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The application of unmanned aircraft systems to plant protection in China

Shulin Yang[1,2] · Xiaobing Yang[2] · Jianyou Mo[3]

Abstract Agricultural use of unmanned aircraft systems (UAS) in China has risen recently with the increased demand for precision agriculture. The focus of UAS use in China is on improving the efficiency of crop production and reducing environmental harm from runoff related to current crop management activities. This use will keep increasing with the support of new policies on land transfer and appropriately scaled operations for farming in the near future. A major agricultural application of UAS in China is plant protection, toward increasing pest and disease management efficiency. The advantages of UAS are apparent in the country, which has the largest number of small-sized farms in the world. UAS in China have advantages for farms in mountainous regions and orchard production, where it is difficult for ground-based machines to manoeuvre. Advances of UAS use in the country have created new challenges to the agricultural aviation industry in crop monitoring, pest sampling, pest detection, pest diagnosis and spraying technology. This article reviews the agricultural use of UAS in China, with a focus on plant protection. The challenges and prospects of UAS use in the country are also summarised.

Keywords Agricultural aviation · UAV · Aerial application · Remote sensing · Farm size

✉ Shulin Yang
s.yang@gznu.edu.cn

[1] School of Life Sciences, Guizhou Normal University, Guiyang 550001, Guizhou, China

[2] Department of Plant Pathology and Microbiology, Iowa State University, Ames, IA 50010, USA

[3] Institute of Plant Protection, Guangxi Academy of Agricultural Sciences, Nanning 530007, Guangxi, China

Introduction

The interest in and use of agricultural aviation with a focus on aerial application (especially pesticide application) by unmanned aircraft systems (UAS) have increased in China in recent decades (Zhou et al. 2013). UAS (or unmanned aerial vehicles (UAV) or drones) have been widely used in agriculture, especially precision agriculture (Zhang and Kovacs 2012; Huang et al. 2013; Shahbazi et al. 2014), in various countries. Crop health monitoring through aerial imagery is among the most popular UAS applications in precision agriculture (Zhang and Kovacs 2012; Shahbazi et al. 2014).

Although aerial application was adopted in China in the 1950s (Luo 2014), its use on private farms was limited. Its application was mostly on state-owned farms in agricultural reclamation areas in northeastern and northwestern parts of the country, and was generally aerial spraying by administrative departments for large-scale pest control (Zhang et al. 2014; Zhang 2011). Complicated terrain, small farm size with separated plots, high cost, poor availability and accessibility of aerial vehicles limited the use of aerial application in China. Mountains, high plateaus and hills comprise ∼69% of the total area in the country (Yang et al. 2002). The average farm size in China is amongst the smallest in the world (0.67 ha compared with 178.35 ha in the United States), and more than half (57.5%) of the farms are small (<2 ha) (Eastwood et al. 2010). The percentage of small farms is also the largest of any country (Thapa 2009). Most farms are in mountainous and hill areas, away from roads. Even farms in plain areas are usually separated by irrigation ditches and small paths, typically with trees and power poles alongside. These have discouraged the agricultural use of large aerial vehicles because of a lack of operational space for loading, takeoff and landing. Furthermore, aerial applications mostly used manned aircraft, and their cost was usually not affordable by general farm owners.

However, the situation has changed and agricultural use of UAS has been rising in China during the past two decades. Increased interest in UAS was driven by the growing need to improve farming efficiency because of the decline in labour force in rural areas caused by urbanization and rural–urban migration (Liu et al. 2003). Operational farm size has increased with the growth of agricultural co-operatives, which are a form of producer association that provide inputs to their members or market their members' output (Sonntag et al. 2005; Deng et al. 2010). Land leasing and contract farming also contribute to the increase of operational farm size. Operational farm size is likely to continue increasing with support from a new policy on rural land transfer and appropriately scaled operations for farming. Declared in November 2014, this policy was aimed at facilitating the right to transfer rural land use to agricultural purposes and promote larger-scale agricultural industry. This leads to increasing demand for accuracy and efficiency in farming. Furthermore, action plans for zero growth in fertilizer and pesticide application by 2020, announced by the Ministry of Agriculture in February 2015, project the need for precise and efficient fertilizer and pesticide application. More than 88% of pesticide sprayers are manually operated in China (China Agriculture Yearbook Editorial Committee 2016), and so labour force shortages have led crop growers to start resorting to aerial application for crop management.

Concerns over the health of farm workers and the environment have also promoted interest in UAS applications in China. To reduce harmful runoff to the environment and the threat of pesticides to farmers, an increasing number of agricultural administration bureaus and village chiefs, especially those in the developed southeastern parts of the country, are more willing to accept and adopt new technologies and to use UAS in crop management.

The latter users (local governments) collectively purchase UAS and provide aerial application services to all growers in their administrative areas. Owing to the farming conditions described above, most UAS users prefer relatively small and low-cost UAS over manned aerial vehicles, and rotary-wing UAS over fixed-wing UAS. These small UAS are flexible to operate in complicated terrain situations, e.g., farms with trees, electric poles, irrigation ditches and small paths between them (Fig. 1).

Currently in China, reported interest in agricultural use of UAS focuses on aerial application, crop management and crop protection materials. UAS are also operated as a remote sensing tool to acquire spectral images by onboard sensors, and as "photographers" with consumer cameras to take digital photos. The spectral images and digital photos are used for crop classification, plant status assessment, information extraction from cultivated land and invasive species monitoring. In the following sections, current applications of UAS to agriculture, especially in plant protection, are discussed and summarised, with an outlook for future use of UAS in China.
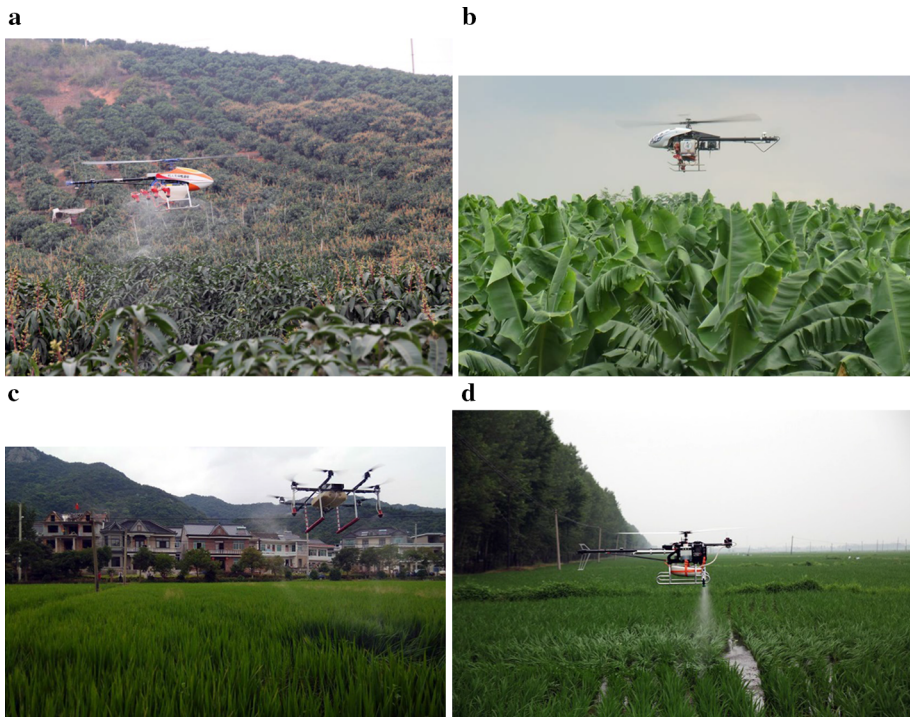

Fig. 1 Four working UAVs. **a** YT-A10 by Yinlong Energy Co. Ltd. (weight 8.7 kg, payload 5 kg) spraying mango plantation in Guangxi province; **b** SW1800ZB by Swiftly UAV Co. Ltd. (weight 11 kg, payload 12 kg) spraying plantain in Guangxi province; **c** JF-DB5 by Jifengchun Hangkong Co. Ltd., (weight 5.5 kg, payload 5 kg) spraying rice in Zhejiang province; **d** JF-Y10 by Jifengchun Hangkong Co. Ltd. (weight 20 kg, payload 10 kg) spraying rice in Liaoning province. (photos **c** and **d** courtesy by Jinfengchun Hangkong Co. Ltd., Shenyang, Liaoning China)

Aerial application

Aerial applications, especially for crop protection, constitute the major use of UAS in Chinese agriculture. Optimal UAS working parameters for best aerial spray droplet deposition, UAS positioning and navigation, and variable rate spraying technology are fundamental to precise aerial spraying and of great interest.

Efficiency of aerial application

In China, small UAS with payload capacity between 10 and 25 kg are generally used for aerial applications (Liu et al. 2014). The payload capacity within this range is 70.5% in a dataset of 237 UAS models from 104 manufacturers (Fig. 2). Field tests for coverage rate and spraying performance were conducted for UAS aerial application, with various flight speeds, altitudes and spray swath settings. From the literature, aerial pesticide application with UAS in China can achieve a coverage of 4–10 ha/h. This is 30–100 times more than manual spraying and 4–33 times more than a ground-based crop sprayer, with associated substantial energy savings and income increase (Table 1). The efficiency of an unmanned helicopter with 20-kg payload is three to four times that of a tractor-mounted sprayer and 30 times that of a manual sprayer (Liu et al. 2014). Compared with ground machinery, aerial application could reduce the cost by 105 CNY (USD 15[1]) ha^{-1} (Zhou et al. 2013). In a plant hopper control test, the 20-kg payload UAS HY-B-15L (Gao Ke Xing Nong Co. Ltd., Shenzhen, Guangdong, China) had a 7.5 times faster spraying rate while still having greater insecticidal efficiency and persistence period than a three-person, hand-operated lance stretcher sprayer (Qin et al. 2016).

Compared with UAS efficiency improvement results from the literature for UAS aerial application in China (Table 1), specifications of the 237 UAS model dataset claimed to achieve application coverage rates from 1.33 ha/h (UAS model 3WDM8-05 by Yuren Agricultural Aviation Co., Ltd., Zhuhai, Guangdong, China) to 120 ha/h (UAS model DB-9 by Linhang Unmanned Aerial Vehicle Co., Ltd., Zhengzhou, Henan, China). These rates are 10–1 200 times higher than manual spraying and 1.33–396 times higher than a ground-based crop sprayer.

Currently, more than 60% of agricultural UAS in China have payload capacities less than 15 kg (Fig. 2). Generally, a UAS sprayer with larger payload capacity can have more spraying efficiency than a smaller-capacity UAS if it can be operated at greater flight speed and spraying swath. With increasing farm size, the demand for >15 kg payload capacity and longer flight duration of UAS increases. As hybrid cars have brought higher fuel efficiency, a hybrid UAS could be a solution to the need for larger payload and longer flight duration. Hybrid UAS for plant protection has been of interest. For example, a power matching experiment was conducted for hybrid coaxial rotors and multi-rotor UAS' power system. The result could satisfy the need for aerial application (Lu et al. 2016).

Optimal UAS operational altitudes and speeds for aerial spraying

Various UAS models have been tested under different flight parameter settings to find optimal working altitudes and speeds that could achieve optimum spray droplet deposition for UAS spraying on many crops (Table 2 is a summary of spray droplet deposition test

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[1] Based on the rate of USD/CNY = 6.75 on 20 October 2016. All currency conversions between USD and CNY are based on the same rate hereafter.
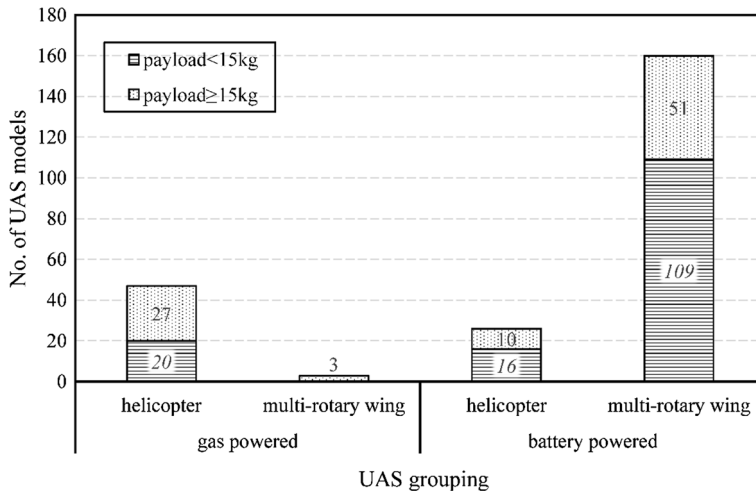
Fig. 2 236 UAS models from 104 manufacturers in China grouped by UAS type, power type and payload capacity (one fixed wing UAS with 100 kg payload capacity was not included into the figure; payload capacities of all three gas powered multi-rotary wing UAS models are greater than or equal to 15 kg)

Table 1 Efficiency improvements from the literature for agricultural UAS aerial application in China

UAS model	Type	Compared to	Improvement	Source
N/A	N/A	Manual spray	4 ∼ 6.6 ha/h, 100×	Zhu (2014)
		High Clearance Crop Sprayer (HCCS)	8×	
N/A	Unmanned helicopter		50% pesticide and 90% water saving	He and Zhang (2014)
		High Clearance Crop Sprayer	Aerial application 8.38 times as the best HCCS	
Tianying—3	Unmanned helicopter	Manual spray	7 ∼ 10 ha/h, 30×	Liu et al. (2014)
		Average crop sprayer	3 ∼ 4×	
N/A	25 kg payload gas powered UAS	Powered crop sprayer	33× (income)	Zhou et al. (2013)
		Manual spray	133× (income)	
	15 kg payload battery powered UAS	Powered crop sprayer	25× (income)	
		Manual spray	93× (income)	
		Manual & powered sprayer	15 ∼ 35% (control result)	
HY-B-15L	20 kg payload battery powered UAS	Hand lance stretcher-mounted sprayer	7.5× (spraying efficiency)	Qin et al. (2016)

results from the literature for UAS spraying in China). Spray droplet deposition distributions of various flight speed and altitude combinations were evaluated in rice fields by an infrared thermal imaging system (VarioCAM hr inspect 480, InfraTec GmbH, Dresden, Germany) for a WPH642 unmanned helicopter. Optimal flight altitude and speed were 2 m

Table 2 Spray droplet distribution test results from the literature for agricultural UAS sprayers in China

UAS model	Type	Flight heights tested (m)	Optimal flight height (m)	Flight speeds tested (m/s)	Optimal flight speed (m/s)	Source
WPH642	Helicopter	1,2,3,4	2	1.5,2.0,2.5	1.5	Zhang et al. (2012)
CD-10	Helicopter	0.5,1,1.5	N/A	1,3,5	N/A	Qiu et al. (2013)
N-3	Helicopter	5,7,9	7	3	N/A	Qin et al. (2014)
HY-B-10L	Helicopter	1.5,2,3	2	$2 \sim 3, 3 \sim 4, 4 \sim 5$	$2 \sim 3$	Chen et al. (2016)
QJ-460	Quad-rotary wing UAS	0.5,1,2	1	N/A	N/A	Zhang et al. (2016c)
3 W-LWS-Q60S	Quad-rotary wing UAS	0.5,1,1.5	1	1	N/A	Zhang et al. (2016b)

and 1.5 m/s, respectively (Zhang et al. 2012). A similar experiment was conducted for a CD-10 unmanned helicopter (Han He Aviation Technology Co. Ltd., Wuxi, China) and a second order regression model for the density of spray droplet deposition was established. The regression model includes the effects of flight altitude and speed, their second order terms, and an interaction term to model spray droplet deposition (Qiu et al. 2013). Spray altitude at 7 and 7-m spray swath were reported to produce the most even droplet distribution for an N-3 unmanned helicopter (Research Institute on Simulation Technique, Nanjing, Jiangsu China) sprayer in a test for maize (Qin et al. 2014). A flight altitude of 2 m and average flight speed of 2–3 m/s produced greater droplet deposition and uniformity than other altitudes (1 and 3 m) and speeds (3–4 and 4–5 m/s) for a HY-B-10L unmanned helicopter (Gao Ke Xing Nong Co. Ltd., Shenzhen, Guandong, China) spraying on rice (Chen et al. 2016). In a spraying test for a QJ-460 quad-rotor UAS (Lv Wei Shi Aerial Plant Protection Technology Co. Ltd., Zhuhai, Guangdong, China) in a citrus orchard, the citrus canopy received the maximum droplet deposition density at a flight altitude of 1 m above that canopy (compared with altitudes of 0.5 or 2 m) (Zhang et al. 2016c). Citrus trees with a central open canopy received greater droplet coverage and density than round-top canopy trees in a test in which both types of trees were sprayed by a 3 W-LWS-Q60S quad-rotor UAS (Crop Guardian Aerial Plant Protection Co., Zhuhai, China) (Zhang et al. 2016b). For studying spray droplet deposition and drift patterns, general test approaches have been proposed. These include test frameworks for spray droplet deposition at top, bottom, upwind and downwind parts (Wang et al. 2016), the NJS-1 type open-circuit, closed low-speed wind tunnel (Ding et al. 2015), and NERCIEA-I (Tang et al. 2016) and NERCIEA-2 high-speed wind tunnels (The Technology Innovation Strategic Alliance for Agricultural Aviation, TISAAA 2017).

UAS positioning and navigation

A remote control UAS test system based on the Laboratory Virtual Instrument Engineering Workbench was developed to track real-time UAS flight routes (LabVIEW, National Instruments, Austin, Texas USA) (Zhang et al. 2015). This route tracking system was assembled in a UAS flight real-time monitoring system. The monitoring system was able to track the UAS flight route in real-time and can be used to assess the performance of UAS operators or auto-navigation systems (Zhang et al. 2016a). Precise flight route control is essential, especially with poor Global Navigation Satellite System (GNSS) signal reception. Positioning methods other than GNSS can ensure a proper UAS flight in such a situation (Table 3). For example, a positioning reference model was combined with GNSS positioning in the controller for rotary-type UAS. Performance of the controller was tested, and strong robustness and tracking ability were reported (Zhao et al. 2016b). A mixed positioning system with a GNSS device and General Packet Radio Service (GPRS) was tested, showing positioning improvement over a positioning system with GNSS alone (Yuan 2016). A Lite V2 LIDAR laser range finder (PulsedLight Inc., Bend, OR, USA) and an MPU6000 accelerometer/gyroscope (InvenSense Inc., San Jose, CA, USA) were used to control altitude for a quad-rotor UAS. This system could control altitude deviation of the UAS within 0.1 m from a pre-defined flight altitude while the deviation for a GNSS device and pressure gauge control system was 0.5 m (Zhao et al. 2016a).

UAS auto navigation is an important component for precise aerial spraying (Table 3). Qu and Liang (2008) developed a real-time wind field estimation and trajectory correction navigation system with a dead reckoning system/radio positioning system/GNSS. Chen and Lu (2012) developed a navigation system based on a TMS320F2812 digital signal processor chip (Texas Instruments, Inc., Dallas, Texas USA) that incorporated GNSS positioning, infrared sensor and electronic compass functions, and was extended with asynchronous communication. Liu and Wang (2013) designed a strap-down inertial navigation system aided by an airborne data collection system and Baidou navigation satellite positioning. Zhang et al. (2016d) presented an obstacle avoidance control system for a low-altitude and slow-speed unmanned helicopter, based on an improved artificial potential field approach. That system substantially reduced avoidance path length and avoidance time for short obstacles and high square-shaped obstacles. Considerable spray uniformity and flight route precision were achieved by an auto-navigation and auto spraying system developed for an N-3 unmanned helicopter in an experiment (Xue et al. 2016). In the future, computer mapping technology could provide digital maps of individual farms in a village for a UAS using an auto-navigation function, which would increase the potential and precision of aerial applications for farm production.

Variable-rate spray technology

Variable-rate spray technology is the core of very precise and efficient UAS aerial spraying. Nozzle designs were developed and tested to achieve variable-rate spraying (Table 4). An electrostatic nozzle design reduced the use of pesticide by 5.22 L ha^{-1} while improving the control rate for a pine tree moth, *Dendrolimus spp.,* by 33.8% (Zhou et al. 2012). In a study of UAS spray control of wheat midge, *Sitodiplosis mosellana* (Géhin), two types of nozzle atomizer were tested, and a centrifugal atomizer was preferred over a hydraulic atomizer (Gao et al. 2013). A rotation centrifugal nozzle was preferable to a pressure nozzle in a citrus spraying test of the QJ-460 quad-rotor UAS (Zhang et al.

Table 3 Agricultural UAS positioning and navigation systems for plant protection from the literature in China

System	System components	Purpose(s)/application(s)	Source
UAS flight real-time monitoring system	LabVIEW	Assessing performances of UAS operators or auto-navigation systems	Zhang et al. (2015), Zhang et al. (2016a)
UAS positioning and navigation	Positioning reference model and GNSS positioning	Precision flight control and navigation	Zhao et al. (2016b)
	GNSS and GPRS	Precision flight control and navigation	Yuan (2016)
	Laser ranger finder accelerometer/gyroscope	Precision flight control and navigation	Zhao et al. (2016a)
UAS auto navigation	Dead reckoning system, radio positioning system and GNSS	Real-time wind field estimation and trajectory correction navigation	Qu and Liang (2008)
	Digital signal processor chip, GNSS, infrared sensor and electronic compass	UAS auto navigation	Chen and Lu (2012)
	Airborne data collection system Baidou navigation satellite positioning	UAS auto navigation	Liu and Wang (2013)
	Obstacle avoidance control system	UAS auto navigation	Zhang et al. (2016d)
	Auto-navigation and auto spraying system	UAS auto-navigation and auto spraying	Xue et al. (2016)

Table 4 Summary of variable-rate aerial spraying for agricultural UAS in China from the literature

Spraying device(s)	Compared to	Improvement/Optimal settings	Source
Modified electrostatic nozzle	Conventional aerial fan nozzle	5.22 L/ha pesticide reduction and 33.8% control rate	Zhou et al. (2012)
Centrifugal nozzle atomizer	Hydraulic nozzle atomizer	8% control rate	Gao et al. (2013)
Rotation centrifugal nozzle	Pressure nozzle	69.96% droplet coverage, 103.85% droplet size, 117.8% droplet deposition density	Zhang et al. (2016c)
Rotary hydraulic atomizing nozzle	N/A	Optimal settings: 10 V for motor voltage, 0.35 MPa for spray pressure and 0.7 mm for nozzle diameter	Ru et al. (2014)
Ultra-low-volume swirl nozzle	N/A	Optimal settings: 1.5 mm for diameter of the nozzle orifice	Wen et al. (2016)

2016c). Combinations of different spray motor voltages, spray pressures and nozzle diameters were tested for effective use of a rotary hydraulic atomizing nozzle spray system, and optimal sets were reported (Ru et al. 2014). Wen et al. (2016) presented an ultra-

low-volume swirl nozzle design whose atomization characteristics met the requirements of ultra-low-volume spraying. Modification of the nozzle design achieved adjustable spray amount and droplet size. It could be applied to variable rate spraying.

Aerial application of other crop management materials

In addition to aerial spraying of chemical pesticides, UAS users in China are exploring aerial application of other crop management materials (Table 5). For example, Li et al. (2013) reported the practical use of UAS for sugarcane pest control, releasing a bio-control agent, *Trichogramma chilonis* Ishii, via its infested host egg solution. UAS can also be used as a tool for supplementary pollination. Wang et al. (2013) suggested that a working altitude of 7 m in downwind direction flight minimized the impact of a tested UAS (Z3 helicopter by Gao Ke Xing Nong Co. Ltd., Shenzhen, Guangdong, China), after they explored optimal parameters for the unmanned gasoline-engine single-rotor helicopter in supplementary pollination of cultivated rice. Li et al. (2014) conducted similar experiments for a uniaxial, single-rotor electric-powered unmanned helicopter, reporting optimal working parameters at a speed of 1.56 m/s, payload of 14.05 kg, and flight altitude of 1.93 m. Seed broadcasting via a 12-axis rotor wing UAS and an artificial seed broadcaster was compared, and the results suggested that UAS seed broadcasting is feasible (Li et al. 2016).

Imaging and remote sensing

Vegetation indices extracted from UAS-acquired images have been used for vegetation status monitoring and disease and pest detection in China (Table 6). Han et al. (2005) included UAS-acquired images for growth status estimation of winter wheat, and this was suggested for practical use. Zhu et al. (2010) combined UAS-acquired imagery with other imagery to conduct nitrogen diagnoses for rice leaves and canopy. Duan et al. (2014) reported that the leaf area index (LAI) of three crops (maize, potato and sunflower) from 128 bands and 0.7-m resolution UAS-acquired hyperspectral imagery could be estimated with reasonable accuracy (13.6% relative root mean square error relative to in situ LAI measurement). High correlations between the wheat powdery mildew disease index and vegetation information have been reported (Qiao et al. 2006). The vegetation information was extracted from digital images acquired by a G2 digital camera (Canon Inc., Tokyo, Japan) onboard a gas-powered UAS or with a FieldSpec handheld spectroradiometer (Analytical Spectral Devices, Inc., Boulder, Colorado, USA). The authors proposed their use for detecting and monitoring wheat disease. Hu et al. (2013) compared three algorithms with images obtained by a double-spectrum camera onboard a UAS, reporting higher

Table 5 Summary of agricultural UAS applications of other crop management materials in China from the literature

Crop management material(s)	Source
Bio-control agent	Li et al. (2013)
Supplementary pollination	Wang et al. (2013), Li et al. (2014)
Seed broadcasting	Li et al. (2016)

Table 6 Summary applications of UAS imaging and remote sensing for plant protection in China from the literature

UAS imaging and remote sensing application	Source
Growth status estimation for winter wheat	Han et al. (2005)
Nitrogen diagnoses for rice leaves and canopy	Zhu et al. (2010)
LAI estimation for three crops (maize, potato and sunflower)	Duan et al. (2014)
Estimating wheat powdery mildew disease index with vegetation information	Qiao et al. (2006)
Diseased pine tree detection	Hu et al. (2013)

accuracy of diseased pine tree detection using a Weighted Support Vector Data Description algorithm.

Although UAS remotely sensed imagery has been increasingly used for vegetation monitoring, it has great potential in pest detection and identification for UAS aerial applications. UAS remote sensing has an advantage over satellite remote sensing at small scale and site-specific crop management, because it is more flexible to schedule and can acquire high-resolution imagery data under favorable atmospheric conditions (Lan et al. 2010) using a variety of image sensors. This is essential when time series of good-quality data are required for vegetation monitoring. With technological advances in big data, image processing and deep learning, UAS imagery acquired by digital cameras or hyperspectral sensors could promote UAS aerial applications to pest detection and pest identification.

Challenges and prospects

Agricultural aviation is growing fast in China. However, compared with other parts of the world with large-scale agricultural production, this growth lags behind the needs of agriculture in the country. The number of large agricultural aircraft is only $\sim 0.13\%$ of those worldwide, and covers 1.7% of arable land in the country (Zhou et al. 2013). Given increasing labour shortages and concerns for environmental health, UAS have received much attention in China. In July 2016, there were 108 agricultural UAS manufacturers and 27 UAS research institutes nationwide (TISAAA 2017). Among the manufacturers, 80 (59.3%) provide UAS with both imaging and aerial applications, 49 (36.3%) focus on UAS aerial application alone, and 6 (4.4%) are dedicated to imaging.

There are concerns that must be addressed for the growth of agricultural UAS in China. Factors that slow the development of agricultural aviation in the country were summarised by Luo (2014). These factors are the needs of administrative policies, regulations, strategies and standards, research on supporting technologies, trained professionals, and recognition and supporting services from the general public. Many of these factors also apply to agricultural UAS. For example, a lag of applicable administrative regulations behind the agricultural UAS industry is a major concern for agricultural UAS in China. Security issues also stress the urgent need of regulations. The Civil Aviation Administration of China has recently released two provisional regulations. One for regulation for civil UAS pilots was released in November 2013 (The Civil Aviation Administration of China, CAAA 2013), and the other for civil uses of small and micro UAS was released in December 2015 (CAAA 2015). The first regulation listed qualifications for UAS pilots and

flight altitudes and ranges for four UAS categories—micro, mini, small and large. UAS for plant protection purposes were listed as a separate category in the second regulation. Relevant qualifications and restrictions that are less strict than other categories for UAS heavier than 7 kg were also specified. Another regulation on business use of UAS was issued as a draft for review in November 2015, and may be officially enforced in the near future.

Cost is a factor that has limited intensive use of UAS for plant protection in China, though agricultural UAS have been successfully used in Asian countries with small farm sizes, such as Japan and Korea (Zhou et al. 2013). China and four other developing Asian countries (India, Indonesia, Bangladesh and Vietnam), have the largest number of small farms in the world (Thapa 2009). Farmers could greatly benefit from aerial applications in agriculture. However, as with many technologies, the high cost of UAS deters their application in developing countries. In China, although increasing demand promotes the agricultural UAS industry, agricultural UAS applications remain in need of improvement in many aspects. Currently, an average domestic agricultural UAS in China generally costs in excess of 100,000 CNY (USD 14815). Prices of imported models are higher. Before technology advances enable UAS to be affordable to the general public, governmental subsidies and aerial application service providers can facilitate UAS agricultural use. In several provinces (e.g., Henan), a grower could spend as little as a third of the regular price of a UAS after subsidies. Aerial application companies provide UAS spraying services with a price range from CNY 100 to 200 (USD 15–30) ha^{-1}. This service could improve efficiency by a factor of 30 (Liu et al. 2014) while reducing production costs by CNY 105 (USD 15) ha^{-1} (Zhou et al. 2013). In addition to UAS production with larger payloads and longer flight ranges at acceptable cost, the development of a reliable auto navigation system, very effective adjustable spray nozzles and related spraying methods for such UAS are necessary for their widespread use.

Similar to the need for regulations, the lack of an industry standard or protocol is another factor limiting widespread agricultural use of UAS, at least from the aspects of portability and governmental subsidies. Because of the lack of a mutually agreed industry standard or protocol, there are many types of agricultural UAS in the Chinese market, e.g., gas- or battery-powered unmanned helicopters, fixed-wing aircraft and rotary-wing aircraft of various sizes. The varieties of UAS types and sizes diminish their portable uses and compatibility. Such varieties also make governmental subsidy policy difficult to implement and enforce. This could deter crop growers from buying a UAS because of not receiving governmental subsidies, for the reason that UAS specifications have not been agreed to by those specifying subsidy policy.

An ultimate UAS application scenario in agriculture would be a combination of aerial remote sensing, real-time image processing and variable-rate aerial application technology as described by Lan et al. (2010), i.e., aerial imagery processed instantly to retrieve and diagnose crops, soil, pest and damage information, then variable-rate spraying used accordingly. This could be described as data gathering, data processing and spraying. Initial pest detection and identification are critical to the full scenario. Image processing methods (see Guan et al. 2009; Sankaran et al. 2010 for review) could be used for detection of disease, pests and weeds. Sankaran et al. (2010) suggested that some disease detection methods could be incorporated into autonomous agricultural vehicles or robots for real-time plant disease detection. These methods include the aforementioned remote sensing and digital photos. Other imaging sources, such as fluorescence spectroscopy and fluorescence imaging, could also be used by UAS and processed for plant disease diagnosis. The image processing detection stage could be facilitated by a fast data link between UAS

and ground stations, to use computation power. Big data and deep learning approaches could also be included in image processing for pest detection and identification stages, as done for 14 crop species and 26 diseases in Mohanty et al. (2016) or for coffee rust development rate in Calvo-Valverde et al. (2016). In another method, an electronic nose system could be installed on a UAS for sampling or detection, once the volatile organic compound profile for a specific plant disease has been well established. Aerobiological sampling and real-time analysis may be another approach to disease detection.

However, cost will continue to be a key factor limiting widespread use of UAS in plant protection for individual farmers in China, unless the operational farm size increases. Even if cost declines to reasonable levels, a practical issue is frequent takeoff and landing for reloading application material, changing batteries or refuelling for small and light UAS. The majority of UAS in China are battery-powered and their payload capacities are less than 15 kg (Fig. 2). For example, for a battery-powered UAS with a typical 15–20 min flight duration, it is suggested to change its battery after each flight task. However, the ultimate UAS application scheme for plant production described above will increase in cost with technology advances, possibly requiring additional costs to users. In addition to operating a UAS per se, pest surveys, flight route planning and variable-rate spray settings based on pest survey results require additional work and expertise. These UAS operations and related pest work are also extra burdens for crop growers, and should be left to specialized operators. A solution is to use UAS as an on-demand service provided by local governments, agricultural co-operatives, and specialized companies for crop growers. The service could be a chain including UAS application and farming material companies, as proposed in Leng et al. (2017). Sales and logistics companies could also be incorporated in the chain.

Conclusions

The agricultural use of UAS in China will increase in the near future with support from new policies on agricultural aviation, land transfer and large-scale farming. Crop growers and the agricultural industry could benefit from its high efficiency. However, agricultural UAS manufacturers and providers must reduce their costs and face the challenges of producing sound solutions for auto navigation, pest detection and identification and variable-rate spraying systems. UAS on-demand application services provided by local governments, agricultural co-operatives and specialized companies may be a practical solution for crop growers in China.

References

Calvo-Valverde, L., Barquero, M., Rojas, V. (2016). Machine learning methods applied to predict the coffee rust development rate: A study case in Costa. In: Proceedings of the 26th International Conference on Coffee Sciences. The Association for Science and Information on Coffee (ASIC) (pp. 64) (distribution to conference attendees).

Chen, T., & Lu, S. (2012). Autonomous navigation control system of agricultural mini-unmanned aerial vehicles based on DSP. *Transactions of the Chinese Society of Agricultural Engineering, 28*(21), 164–169. **(In Chinese with English abstract)**.

Chen, S., Lan, Y., Li, J., Zhou, Z., Jin, J., & Liu, A. (2016). Effect of spray parameters of small unmanned helicopter on distribution regularity of droplet deposition in hybrid rice canopy. *Transactions of the Chinese Society of Agricultural Engineering, 32*(17), 40–46. **(In Chinese with English abstract)**.

China Agriculture Yearbook Editorial Committee. (2016). *2015 China agriculture yearbook*. Beijing: China Agriculture Press. **(In Chinese)**.

Deng, H., Huang, J., Xu, Z., & Rozelle, S. (2010). Policy support and emerging farmer professional cooperatives in rural China. *China Economic Review, 21*(4), 495–507.

Ding, S., Xue, X., Lan, Y., Cai, C., Zhang, L., Qin, W., et al. (2015). Design and experiment of NJS-1 type open-circuit closed wind tunnel for plant protection. *Transactions of the Chinese Society of Agricultural Engineering, 31*(4), 76–84. **(In Chinese with English abstract)**.

Duan, S., Li, Z., Wu, H., Tang, B., Ma, L., Zhao, E., et al. (2014). Inversion of the PROSAIL model to estimate leaf area index of maize, potato, and sunflower fields from unmanned aerial vehicle hyperspectral data. *International Journal of Applied Earth Observation and Geoinformation, 26*(2), 12–20.

Eastwood, R., Lipton, M., & Newell, A. (2010). Farm size. In P. Pingali & R. Evenson (Eds.), *Handbook of agricultural economics* (Vol. 4, pp. 3323–3397). Rotterdam: Elsevier.

Gao, Y., Zhang, Y., Zhang, N., Niu, L., Zheng, W., & Yuan, H. (2013). Primary studies on spray droplets distribution and control effects of aerial spraying using unmanned aerial vehicle (UAV) against wheat midge. *Crops, 2,* 139–142. **(In Chinese with English abstract)**.

Guan, Z., Yao, Q., Yang, B., Hu, J., & Tang, J. (2009). Application of digital image processing technology in recognizing the diseases, pests, and weeds from crops. *Scientia Agricultura Sinica, 42*(7), 2349–2358. **(In Chinese with English abstract)**.

Han, Y., Li, M., Jia, L., Zhang, X., & Zhang, F. (2005). Estimating growth status of winter wheat based on aerial images and hyperspectral data. In: Proceedings 2005 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2005) (pp. 59091 V). IEEE.

He, Y., & Zhang, Y. (2014). Current status and future of the agricultural Unmanned Aerial System. *Modern Agricultural Machinery, 1,* 1–5. **(In Chinese)**.

Hu, G., Zhang, X., Liang, D., & Huang, L. (2013). Infected pine recognition in remote sensing images based on weighted support vector data description. *Transactions of the Chinese Society of Agricultural Engineering, 44*(5), 258–263. **(In Chinese with English abstract)**.

Huang, Y., Thomson, S., Hoffmann, W. C., Lan, Y., & Fritz, B. K. (2013). Development and prospect of unmanned aerial vehicle technologies for agricultural production management. *International Journal of Agricultural and Biological Engineering, 6*(3), 1–10.

Lan, Y., Thomson, S., Huang, Y., Hoffmann, W., & Zhang, H. (2010). Current status and future directions of precision aerial application for site-specific crop management in the USA. *Computers and Electronics in Agriculture, 74*(1), 34–38.

Leng, Z., Jiang, T., Liu, F., Wang, X., & Hu, J. (2017). Study on the extension mode of agricultural service corporation of UAV for plant protection. *Journal of Agricultural Mechanization Research, 39*(1), 6–9. **(In Chinese with English abstract)**.

Li, D., Yuan, X., Zhang, B., Zhao, Y., Song, Z., & Zuo, C. (2013). Report of using unmanned aerial vehicle to release *Trichogramma*. *Chinese Journal of Biological Control, 29*(3), 455–458. **(In Chinese with English abstract)**.

Li, J., Zhou, Z., Hu, L., Zang, Y., Yan, M., Liu, A., et al. (2014). Optimization of operation parameters for supplementary pollination in hybrid rice breeding using uniaxial single-rotor electric unmanned helicopter. *Transactions of the Chinese Society of Agricultural Engineering, 30*(10), 10–17. **(In Chinese with English abstract)**.

Li, J., Lan, Y., Zhou, Z., Zeng, S., Huang, C., Yao, W., et al. (2016). Design and test of operation parameters for rice air broadcasting by unmanned aerial vehicle. *International Journal of Agriculture and Biological Engineering, 9*(5), 24–32.

Liu, M., & Wang, H. (2013). Research on agriculture survey and evaluation UAV navigation system. *INMATEH-Agricultural Engineering, 41*(3), 31–38.

Liu, S., Li, X., & Zhang, M. (2003). Scenario analysis on urbanization and rural-urban migration in China. *Interim Report*. IR-03-036, Laxenburg: International Institute of Applied Systems Analysis.

Liu, J., Jia, S., Du, X., & Deng, M. (2014). Development status quo and trends of low-altitude unmanned aerial vehicles spraying technology. *Agricultural Engineering, 4*(5), 10–14. **(In Chinese with English abstract)**.

Lu, B., Yu, Q., Fu, X., Shi, Y., & Cai, M. (2016). Parameter matching of hybrid coaxial rotors and multi-rotor UAV's power system. In: Proceedings 2016 IEEE/CSAA International Conference on Aircraft Utility Systems (AUS) (pp. 1099–1104). IEEE.

Luo, X. (2014). A contemplation on promoting the development of agricultural aerial technology in China. *Agricultural Technology and Equipment, 5,* 7–15. **(In Chinese)**.

Mohanty, S. P., Hughes, D. P., & Salathé, M. (2016). Using deep learning for image-based plant disease detection. *Frontiers in Plant Science, 7*(1419), 1–7.

Qiao, H., Zhou, Y., Bai, Y., Cheng, D., & Duan, X. (2006). The primary research of detecting wheat powdery mildew using in-field and low altitude remote sensing. *Acta Phytophylacica Sinica, 33*(4), 341–344. **(In Chinese with English abstract)**.

Qin, W., Xue, X., Zhou, L., Zhang, S., Sun, Z., Kong, W., et al. (2014). Effects of spraying parameters of unmanned aerial vehicle on droplets deposition distribution of maize canopies. *Transactions of the Chinese Society of Agricultural Engineering, 30*(5), 50–56. **(In Chinese with English abstract)**.

Qin, W., Qiu, B., Xue, X., Chen, C., Xu, Z., & Zhou, Q. (2016). Droplet deposition and control effect of insecticides sprayed with an unmanned aerial vehicle against plant hoppers. *Crop Protection, 85*(6), 79–88.

Qiu, B., Wang, L., Cai, D., Wu, J., Ding, G., & Guan, X. (2013). Effect of flight altitude and speed of unmanned helicopter on spray deposition uniform. *Transactions of the Chinese Society of Agricultural Engineering, 29*(24), 25–32. **(In Chinese with English abstract)**.

Qu, Y., & Liang, F. (2008). A method of wind field estimation and trajectory correction online in DR/GPS/RP integrated navigation of UAV. In: Proceedings 2008 IEEE International Conference on Automation and Logistics (pp. 1402–1407). IEEE.

Ru, Y., Jin, L., Zhou, H., & Jia, Z. (2014). Performance experiment of rotary hydraulic atomizing nozzle for aerial spraying application. *Transactions of the Chinese Society of Agricultural Engineering, 30*(3), 50–55. **(In Chinese with English abstract)**.

Sankaran, S., Mishra, A., Ehsani, R., & Davis, C. (2010). A review of advanced techniques for detecting plant diseases. *Computers and Electronics in Agriculture, 72*(1), 1–13.

Shahbazi, M., Théau, J., & Ménard, P. (2014). Recent applications of unmanned aerial imagery in natural resource management. *GIScience and Remote Sensing, 51*(4), 339–365.

Sonntag, B. H., Huang, J., Rozelle, S., & Skerritt, J. H. (2005). *China's agricultural and rural development in the early 21st century*. Canberra: Australian Centre for International Agricultural Research (ACIAR).

Tang, Q., Chen, L., Zhang, R., Xu, M., Xu, G., & Zhang, B. (2016). Design and test of IEA I high speed wind tunnel for aerial plant protection. *Transactions of the Chinese Society of Agricultural Engineering, 32*(6), 73–81. **(In Chinese with English abstract)**.

Thapa, G. (2009). *Smallholder farming in transforming economies of Asia and the Pacific: Challenges and opportunities*. Discussion Paper. International Fund for Agricultural Development, Rome.

The Civil Aviation Administration of China. (2013). The interim provisions for civilian unmanned aerial vehicle system operators (AC-61-FS-2013-20). Retrieved from http://www.caac.gov.cn/J1/ZXTG/201312/P020131206548535775686.pdf. Accessed on February 21, 2016. **(In Chinese)**

The Civil Aviation Administration of China. (2015). The interim provisions for light and small civilian unmanned aerial vehicle systems (AC-91-FS-2015-31). Retrieved from http://www.caac.gov.cn/J1/ZXTG/201601/P020160104368061133606.pdf. Accessed on February 21, 2016. **(In Chinese)**

The Technology Innovation Strategic Alliance for Agricultural Aviation. (2017). *2016 Report on industry development of agricultural aviation in China*. Guangzhou: Sun Yag-Sen University Press. **(In publication, In Chinese)**

Wang, P., Hu, L., Zhou, Z., Yang, W., Liu, A., Luo, X., et al. (2013). Wind field measurement for supplementary pollination in hybrid rice breeding using unmanned gasoline engine single-rotor helicopter. *Transactions of the Chinese Society of Agricultural Engineering, 29*(3), 54–61. **(In Chinese with English abstract)**.

Wang, C., He, X., Wang, X., Bonds, J., Herbst, A., Wang, Z., et al. (2016). Testing method of spatial pesticide spraying deposition quality balance for unmanned aerial vehicle. *Transactions of the Chinese Society of Agricultural Engineerin, 32*(11), 54–61. **(In Chinese with English abstract)**.

Wen, S., Lan, Y., Zhang, J., Li, S., Zhang, H., & Xing, H. (2016). Analysis and experiment on atomization characteristics of ultra-low-volume swirl nozzle for agricultural unmanned aviation vehicle. *Transactions of the Chinese Society of Agricultural Engineering, 32*(20), 85–93. **(In Chinese with English abstract)**.

Xue, X., Lan, Y., Sun, Z., Chang, C., & Hoffmann, W. C. (2016). Develop an unmanned aerial vehicle based automatic aerial spraying system. *Computers and Electronics in Agriculture, 128,* 58–66.

Yang, A., Wang, H., Tang, K., & Sun, G. (2002). Soil erosion characteristics and control measures in China. In: Proceedings of 12th International Soil Conservation Organization Conference (pp. 26–31). Beijing: Tsinghua University Press.

Yuan, Y. (2016). Research and design of high-precision positioning system for agricultural plant protection UAV-based on GPS and GPRS. *Journal of Agricultural Mechanization Research, 12,* 227–231. **(In Chinese with English abstract)**.

Zhang, G. (2011). Review of agricultural aviation technologies and research of new-type agricultural aviation technologies. *Jiangxi Forestry Science and Technology, 1,* 25–31. **(In Chinese)**.

Zhang, C., & Kovacs, J. M. (2012). The application of small unmanned aerial systems for precision agriculture: A review. *Precision Agriculture, 13*(6), 693–712.

Zhang, J., He, X., Song, J., Zeng, A., Zeng, A., Liu, Y., et al. (2012). Influence of spraying parameters of unmanned aircraft on droplets deposition. *Transactions of the Chinese Society of Agricultural Machinery, 43*(12), 94–96. **(In Chinese with English abstract)**.

Zhang, D., Lan, Y., Chen, L., Wang, X., & Liang, D. (2014). Current status and future trends of agricultural aerial spraying technology in China. *Transactions of the Chinese Society for Agricultural Machinery, 45*(10), 53–59. **(In Chinese with English abstract)**.

Zhang, K., Zhang, T., Liao, Y., Zhuang, X., Li, S., & Lan, Y. (2015). Remote control unmanned aerial vehicle test system based on LabVIEW. *Transactions of the Chinese Society of Agricultural Engineering, 31*(Supp. 2), 11–16.

Zhang, K., Zhang, T., Liao, Y., & Lan, Y. (2016a). UAV flight status real-time monitoring evaluation system based on LabVIEW. *Transactions of the Chinese Society of Agricultural Engineering, 32*(18), 183–189. **(In Chinese with English abstract)**.

Zhang, P., Deng, L., Lyu, Q., He, S., Yi, S., Liu, Y., et al. (2016b). Effects of citrus tree-shape and spraying height of small unmanned aerial vehicle on droplet distribution. *International Journal Agricultural and Biological Engineering, 9*(4), 45–52.

Zhang, P., Lv, Q., Yi, S., Liu, Y., He, S., Xie, R., et al. (2016c). Evaluation of spraying effect using small unmanned aerial vehicle (UAV) in citrus orchard. *Journal of Fruit Science, 33*(1), 34–42. **(In Chinese with English abstract)**.

Zhang, X., Xu, H., & Zhu, X. (2016d). Design of obstacle avoidance control system for low altitude and low speed eppo unmanned helicopter. *Transactions of the Chinese Society of Agricultural Engineering, 32*(2), 43–50. **(In Chinese with English abstract)**.

Zhao, J., Li, Y., Hu, D., & Pei, Z. (2016a). Design on altitude control system of quad rotor based on laser radar. In: Proceedings 2016 IEEE/CSAA International Conference on Aircraft Utility Systems (AUS) (pp. 105–109). IEEE.

Zhao, L., Zhang, K., & Wang, W. (2016b). Position control system design for multi-rotor type UAV. *Computer Measurement and Control, 24*(3), 84–87. **(In Chinese with English abstract)**.

Zhou, H., Ru, Y., Shu, C., & Jia, Z. (2012). Improvement and experiment of aerial electrostatic spray device. *Transactions of the Chinese Society of Agricultural Engineering, 28*(12), 7–12. **(In Chinese with English abstract)**.

Zhou, Z., Zang, Y., Luo, X., Lan, Y., & Xue, X. (2013). Technology innovation development strategy on agricultural aviation industry for plant protection in China. *Transactions of the Chinese Society of Agricultural Engineering, 29*(24), 1–10. **(In Chinese with English abstract)**.

Zhu, X. (2014). An exploration on agricultural unmanned aerial vehicle for crop protection. *Agriculture Machinery Technology Extension, 5,* 31–32. **(In Chinese)**.

Zhu, J., Chen, Z., Shi, Y., Wang, K., & Deng, J. (2010). Diagnoses of rice nitrogen status based on spectral characteristics of leaf and canopy. *Journal of Zhejiang University (Agriculture and Life Sciences), 36*(1), 78–83. **(In Chinese with English abstract)**.