# Recent development of unmanned aerial vehicle for plant protection in East Asia

He Xiongkui[1*], Jane Bonds[2], Andreas Herbst[3], Jan Langenakens[4]

(1. *College of Science, Centre for Chemicals Application Technology (CCAT), China Agricultural University, Beijing 100193, China*;
2. *Bonds Consulting Group LLC, Panama City Florida 32408, USA*; 3. *JKI - Federal Research Centre for Cultivated Plants, Institute for Application Techniques in Plant Protection, Messeweg 11/12 D-38104 Braunschweig, Germany*;
4. *AAMS-Salvarani, Vliegplein 14A, 9991 Maldegem, Belgium*)

**Abstract:** Recently, the growing use of unmanned aerial vehicles (UAV) for pesticide application has been reported against a wide range of crops with promising results in East Asian countries such as Japan, South Korea and China. This UAV-based application technology for agrochemicals is considered as a high efficiency alternative to the conventional manual spray operations and a low-cost choice as compared to the classical manned aerial application. However, the technology adoption rate and the designed optimal sprayer suitable for drone application for small scale farm remains at the development stage in China and also in Japan. This paper reports the current status of drone pesticide application in China and makes comparisons with its neighbor countries Japan and South Korea in terms of different UAV platforms and their implementation in plant protection for different crops. Challenges and opportunities for future development of UAV-based pesticide application technology are also discussed.

**Keywords:** plant protection, UAV pesticide application, RPA spray technology, spray quality, flight control, agrochemical application

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## 1 Introduction

Nowadays, the structure of the rural labor force in China has changed seriously, with increasing severe contradiction between demand and lack of the rural labor, so high efficient agricultural equipment is urgently needed for serving agricultural production[1-5]. Different from the situation that the crop is cultivated in plain areas in the Occident, the ecological conditions of growth of Asian food crop and commercial crop are complex small plot, small scale and non-planar plantation in highland, and cropping system varies a lot, in addition, pests and diseases of crop happen repeatedly and frequently because of high temperature and humidity[6-8]. According to FAO's data, natural loss ratio was more than 37%[9]. If prevention and control measures were not carried out, Chinese yearly paddy rice yield would have decreased by 50 billion kg and the potential economic loss could have exceeded 200 billion RMB[1,10-12].

Since 21st century, influenced by kinds of factors such as climate warming, cropping system changes, frequent international trade, increasing pesticide resistance, etc., Asian crop pests and diseases show many new characteristics: the frequency of the outbreak of pests is increasing year by year; migratory pests appear continuously; epidemic crop pests and diseases happens

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**Biographies: Jane Bands**, PhD, research interests: aviation chemical application, Email: jasbonds@gmail.com; **Andreas Herbst**, PhD, research interests: plant protection equipment and chemical application, Email: andreas.herbst@julius-kuehn.de; **Jan Langenakens**, PhD, research interests: plant protection equipment test and chemical application, Email: jan.langennakens@aams-salvarani.com.

***Corresponding author: He Xiongkui**, PhD, Professor, research interests: plant protection equipment and chemical application. College of Science, Centre for Chemicals Application Technology (CCAT), China Agricultural University, Beijing 100193, China. Tel: +86-10-62731446, Email: xiongkui@cau.edu.cn.

rampantly; regional disaster pests often break out; resistant pests burst seriously; quarantining pests invade violently. Meantime, the new circumstances of modern agricultural construction are those making agriculture realize the goal of high yield, high quality, high efficiency, ecology and safety, realizing green consumption and sustainable development, and building resource-saving and environmental-friendly agriculture. Therefore, in order to adapt these new circumstances, agricultural UAV is developed quickly in Asia, providing powerful support for promoting agricultural production security, quality and safety of agricultural products, agricultural ecological security and agricultural trade security[1,13-18].

Medium or small unmanned aerial vehicles (UAV), also known as drones or remotely piloted aircraft (RPA) systems are increasingly investigated and used nowadays for pesticide applications in East Asian countries such as Japan, Korea, and China. The rapid development of Asian agricultural UAV is mainly due to its advantages including: (1) UAV does not require any dedicated airport and navigation station, and may land on the edge of cultivated land, the highway and the top of a truck, reducing the expenditure of airline and for agriculture and forestry; (2) the short turning radius of UAV could help it hover and turn round flexibly in the air; (3) the high rate of climb of UAV could help it fly vertically and have good performance of super low flight; (4) low rate of no-load flight of UAV and filling fuel and liquid on the ground of working area could reduce invalid working time; (5) UAV is suitable for working in rough terrain and small plots with high efficiency; (6) high automaticity, less flight crew, low labor intensity and simple to use and maintain as compared to traditional manned aircraft[10,15,19-23].

In terms of spray effect: (1) UAV's high working efficiency and good spray performance is as great as helicopter; (2) UAV can change velocity flexibly, accelerate from 0 to the normal speed directly, and get better droplets coverage at low speed, also especially its downwash flow generated by rotors may reduce the droplets drift and the upflow generated by the downwash flow let droplets crash into the reverse side of plant leaves; (3) UAV is able to spray a single plant of crop as it has the function of hovering in the air[24-28].

In terms of cost and safety: (1) the whole working cost of UAV is relatively less than manned aircrafts – the most part of UAV's expense is purchase and its cost performance is better as UAV doesn't need airport; (2) UAV's security coefficient is much higher, and especially when failure of engine, the operator of unmanned rotorcraft could depend on the rotation of rotors and correct operation to let its forced landing speed close to 0. Besides, the flight security and foreseeability of helicopter is able to be improved via decreasing speed[1,5,29-35].

## 2 Development of small UAV spray technology for plant protection in Asia

### 2.1 Small crop-protection UAV and technology in Korea

South Korea does not produce unmanned aerial vehicle itself and mostly imports Japanese UAV and pesticide application technology. South Korean UAV pesticide application technology is basically similar to Japan, with 2-3 times of yearly UAV pesticide application in paddy field. Therefore, Chinese and Japanese agricultural UAV development situations are mainly analyzed in this paper[25,26,28].

### 2.2 Chinese small UAV and technology for plant protection

Chinese agricultural aviation started relatively late, but developed fast in the past 10 years for low-altitude low-volume aviation pesticide application. Historically, manned aerial application in China began in the early 1950s, when fixed-wing aircraft was the major vehicle used for perform the tasks. Popular aircraft models used in aerial application include 'Y5-B(D)', 'Y-11', 'Blue Eagle AD200N', 'Bee-3', 'Petrel-650B' and others. In the 1990s, the pesticide application model '3QWF' was designed for ultra-light aircraft, with the ability to provide pest control of field crops, such as paddy, wheat and cotton, chemical weeding, prevention locust disaster on the grasslands and forest pest control. Model 'Blue Eagle AD200N' aircraft, produced by Beijing Keyuan Light Aircraft Co. Ltd, was mainly used in agricultural and forest pest control, epidemic prevention and water purification, with the application swath from 22 m to 30 m, the velocity of 110 km/h and daily working area up to 667 hectares, but the application rate was only 1.50-3.75 kg/hm$^2$ and the control efficacy was above 90%. Model 'Petrel-650B' aircraft, combined with model 'HU2-HW1' ultra-low volume spraying device and model 'NT100GPS' navigation system, was applied in pest control in Wuming forest region of Guangxi Region and experiments were researched. Now, China owns 1400 agricultural fixed-wing aircraft, more than 60 helicopters and over 10 000 UAVs, and the area of agricultural and forest pest and disease control and fertilization using fixed-wing aircraft and helicopters reaches two million hectares. However, Chinese agricultural aviation developmental level still lags behind those developed nations. Chinese agricultural aircraft quantity is only 0.13% of the sum of global agricultural aircraft; the working area of agricultural aviation accounts for 1.70% of cultivated area (developed nations 40%-50%); spraying device has poor performance[1,25,28,36-40].

Chinese universal light agricultural UAVs are mostly 'Z-3', DJI 'MG-1', 'Tianying-3', single-rotor model 'CAU-3WZN10A' and multi-rotor model '3WSZ-15' developed by China Agricultural University, and so on. In the recent 10 years, agricultural UAV low-altitude and low-volume application sprang up gradually and developed fast. According to the statistics of Chinese Ministry of Agriculture, before May of 2016, there were totally 178 types of agricultural UAVs in the whole nation, whose working efficiency can up to 6-10 hm$^2$/h with 5-20 L liquid-tank and 5-20 m spraying swath under different application conditions, applying for field crops chemical control. Up to now, 95% of Chinese agricultural aviation technology was applied in aerial plant protection works, and other 5% was applied in agricultural information acquisition, aerial photography, assisted breeding, and so on. Agricultural and forestall aerial working time was 33 158 h in 2011 and it was mainly used in Heilongjiang, Inner Mongolia, Xinjiang, Henan and other major grain producing areas, but the aerial application area is less than 3% of total plant-protection working area[1,25,38,41-45].

Chinese agricultural UAVs are divided into two types according to the structure: single-rotor UAV and multi-rotor UAV, and the power system can be divided into two types: motor and diesel, and there are more than 10 types of UAVs. The empty weight is generally from 10 kg to 50 kg, and the working height is from 1 m to 5 m, and the working velocity is less than 8 m/s. The kernel of electric power system is the motor, with the characteristics of flexible operation, rapid rising and landing and 10-15 min's single flight time. The key of diesel power system is the engine, so the diesel UAV needs a longer time of rising and landing because of poor flexibility and large fuselage, and this type of UAV's single flight time can exceed 1 h and the maintaining is more complex. The tank volume of single-rotor UAV is mainly 5-20 L and part of UAVs may achieve 30 L. The multi-rotor UAV mostly adopts the electric power system, with less loading than single-rotor UAV, and the tank volume mostly ranges from 5 L to 10 L. The multi-rotor aircraft has the features of simply structure, convenient maintaining and high stability, and the spraying efficiency can reach 0.2 hm$^2$/min as shown in Figure 1[1,25,40,42,46-51].

a. Single-rotor battery-powered UAV designed by China Agriculture University (CCAT) in 2010 with 10 L chemical liquid-tank (CAU-3WZN10A)

b. Eighteen rotors battery-powered UAV made in China with 15 L chemical liquid-tank (3WSZ-15)

c. Sixteen rotors battery-powered UAV made in China with 30 L chemical liquid-tank (3WYR-30)

Figure 1 Single- and multi-rotor UAVs for plant protection in China

In 2009, Centre for Chemicals Application Technology (CCAT) in China Agricultural University has cooperated with Weishi company in Shandong province to develop the first model of multi-rotors with eight wings (chemical tank 10 L) and eighteen wings (chemical tank 15 L) UAV in China for chemical application, in Figure 1b[1,51].

Up to 2016, China has more than 200 UAV manufacturers and over 169 types of agricultural unmanned aerial vehicles for chemical application in Chinese market, having already conducted the work of the control of pest and disease in the fields of paddy, wheat, corn, cotton and sugarcane and in the orchard. The real effect proves that the UAV pesticide application meets the requirement of practical level and it is in a rapid development stage[28,52-54].


Figure 2 Typical UAV aircraft developed in China: 178 different UAV types for chemical application in China market in 2016 year from more than 200 manufactures

### 2.3 Small UAV spraying technology in Japan

Japan is the first country that used unmanned helicopter for agricultural pesticide application and also one of the leading countries for successful commercialization of this technology. The small scale farms in Japan cannot adopt the conventional large-scale boom sprayers which are developed for agricultural operation with spacious crop fields. Hence, Japanese agricultural aviation gives priority to unmanned helicopter. In the year of 1985, Yamaha initially launched the world first agricultural UAV Model R50 as shown in Figure 3a for pesticide application, an unmanned medium scale helicopter with 5 kg payload capacity. By the end of October in 2005, the inventory of Japanese registered agricultural UAVs had already increased from 307 in 1995 to 2002 with the annual average growth rate of 13.80% and there were just 1200 UAVs of Yamaha RMAX series. In addition, the control area rose by 20.10% per year from 200 000 $hm^2$ in 1997 to 600 000 $hm^2$, and it exceeded the control area of manned agricultural helicopter. As of the year of 2012, the working area covered by Japanese agricultural UAV was 963 000 $hm^2$/a and accounted for 50%-60% of cultivated area; there were 2346 unmanned helicopters for agriculture and forestry and 14 163 operators all around the nation; the working efficiency of UAV plant protection was up to 7-10 $hm^2$/h. SUZUKI and YAMA MOTOR also produce small UAV for chemical application in rice field besides YAMAHA in Japan. The market share of YAMAHA UAV accounts for 90%. Multi-rotors UAVs, include four rotors, six rotors and eight rotors, were developed in Japanese companies since

2015 year[1,5,9,52-54].

Along with the continuous development of agricultural aircraft, Japanese aerial spraying technology made considerable progress. The volume of the tank increased from 5 L to 24 L, and the application rate developed from the original application rate of 30 L/hm$^2$ to a lower application volume of 5 L/hm$^2$ and finally to an ultra-low volume spraying of less than 1 L/hm$^2$. Ultra-low volume technology has been well developed in Japan. The Yamaha's newest model 'R-Max 3880' invented in 2010 has equipped with two tanks of 12 L each mounted on the both sides of the fuselage, and the time required to fill two tanks is less than 1 min with simple operations of launching, controlling and spraying as shown in Figure 3b.

a. Yamaha's first generation petrol-powered agricultural UAV in Japan: Model 'R50'

b. Newest model 'R-Max 3880' in the process of launching in Japan in 2015

Figure 3 Yamaha's agricultural UAVs

Nowadays, Japanese research of aerial spray and control technology gives priority to the following two aspects: (1) Building droplet distribution simulation mathematical model of aerial spraying and analyzing the effect of different altitudes, wind speeds and types of aircrafts on droplet size and droplet drift. Another technology in use is controllable droplet technology, that pilot choose the corresponding nozzle and spraying parameters to control the droplet classification, size and drift rate, achieving the best spraying result. (2) GPS system and precise pesticide application in the aviation work. When aerial plant protection works, variable-rate pesticide application would be conducted according to the amount of pesticide and fertilizer of different areas from Sub-Scriber Module (SSM). Recently, long-range control platform is taken into application. When the aircraft reaches the working area, GPS system can send the real-time information and image of the sprayed area to the control platform, but if the aircraft velocity is equal or greater than 65 m/s, GPS technology cannot transfer the real-time data back well. However, with lower velocity the technology can attain accurate positioning of operation site, finally realize precise pesticide application and the accurate docking of spray swath[14,28,41,52,55-59].

The working parameters of Yamaha 'R-Max 3880' helicopter with standard configuration are shown in Tables 1 and 2.

**Table 1 Technical, economic and performance parameters of Yamaha 'R-Max 3880'**

| Parameter | Value |
|---|---|
| Diameter of the rotor/m | 2.1 |
| Volume of the tank/L | 24 |
| Working altitude/m | 1-4 |
| Working velocity/$m \cdot s^{-1}$ | 1-4 |
| Spray swath/m | 2-5 |
| Nozzle type | cone or flat-fan nozzle (3) |
| Application rate/$L \cdot hm^{-2}$ | 1-5 |
| Price/yen | 10 000 000 |

**Table 2 Cost of Yamaha 'R-Max 3880'/(million yen)**

| Price | Annual maintaining cost | Annual insurance expense | Training expense of operator |
|---|---|---|---|
| 10 | 1 | 0.4 | 0.6 |

In Japan, the selling price of Yamaha's 'R-Max 3880' is about 10 million Japanese yen, but Japanese local governments would subsidize the purchase 50% of the selling price. The after-sales service is very thorough and there are lots of authenticated salvage shops all over the nation. If the UAV break down, the UAV could be repaired in the 24-hour salvage shop[28,53,62].

The failure rate of Yamaha's UAV is not more than 5.8%, and the malfunction is mainly caused by personal misoperation, such as the fall due to the touch between aircraft and electric wire or branch. But the maintaining cost is extremely high: a pair of paddle is 300 000 yen and the expense of a single fall is 2-3 million yen, so every UAV is insured[28,59,60,61].

The spray system in UAV equips three cone or flat-fan nozzles, avoiding using rotary nozzle. One of nozzles is set in the center and the other two nozzles are symmetrically set on the two sides of the helicopter. The service life of the helicopter is 1000 h and the durable years are 6-9 years. There are two 12 L tanks on the two sides of the UAV and the installation of the plug-in tank only need 1 s. The working area of every single aircraft is almost 0.2-0.3 km$^2$ and the hang time can be up to 5 h[59-62].

The UAVs mostly adopt semi-autonomous control: the altitude is of autonomous control; the spraying space use manual control and the control range is 200-300 m in visible distance; the flight attitude is controlled automatically and the velocity and direction are controlled artificially[28,53].

The training of UAV operator should last for 15 d and the expense is 600 000 yen per person. The prices of the spraying service are 20 000 yen/hm$^2$ (not including pesticide) or 30 000 yen/hm$^2$ (including pesticide)[1,28,52,62]. Japanese unmanned helicopter's distribution is shown as Table.3.

**Table 3 Distribution of Japanese unmanned helicopter**

| Owner | Number | Number of UAVs | Percentage/% |
|---|---|---|---|
| Agricultural association | 245 | 537 | 28.4 |
| Organization | 58 | 151 | 8.0 |
| Plant protection combination | 261 | 382 | 20.2 |
| Plant protection service company | 234 | 475 | 25.1 |
| Local government | 44 | 69 | 3.6 |
| Individual | 252 | 277 | 14.6 |
| Total | 1094 | 1891 | 100.0 |

## 3 Agricultural UAV application for plant protection in China, South Korea and Japan

Ministry of agriculture of the People's Republic of China organized a two-year UAV International Co-operation Project "UAV chemical application technique for rice" among China, Japan and South Korea during 2012 to 2013. CCAT was in charge of Chinese side, experiments were taken in different time in three countries and all members of the project shared all information and technology of UAV together.

a. Project field trails using YAMAHA 1880 UAV in Japan in 2012


b. Project meeting in Soul in 2013

Figure 4 International Co-operation Project "UAV chemical application technique for rice"

### 3.1 Application of small UAV for plant protection in China

Taking paddy as example, Chinese paddy planting area reaches up to 30.6 million hectare and self-sufficiency rate is more than 99%, but the land disperses and the planting area per household is only approximately 1.15 hm$^2$. However, the equipment for paddy chemical control falls behind completely - the technical level of almost 70% of plant protection machinery products is only equivalent to that of developed nations during the 1960s to the 1970s and 10% of products' technical level could achieve international advanced level at the end of 1980s and the early 1990s. The ubiquitous situation of backward pesticide application equipment and technology cannot match the rapid development of pesticide, obstructing the control of pests, diseases and weeds in agriculture and forestry and contributing to lots of negative effects such as low pesticide use ratio, the overproof pesticide residue of produce, environmental pollution, phytotoxicity of crop, chemical damage to operators and so on, which cannot meet the requirements of new plant protection mission. Then aerial spray is a kind of important and efficient pesticide application methods, and its characteristics are high efficiency, good effect, three-dimension ability, no damage to crops, low labor intensity, multi-role ability, etc. Due to the limit of various factors, now Chinese aircrafts in agriculture and forestry application are still primarily manned fixed-wing aircrafts and helicopters and it is about 10 years since little UAV's research and application started to develop in Chinese agriculture[1,10,28,60].

CCAT has evaluated 13 kinds of Chinese UAVs in rice fields in Hainan Province during January 2013. The test results showed that the 13 kinds of Chinese UAVs had an apparent biological control effect in paddy fields. Ministry of China has begun to generalize this UAV technology in China since then.


Figure 5 Evaluation of 13 kinds of Chinese UAVs in rice fields in Hainan Province in 2013

CCAT has cooperated with experts from US and Germany to develop a test system based on spatial spraying deposition quality balance (SSDQB) to evaluate characteristics of deposition and drift distribution in Anyang, Henan Province in 2015 year. Three models '3WQF80-10' single-rotor diesel UAV, 'CG-Q60S' four-rotors battery power UAV and 'LHX8-3WD10' eight-rotors battery power UAV were tested using this method in 1 hm$^2$ wheat field and the effects of flight direction, flight parameters and crosswind on the distribution of spatial spraying deposition quality balance and the downwash flow field distribution were researched. The test results showed that regardless of the flight direction and height and the crosswind, all these factors influenced the droplets deposition distribution via weakening the intensity of the downwash airflow field in the direction perpendicular to the ground.

a. 3WQF80-10 (Quanfeng, Anyang)

b. CG-Q60S (Crop Guard, Zhuhai)

c. LHX8-3WD10 (Look Heed, Wuhan)

Figure 6 Three test UAV types of SSDQB system

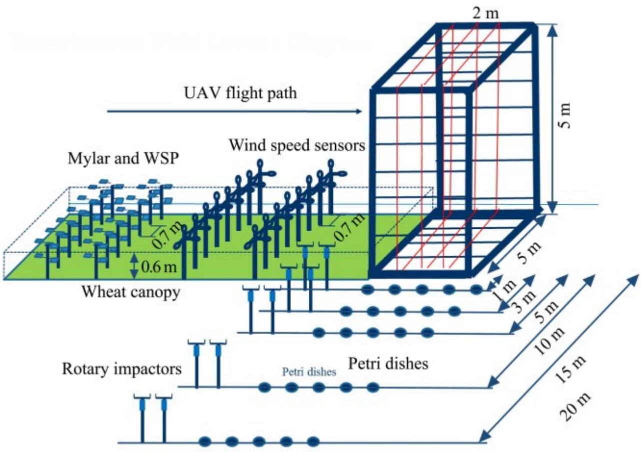


Figure 7 Experimental field layout of SSDQB system

### 3.2 Application of small UAV for plant protection in Japan

There is 16 million hectare of paddy field in Japan and the lands also disperse and planting area per household is nearly 1.5 hectare. Japanese agricultural products' self-sufficiency rate is only approximately 40%, but that rate of rice can reach up to 96%. Additionally, with serious aging of agricultural population, the average age is 66 years old. Japanese agricultural modernization level is fairly high and the rice production basically realizes mechanization, and the degree of installation of economic crop production is also high. A great deal of fund was invested in the construction of farmland water conservancy infrastructure from the 1980s to the 1990s, contributing to the good irrigation conditions of Japan. Pesticide application in the rice fields is conducted by the government and Japan Agricultural cooperative (JA). JA and service organizations are advanced, making an impact on production, technology promotion and service[1,10,28,60,62].

The main kinds of pests and diseases of Japanese paddy rice are rice planthopper (small brown planthopper, brown planthopper and *sogatella furcifera*), *Lissorhoptrus oryzophilus*, Polypylis, rice blast, and rice sheath blight, which are less than those in southern rice region of China, and the degree of the outbreak is lighter than south China, which is similar to the northern rice region of China. The control of rice pests and diseases is also mainly chemical pesticide control. On the basis of Japan Pesticide Industry Association's statistics, in the year of 2011 the pesticide production applied in the rice field was 72 162 ton, including 31 729 ton herbicide (accounting for 44.0%), 17 620 ton mixture of insecticide and fungicide (accounting for 24.4%), 14 285 ton insecticide (accounting for 19.8%) and 8528 ton fungicide (accounting for 11.8%). Seed treatment and control during seedling stage are taken seriously and the amount accounts for 70% of total, reducing field pesticide application frequency greatly to two times. Moreover, large-scale efficient pesticide application machineries are widely used, with high working efficiency and utilization, including 30% of self-propelled paddy field boom sprayers, almost 60% of unmanned helicopters and 10% of other small-scale machineries. Japanese level of the UAV aerial pesticide application technology and equipment in paddy field is most advanced in Asia[1,10,28,52,60,62].

### 3.3 Application status of UAV for plant protection in South Korea

The Republic of Korea has 476 million people and 2.2 million km$^2$ of land area, mainly highland. There are 19 000 km$^2$ of cultivated lands and 1.2 million farmers accounting for 7.5% of total population in Korea. On average, the area of per household cultivated land is 1.4 hm$^2$. Besides, the area of crop field is 170 000 km$^2$, consisting of 8900 km$^2$ of paddy, 2000 km$^2$ of vegetable and 150 000 km$^2$ of fruit, and it shows a descent tendency year by year. Korean agricultural products' self-sufficiency rate is low but that of rice can reach up to 98%. The degree of installation of vegetable production is high and Korean rice production basically realizes mechanization. The area of manned aerial application for pesticide reaches 15% and the area of UAV application accounts for 10%[1,10,28].

Korean agro technical popularization, agricultural science research and peasant education are a trinity and they are responsible for Korea Rural Development Administration (RDA). There are all departments of research, agro technical popularization and experimental field in the RDA and nine provinces' governments and it is equipped with agricultural technology center and the course of technology popularization for 157 cities. The system of agricultural technology and popularization has more than 10 000 civil servants, including 19% of researcher, 50% of agricultural extension staff and 31% of manager. Korean rice pests are mainly rice planthopper (small brown rice planthopper, brown planthopper and *sogatella furcifera*) and rice leaf folder, and the rice diseases are rice blast and rice sheath blight, which is lighter than the degree of the Chinese southern rice region but more serious than the northern rice region of China. No pests and diseases control could contribute to 19% of rice damage while there is only less than 3% of loss via control measures. The paddy is the most primary kind of crop in South Korea and accounts for 50% of crop acreage, so that the monitoring and control of rice pests and diseases are attached great importance. There are 150 national nurseries for forecasting rice diseases and pests all around the Republic of Korea and plenty of observation spots in every 10 $km^2$ of rice planting area, providing information for the Internet and mass media to publish forecasts, attentions and alerts irregularly. The RDA would organize experts to make an inspection tour and the technicians of each city's agriculture technical center would give guidance of the control of pests and diseases in the farmland when the pests and diseases appear. The farmer training, technical demonstration and site instruction are paid more attention. Though seed treatment and control during seedling stage, the field pesticide application frequency decreases from 4-5 times to 2-3 times. The level of Korean rice aviation pesticide application technology is lower than China[1,10,28,51-53,60,62].

**Table 4 Paddy planting area and status of small agricultural UAV pesticide application in China, Japan and South Korea**

| Nation | Total agricultural acreage (bill. $hm^2$) | Ratio of paddy planting area/% | Ratio of UAV pesticide application |
|---|---|---|---|
| China | 0.0036 | 51.12 | <1 |
| Japan | 0.0048 | 48.62 | 60 |
| South Korea | 0.0017 | 52.35 | 15 |

## 4 Challenges and outlook for the development of UAV pesticide application technology

As a consequence of population aging and shrinkage in Asian countries like China, the trend of labor shortage for agricultural production has grown and will continue in future. Acceleration of agricultural mechanization has been proposed as a developmental strategy at the national level in support of steady and sustainable development of agriculture in China. In alignment with this national developmental plan, the use of UAV for pesticide application contributes to the advancement of plant protection mechanization by providing improved ability to apply pesticide in a time sensitive manner with enhanced safety and efficiency. In the process of the rapid and swift development of agricultural UAV for pesticide application, there are full of opportunities and challenges. Several advantages and challenges relevant to further development of UAV spraying technology are discussed.

(1) Using of UAV for pesticide application offers attractive advantages over traditional spray operations. Low-volume pesticide application using agricultural drones at the low flight altitude has been implemented in corn and paddy fields as well as hill lands in China. The potential ease of deployment of UAVs, in particular for spraying in small crop fields or complex geographic terrains that are not easily accessible by personnel or ground plant-protection machinery, adds distinct values to UAVs. Limitations of payload and battery life of small UAVs are not a major barrier when using a UAV to spray a small patch of farmland that is typical in many regions of China. But market occupancy for UAV pesticide application will favor to such UAVs that can not only provide greater lift and longer flight endurance, but also can offer exceptionally durable and rugged designs for operations under extreme agriculture conditions for pesticide applications. Various field trials and evaluations have proved that the actual working effect of UAVs pesticide application is feasible for practice in China.

(2) Given the novelty and complexity of UAVs technology, research and development of UAV-based application technology takes priority. Spraying low-volume pesticide using UAVs at low flight altitude differs from either conventional manned aerial application or ground equipment based application, and thus a wide variety of spray parameters warrants further investigations. Currently, there is a lack of any existing pesticide application technology that is well-suited for spraying pesticides using agricultural UAVs at a low-volume application rate in China. Spray system configurations equipped on UAV have not yet been optimized to complement spray pattern based on the proper nozzle selection, spray tank design, pesticide handling systems, and so on. Also, there are neither industrial standards nor sufficient scientific understandings that can provide sound guidance in determination of appropriate operation parameters used in UAV spraying as influenced by weather and land conditions.

(3) Assessment of UAV spray technology in field trials for spray quality, efficacy, and safety considerably

influence the forward progress of UAV deployment. Pesticide canopy penetration, droplet deposition and coverage, spray drift control are priorities to evaluate the efficiency and efficacy of crop protection products applied through UAV's. Advanced flight control system, sensing systems, software platform for mission planning permit flight stability and accuracy need urgent new development. Spray aerodynamics of small single or multi-rotor UAVs and the interactions with environmental factors such as temperature, humidity, wind speed, still need to be clearly understood for better engineering design UAV airframe designated to pesticide applications. Otherwise, spray drift or spray out of the targeted area can cause severe damages to adjacent crops and injuries to spray operators. Especially, when spraying herbicide, the spray height in the range from 1 m to 4 m about the crop canopy surface can easily cause potential pesticide drift and the phytotoxicity of the herbicide to the sensitive crop nearby spray area can result in a big challenge. Risk assessments on drift-able droplets based on field measurements and implementation of drift-reduction-technology are important aspects to consider in developing the UAV pesticide application technology.

(4) Commercialization of UAV spraying technology requires collaborative and constructive participations of stakeholders from governments, research institutions, and industries. Professional organizations, which can provide comprehensive services for pest or disease control using UAVs at a reasonable cost, would allow the sophisticated drone technology achievable and acceptable by farmers. For instance, using UAVs to spray chemicals can be provided through professional services to farmers via local agricultural cooperatives or plant protection companies under the government leadership. These professional organizations would play a critical role in the delivery of agrochemicals for pest/disease control and be responsible for provision of trainings to applicators and pilots, perform UAV operation, activities related to maintenance, insurance, and the product handling and delivery. Professional service organizations would also have the accumulative experience and capability to develop professional pest control system to handle sophisticated or time-sensitive large-scale pest prevention and controls. Introduce of the service-based business mode may help pesticide sales and promote the use of UAV for pesticide application. Growers and farmers started as observers of new technologies are price-sensitive. Governmental stimulus and procurement plans for plant protection services would be influential to famer's enthusiasms and participation of using UAV for pest controls. Government procurement and support would also encourage the professional organization of crop protection and UAV manufactures to collaborate and invest more into such services. By far, government policy makers have not issued any plans to purchase plant-protection pesticide application via UAV nor to support the construction of such professional service organization.

(5) Development of new formulations suitable for drone application and modifications in product labels offers potentials to improve the technique development. Formulation of pesticides is an extremely important factor in practical pesticide application, which can affect the droplet atomization process, reduce drift, and increase retention on target surface and so on. Up to date, commercial formulation dedicated to UAV spraying has not been reported but R&D and manufacturing activities are underway. Formulations suitable for ultra-low or low volume application through UAVs may help distribute pesticide more evenly for small quantities and reduce the drift potentials. In addition, pesticide labels will essentially have the controlling authority to grant permission to apply a pesticide through UAVs. By far, there is no enforcement statement and recommendation on product labels for pesticide application through UAVs. But, compatibility of the emerging drone application method with existing product labels is an important aspect for pesticide manufactures and regulatory agencies. Potential modification of product labels or providing supplementary labels may become to discuss and imperative in future, where the label needs to specify minimal spray volume and acceptable range of use rate for pesticide delivery through the drone application.

In summary, given the complexity involved in drone pesticide applications and the rapidly evolving of agricultural drone industry, the urgency to develop in-depth understanding of the drone spraying technology in China cannot be ignored. Better understanding of the emerging UAV application technology would enable better engineering design for UAV aircrafts, promote the efficient and safe use of pesticide, and contribute to an ordered and healthy development of the agricultural UAV market in China.

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## [References]

[1] He X K, Chen J H, Sun Y M, Cheng X G, Guo H M. Chemical application techniques and equipment for rice in Japan and Korea. Technology Innovation and Modern Plant Protection, 2012; 11 (ISSN 978-7-109-17356-9, Beijing): 95–99. (in Chinese)

[2] Wang J, Jian J, Yang D X. The drift of droplets and the mathematical analysis in aerial spray. Journal of Plant Protection, 1994; 21(3): 275–281. (in Chinese)

[3] Bird S L, Esterly D M, Perry S G. Off-target deposition of pesticides from agricultural aerial spray applications. Journal of Environmental Quality, 1995; 25(5): 1095–1104.

[4] Huang X D, Fang Z R. Study on comparing helicopter with plane application in forest pest and disease control. Journal of Changsha university of electric power: Science, 1999; 14(3): 279–281. (in Chinese)

[5] He X K. Improving severe draggling actuality of plant protection machinery and its application techniques. Transactions of the CSAE, 2004; 20(1): 13–15. (in Chinese)

[6] Leinonen I, Jones H G. Combining thermal and visible imagery for estimating canopy temperature and identifying plant stress. Journal of Experimental Botany, 2004; 55(401): 1423–1431.

[7] Li Y H, Sun X G, Yuan G B. Accurate measuring temperature with infrared thermal imager. Optics and Precision Engineering, 2007; 15(9): 1336–1341.

[8] Fu Z T, Qi L J, Wang J H. Developmental tendency and strategies of precision pesticide application techniques. Transactions of the CSAM, 2007; 38(1): 189–192. (in Chinese)

[9] Huang Y B, Hoffmann C, Fritz B, Lan Y B. Development of an unmanned aerial vehicle-based spray system for highly accurate site-specific application. ASABE Meeting Presentation. 2008. Paper number: 083909.

[10] Xue X Y, Liang J, Fu X M. Prospect of aviation plant protection in China. Chinese agricultural mechanization, 2008; (5): 72–74. (in Chinese)

[11] Deng W, He X K, Ding W M. Droplet size and spray pattern characteristics of PWM-based continuously variable spray. Int J Agric Eng, 2009; 2(1): 8–18.

[12] Liu X H, Xu X Z, He X K, Zhang L D. Study on the application of supervised principal component regression procedure to near-infrared spectroscopy quantitative analysis. Spectroscopy and Spectral Analysis, 2009; 29(11): 2959–2961.

[13] Zia S, Spohrer K, Merkt N, Du W Y, He X K. Non-invasive water status detection in grapevine (*vitis vinifera* L.) by thermography. Int J Agric & Bio Eng, 2009; 2(4): 46–54.

[14] He X K, Zeng A J, Liu Y J, Song J L. Precision orchard sprayer based on automatically infrared target detecting and electrostatic spraying techniques. Int J Agric & Bio Eng, 2011; 4(1): 35–40.

[15] He X K. The opportunity and challenge of pesticide application for agriculture and horticulture in China. International Advances in Pesticide Application, 2010, 99: 157–164.

[16] Du W Y, Zhang L D, Hu Z F, He X K. Utilization of thermal infrared image for inversion of winter wheat yield and biomass. Spectroscopy and Spectral Analysis, 2011; 31(6): 1476–1480.

[17] Huang Y B, Hoffmann W C, Lan Y B, Wu W, Fritz B K. Development of a spray system for an unmanned aerial vehicle platform. Applied Engineering in Agriculture, 2009; 25(6): 803–809.

[18] Huang Y B, Fipps G. Developing a modeling tool for flow profiling in irrigation distribution networks. Int J Agric &

Bio Eng, 2009; 2(3):17–26.

[19] Zhang H H, Lan Y, Lacey R E, Huang Y B, Hoffmann W C, Martin D, et al. Analysis of variograms with various sample sizes from a multispectral image. Int J Agric & Bio Eng, 2009; 2(4): 62–69.

[20] Huang Y B, Thomson S J, Lan Y B, Mass J S. Multispectral imaging systems for airborne remote sensing to support agricultural production management. Int J Agric & Bio Eng, 2010; 3(1): 50–62.

[21] Huang Y B, Thomson S J. Characterization of spray deposition and drift from a low drift nozzle for aerial application at different application altitudes. Electronics Letters, 2011; 38(17): 967–968.

[22] Zhang G Q. Review of agricultural aviation technologies and research of new-type agricultural aviation technologies. Jiangxi Forestry Science and Technology, 2011; (1): 25–31. (in Chinese)

[23] Zhang G Q. Review of agricultural aviation technologies and research of new-type agricultural aviation technologies. Jiangxi Forestry Science and Technology, 2011; (1): 25–31. (in Chinese)

[24] Bradley K F, Hoffmann W C, Bagley W E, Hewitt A. Field scale evaluation of spray drift reduction technologies from ground and aerial application systems. Journal of ASTM International, 2011; 8(5): 1–11.

[25] Zhang G Q. Measures to deal with present bottlenecks of agricultural aviation development in China. China Civil Aviation, 2011; 124(4): 31–33. (in Chinese)

[26] Zhang J, He X K, Song J L, Liu Y J, Zeng A J. Influence of spraying parameters of unmanned aircraft on droplets deposition. Transactions of the CSAM, 2012; 43(12): 94–96. (in Chinese)

[27] Huang Y B, Ding W, Thomson S J, K. N. Reddy, R. M. Zablotowicz. Assessing crop injury caused by aerially applied glyphosate drift using spray sampling. Transactions of the ASABE, 2012; 55(3): 725–731.

[28] He X K. Plant protection machinery and pesticide application techniques, 1st edition. Beijing: China Agricultural University Press, 2013.

[29] Zhou J Z, He X K, Andrew L. Dosage adjustment for pesticide application in vineyards. Transactions of the ASABE, 2012; 55(6): 2043–2049.

[30] Huang Y B, Sui R X, Thomson S J, Fisher D K. Estimation of cotton yield with varied irrigation and nitrogen treatments using aerial multispectral imagery. Int J Agric & Bio Eng, 2013; 6(2): 37–41.

[31] Huang Y B, Thomson S J, Hoffmann W C, Lan Y B, Fritz B K. Development and prospect of unmanned aerial vehicle technologies for agricultural production management. Int J Agric & Bio Eng, 2013; 6(3):1–10.

[32] Wei D, Huang Y, Zhao C J, Wang X, Liu J L. Spatial distribution visualization of PWAT continuous variable-rate spray. Int J Agric & Bio Eng, 2013; 6(4): 1–8.33.

[33] Zhou Z Y, Zang Y, Luo X W. Technology innovation development strategy on agricultural aviation industry for plant protection in China. Transactions of the CSAE, 2013; 29(24): 1–10. (in Chinese)

[34] Bai Y, Koo Y M. Flight attitudes and spray patterns of a roll-balanced agricultural unmanned helicopter. Applied Engineering in Agriculture, 2013; 29(5): 675–682.

[35] Xue X Y, Lan Y B. Agricultural aviation applications in USA. Transactions of the CSAM, 2013; 44(5): 194–201. (in Chinese)

[36] Gao Y Y, Zhang Y T, Sun N. Primary studies on spray droplet distribution and control effects of aerial spraying using unmanned aerial vehicle (UAV) against the corn borer. Plant Protection, 2013; 39(2): 152–157. (in Chinese)

[37] Qiu B J, Wang L W, Cai D L. Effect of flight altitude and speed of unmanned helicopter on spray deposition uniform. Transactions of the CSAE, 2013; 29(24): 25–32. (in Chinese)

[38] Xue X Y, Tu K, Lan Y B. Effects of pesticides aerial applications on rice quality. Transactions of the CSAM, 2013; 44(12): 94–98. (in Chinese)

[39] Thomson S J, Huang Y B, Smith L A. Portable device to assess dynamic accuracy of global positioning system (GPS) receivers used in agricultural aircraft. Int J Agric & Bio Eng, 2014; 7(2): 68–74.

[40] Qin W C, Xue X Y, Zhou L X. Effects of spraying parameters of unmanned aerial vehicle on droplets deposition distribution of maize canopies. Transactions of the CSAE, 2014, 30(5): 50–56. (in Chinese)

[41] Zhang D Y, Lan Y B, Chen L P. Current status and future trends of agricultural aerial spraying technology in China. Transactions of the CSAM, 2014; 45(10): 53–59. (in Chinese)

[42] Zhang D Y, Lan Y B, Chen L P. Measurement and analysis of aviation spraying key parameters for M-18B Dromader and Thrush 510G aircraft. 2014 ASABE and CSBE /SCGAB Annual International Meeting, 2014. Paper number: 141907461rev. doi: 10.13031/aim.20141907461

[43] Zhang R R, Chen L P, Lan Y B, Zhao C J. Development of a deposit sensing system for aerial spraying application. Transactions of the CSAM, 2014, 45(8): 123–127. (in Chinese )

[44] Giles D K, Billing R. Unmanned aerial platforms for spraying: deployment and performance. Aspects Appl. Bio., 2014; 12: 63–69.

[45] Zhan S C, Xue X Y, Qin W C. Simulation and experimental verification of aerial spraying drift on N-3 unmanned spraying helicopter. Transactions of the CSAE,

2015; 31(3): 87–93. (in Chinese )

[46] ISO/TC 23/SC 6. ISO 16122-2:2015. Agricultural and forestry machinery–Inspection of sprayers in use–Part 2: Horizontal boom sprayers.

[47] ISO/TC 23/SC 6. ISO 24253-1:2015. Crop protection equipment–Spray deposition test for field crop.

[48] Shi Q. Numerical simulation for downwash flow field of small-size unmanned helicopter hedgehopping. Journal of Drainage and Irrigation Machinery Engineering (JDIME), 2015; 33(6): 521–525. (in Chinese )

[49] Huang Y B, Lee M A, Thomson S J, Reddy K N. Ground-based hyperspectral remote sensing for weed management in crop production. Int J Agric & Bio Eng, 2016; 9(2): 98–109.

[50] Huang Y B, Thomson S J, Brand H J, Reddy K N. Development and evaluation of low-altitude remote sensing systems for crop production management. Int J Agric & Bio Eng, 2016; 9(4): 1–11.

[51] Wang C L, He X K, Wang X N, Bonds D J, Herbst A. Testing method of spatial pesticide spraying deposition quality balance for unmanned aerial vehicle. Transactions of the CSAE, 2016; 32(11): 54–61. (in Chinese)

[52] Giles D K, Billing R, Singh W. Performance results, economic viability and outlook for remotely piloted aircraft for agricultural spraying. Aspects of Applied Biology, 2016; (132): 15–21

[53] Wang C L, He X K, Liu Y J, Song J L, Zeng A J. The small single- and multi-rotor unmanned aircraft vehicles chemical application techniques and control for rice fields in China. Aspects of Applied Biology 132, International Advances in Pesticide Application, 2016: 73–81.

[54] Li L L, He X K , Yao Q, Song J L. Design of VAV system of air assisted sprayer in orchard and experimental study. Aspects of Applied Biology, 2016; (132): 159–168.

[55] Li J Y, Lan Y B, Zhou Z Y, Zeng S, Huang C, Yao W X, et al. Design and test of operation parameters for rice broadcasting by unmanned aerial vehicle. Int J Agric & Bio Eng, 2016; 9(5): 24–32.

[56] Zhang P, Deng L, Lyu Q, He S L, Yi S L, Liu Y D, et al. Effects of Citrus tree-shape and spraying height of small unmanned aerial vehicle on droplet distribution. Int J Agric & Bio Eng, 2016; 9(4): 45–51.

[57] Wang L, Lan Y B, Hoffmann W C. Design of variable spraying system and influencing factors on droplets deposition of small UAV. Transactions of the CSAM, 2016; 47(1): 15–22. (in Chinese )

[58] Zhang P, Lv Q, Yi S L, Liu Y D. Evaluation of spraying effect using small unmanned aerial vehicle (UAV) in citrus orchard. Journal of Fruit Science, 2016; 33(1): 34–42. (in Chinese)

[59] Wang S L, He X K, Wang X N, Song J L. Testing method of spatial pesticide spraying deposition quality balance for unmanned aerial vehicle. Transactions of the CSAE, 2016; 32(11): 54–61. (in Chinese)

[60] Ma X Y, Wang Z G, Jiang W L, Ren X L, Hu H Y, Ma Y J, et al. Analysis of current status and application prospects of unmanned Aerial Vehicle Plant protection technology in cotton field in China. China Cotton, 2016; 43(6): 7–11. (in Chinese)

[61] Qin W C, Qiu B J, Xue X Y, Chen C, Xu Z F, Zhou Q Q. Droplet deposition and control effect of insecticides sprayed with an unmanned aerial vehicle against plant hoppers. Crop Protection, 2016; 85: 79–88.

[62] Giles D K. Use of Remotely Piloted Aircraft for Pesticide Applications: Issues and Outlook. Outlooks on Pest Management. 2016; 27(5): 213–6.