & Standardization Administration.

Sogatella furcifera. These technical specifications have been implemented throughout the country since December 1995. Some of these have been revised and reissued. Since 2002, 38 technical specifications proposed by the NATESC have been introduced for the forecasting of other dominant pests hampering crop production security.

5.2.4 Data collection and epidemic information release

The focus of the implementation of the NMEWS is to provide timely and precise forecast information and to announce early warnings of crop pests over longer periods. The means of information transmission is critical to all facets of the NMEWS application. The comprehensive method of analysis and prediction is widely applied to provide short-, medium-, or long-term forecasts of crop pest occurrence. More specifically, statements on forecast or early warning about "what will happen" and "whether, when and how to respond" in the subsequent phase are principally obtained from the practical and scientific knowledge of the forecasters, relevant experience, and a large amount of data and other information they collect, which largely depends on their expert acuity and logical mindset. After a brief discovery phase in the late 1970s, mathematical and statistical models and a question answering system (i.e., expert system) have been effectively used to increase the accuracy and effectiveness of prediction.

As recommended in the *Interim Regulation on Control of Monitoring and Early Warning of Crop Pests in China* and improved in the draft *Management Measures for Crop Pest Monitoring and Forecasting*, the submission channels and platforms, both onsite and online, have been updated from telegram and letter to modern media including broadcast, press, website and WeChat subscription. As stipulated, the monitoring information and forecast of crop pests belonging to Category 1 should be regularly reported to the MARA and the provincial government. During the crucial period of occurrence of the pest targets of Category 1 the nation should implement a strict weekly-submission mechanism. When the invasion, emergent epidemic or outbreak of any crop pest occurs the local government at the county level or above should report the information within 24 h after verifying the situation. The draft has substantially expanded the coverage of forecasts to prepare local governments and farmers for the battle against serious crop pests. Consequently, detailed management and control strategies for crop pests can be proposed timely and accurately by the local or the state governments to ensure optimum harvest and maintenance of overall economic and social stability. In contrast, long-range monitoring of windborne diseases and migratory insect pests can help agricultural governors make better decisions on construction of new monitoring sites and establishing nationwide light- or pheromone-trapping networks in the source/landing regions and along the migration corridors.

6 PRESENT AND FUTURE OUTLOOK

As documented in this review, legislative efforts have been increasingly implemented to ensure that the monitoring and early warning of crop pests is done on a sound legal basis. Experience shows the importance of laws and regulations in ensuring food supply and achieving sustainable growth in agricultural production. Although NMEWS has entered a new period of rapid and efficient development, local authorities should effectively fulfil their obligations and responsibilities under the national legal instruments on crop pest monitoring and early warning as well as consolidate and develop the existing legal system for the implementation of the NMEWS. In addition, the implementation of the *Biosecurity Law*, the *Regulation*, and other rules related to the NMEWS needs to be further supervised.

Experience also shows that scientific advances and technological innovations and the education and fostering of scientists, technologists and engineers, as well as high-performance innovation teams, are critical to the improvement of the law-based NMEWS by the reconstruction of agricultural production. According to the implementation of the Rural Vitalization Strategy, a significant national strategy in China, modern, high-quality, ecologically-sound and sustainable development of agriculture is pursued through scientific and technological innovation. Despite the unprecedented growth in the supply of agricultural products and noticeable improvement in food security, China is still under high pressure to deal with both domestic and exotic economically important crop pests. To prevent frequent outbreaks of major crop pests scientifically, technological innovation-led management and control strategies are implemented based on the performance, improvement, and modernization of the NMEWS. According to the Ministry of Science and Technology, China has substantially increased funding and provided more resources and policies to accelerate breakthroughs on core and key agricultural technologies and to introduce advanced technologies and scientific ideas. Future studies based on the rapid progress of basic research and advances in internet technology and cloud technology, an integrated space, air and ground network for precise long-term monitoring and forecasting of crop pests, should be conducted where the workflow is initiated by big earth data from remote sensing (e.g., radar, satellite and sensor), trapping (e.g., food attractants, light traps, pheromone traps and searchlight traps), detection (e.g., field investigation), and climate and weather monitoring and forecasting, and then operated with AI-supported real-time monitoring, mathematical simulation, forecasting models and algorithms for all aspects. Subsequently, all information is displayed via the platform, processed for decision making and effective action is rapidly taken when necessary.

Other countries are also affected by crop pests and for other countries that are currently impacted by devastating crop pests or where the mitigation of damage largely relies on synthetic pesticides there are lessons in Chinese experience of government-led buildup and implementation of the NMEWS to ensure food security for the whole of society. As most predominant and serious crop pests are easily spread through frequent international transportation, agricultural product trades, or even wind-assisted spread, the rapid development of NMEWS may provide more useful data and information on pest occurrence to other countries. Some of the most dangerous transboundary crop pests such as locust and fall armyworm require some international organizations such as the Food and Agriculture Organization of the United Nations to construct an intercontinental or transnational monitoring and early warning network through exchange and cooperation projects between countries to guide and coordinate the prevention and management of the pests in large regions across the countries involved.

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Compliance with ethics guidelines

Qiulin Wu, Juan Zeng, and Kongming Wu declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any study with human or animal subjects performed by any of the authors.

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