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Perspectives and experiences on the development and innovation of agricultural aviation and precision agriculture from the Mississippi Delta and recommendations for China

Yanbo Huang

（*United States Department of Agriculture (USDA), Agricultural Research Service (ARS), Crop Production Systems Research Unit (CPSRU), Stoneville, MS*38776, *USA*）

Abstract: Crop production management has advanced into the stage of smart agriculture, which is driven by state-of-the-art agricultural information technology, intelligent equipment and massive data resources. Smart agriculture inherits ideas from precision agriculture and brings agricultural production and management from mechanization and informalization to intelligentization with automatization. Precision agriculture has been developed from strategic monitoring operations in the 1980s to tactical monitoring and control operations in the 2010s. In its development, agricultural aviation has played a key role in serving systems for spray application of crop protection and production materials for precision agriculture with the guidance of global navigation through geospatial prescription mapping derived from remotely-sensed data. With the development of modernized agriculture, agricultural aviation is even more important for advancing precision agricultural practices with more efficient soil and plant health sensing and more prompt and effective system actuation and action. This paper overviews the status of agricultural aviation for precision agriculture to move toward smart agriculture, especially in the Mississippi Delta region, one of the most important agricultural areas in the U.S. The research and development by scientists associated with the Mississippi Delta region are reported. The issues, challenges and opportunities are identified and discussed for further research and development of agricultural aviation technology for next-generation precision agriculture and smart agriculture.

Key words: aerial application technology; agricultural aviation; big data; precision agriculture; remote sensing; smart agriculture

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1 Introduction

Precision agriculture has been established on agricultural mechanization since the late 1980s with the integration of global positioning system (GPS), geographic information system (GIS) and remote sensing and has revolutionized crop production management since the late 1980s. With the advance-

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*Biography: Yanbo Huang (1958-), Research Agricutulral Engineer, Lead Scientist, research interests: aerial application technology, remote sensing, precision agriculture, artificial intelligence and machine learning, system modeling and process control and automation, Tel: +1 662-686-5354, Email: yanbo.huang@usda.gov.

ment of information and electronic technologies, agricultural production and management can be offered to have smart operations for so-called smart agriculture. Although a scientific and unified definition of smart agriculture does not exist yet[1], the operations of agricultural production and management have moved to levels that can be supported with supercomputing, inter-networking, machine or artificial intelligence and massive data resources, which makes the integration and optimization of agricultural production systems and resources greatly advanced.

Over almost forty years, precision agriculture has been advanced greatly. One important characteristic of this advancement is that precision agricultural production and management have developed from strategic monitoring using satellite imagery for regional decision making to tactical monitoring and controlled using low-altitude remotely sensed data for field-scale site-specific treatment. Agricultural aviation is a key technology for advancement of precision agricultural operations[2-4]. As defined by the National Agricultural Aviation Association (NAAA) (Alexandria, Virginia, USA), agricultural aviation is an industry that "consists of small businesses and pilots that use aircraft to aid farmers in producing a safe, affordable and abundant supply of food, fiber and biofuel" while "aerial application is a critical component of high-yield agriculture" (https://www.agaviation.org/aboutagaviation). In order for precision agriculture to be applied to conduct aerial spray application precisely to the parts of a field as needed, the system should be guided by a prescription by geospatial data of distributed agricultural variables over the field, which completely conceptualizes agricultural aerial spray application technology for precision agriculture, or precision agricultural aerial application.

Agricultural aviation started in 1906 when John Chaytor spread seed over a swamped valley floor in Wairoa, New Zealand, using a hot air balloon with mobile tethers[5]. In 1924, the first commercial operation of crop dusting was conducted in Macon, Georgia, USA, by Huff-Daland Crop Dusting, a company co-founded by a pilot Lt. Harold R. Harris, who tested the system in McCook Field, Dayton, Ohio, USA[5]. Agricultural remote sensing can be traced back to the late 1920s when aerial photography was used to identify cotton root rot in College Station, Texas, USA[6-8]. These technologies for agricultural aviation still continue to be developed today and are developed with precision agriculture to offer smart operations to promote agricultural productivity and greatly improve agricultural management[9].

This paper provides an overview the status of agricultural aviation for precision agriculture to move toward smart agriculture, focusing on the region of the Mississippi Delta, one of the most important agricultural areas in the U. S. The research and development by scientists in this aspect for the Mississippi Delta are reported. The issues, and coexisting challenges and opportunities are identified and discussed for further research and development.

2 Agriculture in the Mississippi Delta

Agriculture is a major industry in the U. S., which is a net exporter of food[10]. In 2007, the production of America's farms contributed $132.8 billion, which is about 1% of U. S. gross domestic product (GDP) [11]. Agricultural activity takes place in every state in the U.S. The most concentrated agricultural area in the U.S. is the Great Plains, a vast expanse of flat, arable land in the center of the nation in the region west of the Great Lakes and east of the Rocky Mountains (Figure 1), with the major crops of corn, soybean, cotton and wheat in the regions known as the Corn Belt, the Wheat Belt and the Cotton Belt[12].

Fig. 1 Maps of Great Plains and Mississippi Delta over the U.S. and the location of Stoneville, Mississippi (Courtesy of https://en.wikipedia.org/wiki/U.S._statefor the base map of the U.S.).

The Mississippi Delta is located in the northwest section of the state of Mississippi (Figure 1). This region is one of the largest contiguous agricultural areas in the U.S., with an area of more than 1.6 million hectares and has many advantages for massive commercial crop production with plain topography, extensive surface, ground water resources, and nutrient-rich soils. With deep, alluvial soils, 220 to 260 frost-free days per year, average annual soil temperatures greater than 15° C at a 50cm depth, and annual precipitation ranging from about 114cm in the northern Delta to 150cm in the southern Delta, this region is well-suited for mechanized agriculture for large-scale crop production in large flood plains with the area ranging from nearly flat to undulating, gentle slopes[13] and agronomically very productive under proper management. Major agricultural crops and enterprises of the Mississippi Delta include cotton, soybean, rice, corn, small grain, forage, vegetables, and catfish. Delta Council, created in 1935, is a regional economic development organization representing the areas of the Mississippi Delta from 18 counties in Northwest Mississippi. This organization provides a medium through which the agricultural, business, and professional leadership of the region could work together to solve common problems and promote the development of the economy in the Mississippi Delta.

The Mississippi Delta is known for traditional row crop agriculture, including cotton, soybean, and corn. However, there are growing interests to develop non-traditional specialty crops, such as vegetable crops and fruit crops, in the Mississippi Delta. That aspect brings new research needs for precision agriculture of specialty crop farming in the Mississippi Delta. Due to extensive agricultural activities with great productivity, federal and regional agencies, universities, and major companies in the agricultural industry have experiment stations and offices with many experimental fields in this region centered at Stoneville, Mississippi (Figure 1), which are called "Silicon Valley of Agriculture".

The research team of agricultural aviation for aerial application technology and remote sensing conducts independent and collaborative research in a 400ha area (33.445752°, -90.881842°) with several research farms for precision agriculture, weed science and crop genetics research. Delta Research and Extension Center (DREC), Mississippi State University, is also located at Stoneville, Mississippi. DREC researchers focus on agricultural and aquaculture commodities like cotton, rice, soybeans, corn, and catfish. They strive to advance technology, develop best practices, and provide practical solutions to challenges faced by Delta producers. Major agricultural companies all, have offices and experimental fields and send researchers over to conduct experiments every year in the Stoneville location.

3 Agricultural aviation in the Mississippi Delta

Agricultural aviation is conducted worldwide. Because of environmental and public health hazards, like spray drift, many countries seriously limit aerial application of pesticides and other products. The European Union banned the practice in all member states with a few highly restricted exceptions in 2009[14]. In the U.S., aerial applications are conducted in all 50 states with about 1,600 aerial application businesses. NAAA is an organization that provides networking, educational, government relations, public relations, recruiting, and informational services to its members and the aerial application industry in the U.S. as a whole. There are 35 regional and state agricultural aviation associations throughout the U.S. representing the regional, state, and local interests of aerial application businesses and pilots, including the Mississippi Agricultural Aviation Association (MAAA). NAAA defines agricultural aviation as an important part of the overall aviation and agriculture industries with highly professionally trained aerial applicators, and aerial application as a critical component of high-yield agriculture[15].

Aerial application is often the only, or most economic method for timely pesticide application and permits large and often remote areas to be treated rapidly, far faster than any other form of application[16], especially abnormally wet weather conditions across the Midwest and Midsouth areas making aerial application an indispensable tool for ensuring high yields. Based on the most recent available survey and statistics in the U.S., there are approximately 3,600 agricultural aircraft (87% fixed-wing and others are helicopters) for about 25% of crop protection work[17] and 4% of their operations use UAVs (Unmanned Aerial Vehicle) [18]. In the 1980s, Japan developed UAV with Yamaha technology for crop dusting[19]. China is rapidly developing UAV-based plant protection technology[20,21]. The U.S. has strongly capable aerial and ground-based spray application systems in use. Therefore, UAV-based spray systems have been limitedly developed and applied in the states, except in a few spray systems and performance studies over agricultural fields[22-24]. In 2013, Dr. Ken Giles, professor at the University of California at Davis, stated that "In the U.S. right now there is no commercial use of this technology - it's strictly a research and development effort"[25], which, as he had described, has been the status quo up to last few years. Currently, UAV-based aerial technology is gaining traction for applying pesticides and fertilizers in the U.S. because it offers several advantages to the users. American Society of Agricultural and Biological Engineers (ASABE) and American Society of Agronomy (ASA) hosted sessions in annual meetings and created committees for coordinating UAV research, development and application in agriculture. ASABE organizes to develop UAV standards, including standards for UAV spray application. These standards are accredited by the American National Standards Institute (ANSI) to coordinate and develop the U.S. position in international UAV standards development by International Organization of Standardization (ISO). American Chemical Society (ACS) held a symposium "Unmanned Aerial Vehicles (aka Drones): Pesticide Spraying and Other Agricultural Applications" at the 258th National Meeting and Exposition in August 2019. The National Aeronautics and Space Administration (NASA, Washington, DC, USA) organized the 3rd Federal UAS Workshop for partnerships to accelerate UAS use throughout the federal enterprises. FMC (Philadelphia, Pennsylvania, USA), an American chemical manufacturing company, developed a BMP (Best Management Practices) for UAV spray applications. With UAV technology, the spray applicator is removed from the spray process, and the UAV can reach areas inaccessible to man and at times inaccessible to aircraft and ground sprayers. UAVs provide an opportunity to get better spray coverage, especially for rotor-winged systems that can hover over a specific area while applying pesticides. Also, the UAV does not come into direct contact with the soil surface. Thus, it does not contribute to soil compaction.

Available statistics show that across Mississippi, there are over 200 licensed agricultural aviation pilots and more than 100 aerial application businesses and 190 registered aircraft[26]. Generally, aerial applicators can spray 40 ha in under 30 minutes, depending on ferry distance to the field and size of fields. A plane, depending on size, can carry 1,000 to 2,000 kg of dry fertilizer, and there are 1,500 to 3,000 liter hoppers on planes currently in production.

General aviation remote sensing platforms are typically used to support site-specific agricultural management, and these platforms are now available as a component of whole-farm management[27]. Now, 12% of operators use remote crop sensing or aerial imaging as part of their operations[18]. However, to promote wider utilization of remote sensing systems for area and targeted management, agricultural aircraft have potential to provide a most convenient platform for plant mapping, especially in rural areas that do not have immediate access to general aviation aircraft. In the Mississippi Delta, a predominately rural agricultural region, spray planes are widely used to apply agricultural chemicals. However, remote sensing systems for practical use by pilots have not yet achieved the right balance between cost, user friendliness, and imaging capability.

4 Research and development of agricultural aviation

Agricultural aviation has been widely developed and used in the U.S. several universities, such as the University of Illinois, Louisiana State University, and University of California, used to have aerial application research and extension programs. USDA-ARS also has research units that undertake research projects on aerial application technology. The research conducted in Stoneville, Mississippi, in the region of the Mississippi Delta, is to renovate nozzle configurations, systems operation, and aircraft navigation with simulation of draft models for better spray efficacy, determine atmospheric stability for timing of long-distance movement of spray deleterious to susceptible crops downwind from spray application, and develop low-altitude remote sensing systems for precision weed management for assessing crop herbicide damage and detection herbicide-resistant weeds.

Stoneville, Mississippi is at the center of Mississippi Delta, which is an important agricultural research and production area as described above. In this area, scientists have been conducting research of aerial application technology with low-altitude remote sensing for improved precision agricultural operations during the last two decades.

4.1 Aerial application technology

The research of aerial application technology has been conducted by scientists at Stoneville, Mississippi for almost twenty years[28,29]. In the past two decades, these scientists have evaluated various nozzles for drift control and tested a hydraulic pump with an automatic flow controller for aerial variable-rate spray studies. They also collected meteorological data and studied the daily atmospheric stability change and daily probability of atmospheric stability for the likelihood of surface temperature inversion. Using this data, an algorithm was developed for a website, which was published to guide aerial applicators on the timing to conduct spray application to avoid off-target drift caused by temperature inversion.

Figure 2 shows the Air Tractor 402B (Air Tractor Inc., Olney, Texas, USA) with spray booms and flow control system for different nozzles, which has been the research and testing platform for scientists in Stoneville, Mississippi.

4.1.1 Nozzle characterization

A low drift CP flat-fan nozzle was evaluated

Fig. 2 Air Tractor 402B with spray booms and flow control system for different nozzles used for aerial application research in Stoneville, Mississippi.

for characterization of aerially applied in-swath spray deposition[30]. In this study, the CP flat-fan nozzles with selectable tips and swivel angles were evaluated with different application volumes for droplet spectra and coverage using water sensitive papers placed in the spray swath. Another study was further conducted to evaluate the CP flat-fan nozzle to characterize the drift of aerial spray application at different delivery heights with a downward nozzle angle of 30 optimized from the previous study[31]. With the optimized parameters from these two studies, the nozzles were used to assess crop injury from the downwind drift of the aerially applied glyphosate[32-34].

At the Stoneville research station, other nozzles were evaluated for general and specific purposes, such as Davidon tri-set nozzles (Davidon, Inc., Vienna, Georgia, USA) for spray deposition and drift studies and Micronair rotary atomizers (Micron Sprayers, Herefordshire, UK) for spraying biological control agents[35]. When applying liquid tank mixes from aerial platforms, there are numerous nozzle types available with differing spray characteristics. More information is needed, however, on the ability of aerial delivery systems to effectively apply biological agents. The release of non-toxigenic A. flavus into corn fields has shown promise as a biological control agent for aflatoxin-producing strains of the fungus. However, the application of a coarse granule to mature, two meters tall corn is a challenge. Thus, there would be substantial advantages to a liquid formulation with necessary identification of appropriate adjuvants to disperse the highly hydrophobic spores of A. flavus. The study was conducted for effective use of these nozzles and other nozzles in application of biological control agents, especially Afla-Guard®, a commercially available product containing non-toxigenic A. flavus as a biological control agent, and related products.

4.1.2 Spray drift management and control

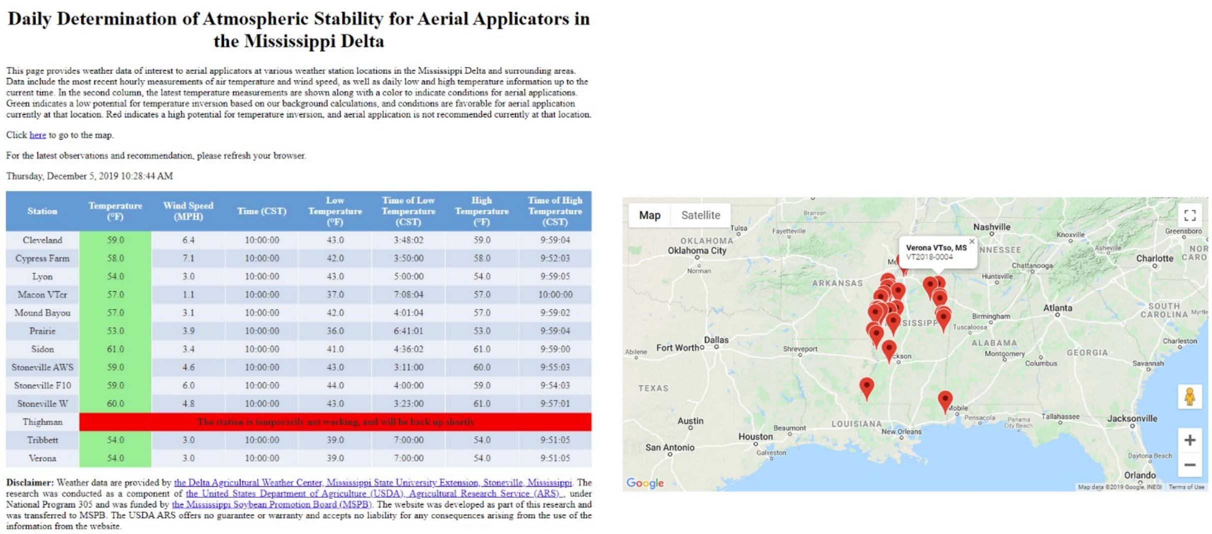
Aerial spray drift can be caused by downwind vertical to the spray line. Downwind drift was characterized by using low-drift nozzles[31] and assessing crop glyphosate injury[32,34]. The Agricultural Dispersion Model (AGDISP) was conducted to evaluate the factors that have impacts on downwind drift[36]. AGDISP is a Lagrangian-based aerial spray dispersion simulation model that models spray material movement, accounting for effects of aircraft wake and turbulence from both aircraft and ambient sources. AGDISP is, however, a sequential cause and effect model that could benefit practically from analysis of multiple factors to obtain a set of optimal results. An approach to modeling called the Design of Experiments (DOE) technique was first introduced by Tauguchi in 1987[37] and can be used to systematically study the influence of many factors and their interactions on an outcome. With the DOE technique, scientists developed a new approach to identify the main factors and interactions that have significant influence on drift of aerially applied spray for AGDISP[38]. With DOE, input values of the AGDISP simulation were generated randomly with a probability distribution within predetermined ranges of the input variables. In this way, outputs of AGDISP resulted from all possible values within ranges of those input variables. Then, with the simulation data and through factorial statistics, DOE identified the impact of factors on the outcomes, such as total downwind drift, and interactions among the factors. Based on the results of DOE-based AGDISP simulation, Huang et al.[39] further optimized selection of controllable variables to minimize downwind drift from aerially applied sprays using the AGDISP model through DOE. With the DOE method, several near-optimal solutions for reduction of spray drift can be determined, and one could be chosen within the constraints of the aerial applicator's spray setup and weather conditions. Field validation and appropriate sensitivity analyses of this DOE-based AGDISP simulation are needed as first steps towards promoting this method to aerial applicators.

Aerial spray drift also can be caused by temperature inversion from atmospheric stability. To know the spray timing to avoid the atmospheric-induced drift, a meteorological calculation is needed to determine the atmospheric stability for occurrence of temperature inversion to recommend when is appropriate during a day for aerial applicators to conduct aerial spray. Based on the wind speed and temperature measured at different heights on a 30m tower over the crop growth season in a year, the daily likelihood of temperature inversion was determined based on classification of atmospheric stability[40] and the effect of data sampling intervals was evaluated[41]. To guide aerial applicators' field operation, a website has been developed with weather data collected hourly from weather stations spread over the Mississippi Delta to provide online recommendation of timing for aerial application to avoid spray drift caused by temperature inversion[42]. The website has been formatted and deployed on mobile platforms, such as smart phone, tablet, and iPad regardless of Google's Android or Apple's iOS operating systems. This website was transferred to the Mississippi Soybean Promotion Board, which is composed of 12 farmer-leaders on behalf of all Mississippi soybean farmers, for them to use to guide appropriate timing of aerial application every day during the growth season (Figure 3).

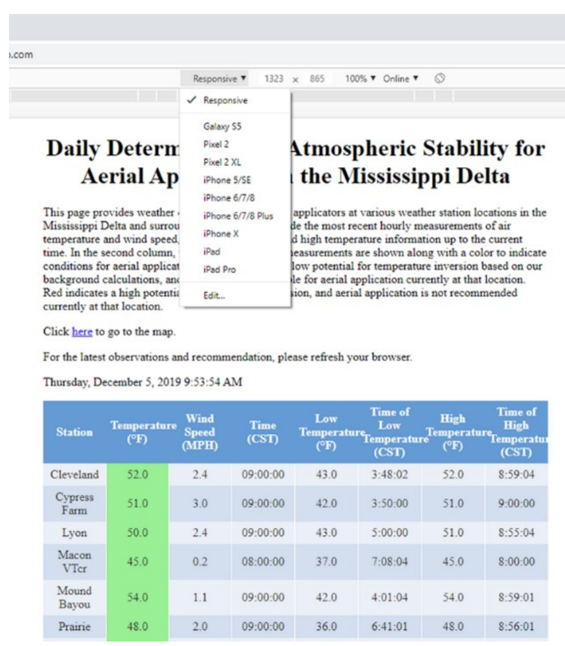
Similarly, another website has been developed specifically for Stoneville, Mississippi, with the data measured at 30 minutes intervals from weather stations, which were built with inexpensive open-source electronics, accessories and software, deployed within the area of Stoneville for more accurate online guidance for site-specific drift management[43]. This web application is also adapted for accessing on mobile terminals, such as smartphones and tablets, and provides a timely guide for aerial applicators and producers to avoid crop damage and air quality issues long distances downwind in the local area.

4.1.3 Variable-rate application

Scientists in Stoneville, Mississippi began to study automated flow control for aerial spray applications in the late 1990s[44]. This research was continued by improving flow response of the aerial variable-rate spray application system[45]. On this basis, experiments were further conducted to evaluate response of a variable-rate aerial application controller to changing flow rates and to improve its response at correspondingly varying system pressures[46]. The variable-rate application system consists of a differential global positioning system (DGPS)-based guidance, an automatic flow controller, and a hydraulically controlled spray pump. The controller was evaluated for its ability to track desired flow rates set by the pilot, and then the system was evaluated over several field trials to quantify its response to rapidly changing flow requirements and to determine the effect of the latest control algorithm improvements on response characteristics. The experiments illustrate an example of how iterative refinement of control algorithms in collaboration with the control system manufacturer could improve system response characteristics. System evaluation techniques described should also apply to aircraft that use propeller-driven spray pumps as well as hydraulically controlled spray pumps.



(a)



(b)

Fig. 3 Website showing daily possible temperature inversion timing for aerial applicators (a); Google Chrome inspect for visualization of website layouts different on mobile platforms (b)

4.2 Low-altitude remote sensing

Remotely-sensed data acquired with aircraft and satellite imaging sensors have been widely used for precision agriculture[47-51]. The major challenges affecting manned aircraft and satellite imaging systems for precision agriculture are appropriate spatial and temporal resolution of imagery and acquisition of usable imagery during partly cloudy conditions. Ground-based systems provide high spatial-resolution data; nevertheless, they are mostly suitable for spot measurements and are often limited by slow movement from place to place and poor field-surface conditions. Low-altitude remote sensing offers a solution for consistent, reliable and high-quality image acquisition (remote sensing), monitoring (e. g., weed infestations), and applying management inputs (e.g., pesticides).

With the research and development of aerial application technology, scientists in Stoneville, Mississippi have also conducted studies of remote sensing, especially at low altitude, to provide site-specific information for precisely targeted aerial spray of crop protection and production materials. In the past two decades, the scientists evaluated various multispectral and thermal cameras for crop field sensing on the Air Tractor 402B to fly over research farms. In recent years, UAVs have been developed and used to carry portable cameras to sense certain parts of the research farms with high spatial resolution. Figure 4 shows the mosaicked RGB image of entire USDA research farm area (~300ha) using the images acquired on Air Tractor 402B and the mosaicked color-infrared (CIR) image and the mosaicked RGB image using the images acquired on a UAV for two fields (~0.3ha and ~4.5ha, respectively) within the area in Stoneville, Mississippi. The spatial resolution of the entire area image is about 50 cm per pixel with the flight altitude of 850m, while the resolution of the UAV images is about 2cm per pixel with the flight altitude of 20m.

With imagery acquired from the multispectral camera on Air Tractor 402B, a study has been conducted to assess crop injury caused by off-target drift of aerially applied glyphosate. The widespread adoption of glyphosate-resistant (GR) crops in the U.S. has led to an unprecedented increase in glyphosate usage in recent years. Glyphosate is the most

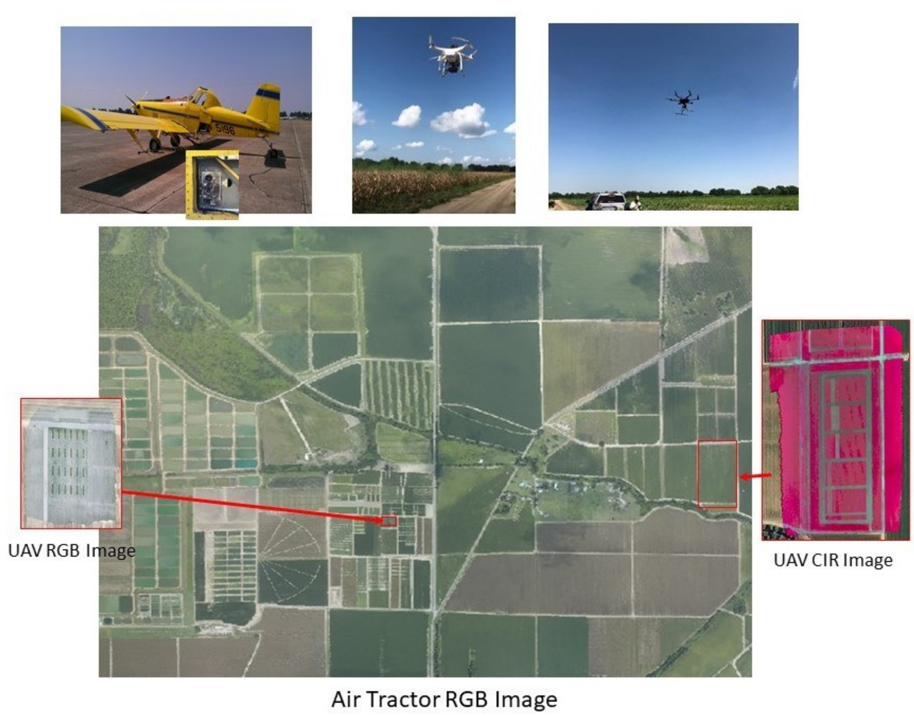


Fig. 4 Mosaicked RGB image using the images acquired on Air Tractor 402B and mosaicked UAV CIR and RGB images for two fields within the entire research farm area in Stoneville，Mississippi

commonly applied herbicide, used either alone or with other herbicides to manage a broad spectrum of weeds. Pesticide drift, the physical movement of a pesticide particle onto an off-target location, can occur when applied under weather conditions that promote drift. In virtually all pesticide applications, a small fraction of the pesticide drifts downwind and can be deposited on off-target surfaces. Off-target drift of aerially applied glyphosate can cause plant injury, which is of great concern to farmers and aerial applicators. To determine the extent of crop injury due to near-field drift, an experiment was conducted with a single aerial application of glyphosate. For identification of the drift effect on cotton, corn and soybean plants, a field was planted in replicated blocks of the crops[32,33,52]. Spray samplers were placed in the spray swath and in several downwind orientations to quantify relative concentration of applied chemical. An Air Tractor 402B spray airplane equipped with fifty-four CP-09 nozzles was flown down the center of the field to apply Roundup Weathermax (Monsanto, St. Louis, Missouri, USA), a commercial glyphosate herbicide product, mixed with Rubidium Chloride tracer. Relative concentrations of the tracer were quantified at downwind spray samplers[53]. At one, two and three weeks after glyphosate field spray, aerial color-infrared imagery was obtained over the field using a GPS-triggered multispectral MS-4100 camera system[54,55] with the flight altitude of 300m. This study's main focus was to assess glyphosate spray drift injury to cotton using spray drift sampling and the color-infrared imagery. The processed drift and image data were highly correlated. The drift and image data were used as the indicators of percent visual injury in regressions with a strong ability of variability explanation.

This study was extended to assessing crop injury caused by another herbicide, dicamba, which is popularized in recent years due to increased glyphosate resistance developed for more and more weeds[56] and is mainly used for postemegence control of several broadleaf weeds in corn, grain sorghum, small grains, and non-cropland. With the popularity of dicamba, there are more and more reports and complaints about susceptible crop damage from dicamba drift locally and regionally. For detection of crop herbicide injury, a field experiment was conducted in a soybean field at the research farm in Stoneville, Mississippi. In the first few years, the MS-4100 Air Tractor imaging system was used to image the field for study and then UAVs were used to focus on the areas of interest in the field[57]. Using UAVs a few weeks after dicamba treatment, RGB and CIR images were acquired with the cameras mounted on a small octocopter and a model fixed-wing airplane flying over the field[57-59]. This study indicated that the high-resolution UAV image data performed consistently well in characterizing image features within the crop yield in quantifying soybean injury from dicamba spray[56].

UAVs are a unique platform to perform crop field sensing with high resolution and least atmospheric interference without restriction of field conditions. Other successful research activities of UAV remote sensing by scientists at Stoneville, Mississippi are described below.

4.2.1 Build DSM to estimate plant height

Low-altitude remote sensing with a small UAV was developed for estimation of crop plant height, which is the most important indicator of crop plant ecological development, and hence estimation of the crop yield. The plant height was estimated by building a digital surface model (DSM) of the crop field by manipulating 3D point cloud data generated by stereo vision using the images acquired by UAV.

The estimation of cotton and soybean plant heights was highly accurate to infer the yield of the crops[60].

4.2.2 Extract depth image features to estimate cotton yield

This study showed that low-altitude remote sensing using a small UAV can offer reliable cotton yield estimation based on estimation of Cotton Unit Coverage (CUC) by Laplacian image processing and identification of plots with poor illumination[60]. The relationship between estimated CUC and measured lint yield using the methods of direct image pixel intensity thresholding (pixel-based) could not be well established. Use of the Laplace operator to obtain the divergence of the gradient (spatial second derivative) of the image pixel intensity significantly improved the linear relationship of CUC with the lint yield after using the Laplacian Gaussian to extract the cotton boll and boll cluster features on and under canopy in the images (object-based).

4.2.3 Identify herbicide-resistant weeds

As mentioned above, glyphosate is the most widely used herbicide, with increased frequency of use and amount in fields planted with GR crops. Repetitive and intensive use of glyphosate has exerted a high selection pressure on weed populations, resulting in the evolution of tens of GR weed species in the world[61], ten of them have appeared in Mississippi. Hyperspectral plant health sensing techniques have been developed to effectively detect GR and GS Palmer amaranth (*Amaranthus palmeri* S. Wats.) and Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] in greenhouse and soybean fields with detection rates of 90% and 80%, respectively[62-64]. However, in-field hyperspectral plant health sensing is still time-consuming and laborious because the current sensors are either operated on a slow-moving tractor for imaging certain areas in the field, or handheld by a technician to measure canopy spectra at certain points in the field. This tedious manner of hyperspectral data acquisition is an obstacle to extend the research results to practical uses. Use of UAVs is an innovative way to fly over a crop field to rapidly determine the distribution of weeds. We are undertaking a research project to mount a portable hyperspectral sensor on a small UAV to overfly a soybean field at a very low altitude to quickly determine the locations and distribution of naturally occurring GR and GS weeds[56].

4.2.4 Crop breeding by observing crop phenotypes

High-throughput automated phenotyping needs interdisciplinary collaboration of expertise from biology, engineering and computer science. In plant breeding, automated phenotyping could be used to screen germplasm collections for desirable traits and to dissect traits shown to be of value to reveal their mechanistic basis, including various physiological, biochemical, and biophysical processes and genes controlling these traits[65,66]. The greatest benefit of automated phenotyping would be achieved if this technology allows breeders to select superior plants that would otherwise be rejected by using conventional phenotyping methods[67]. UAV-based remote sensing is one of the important tools for high quality high-throughput automated phenotyping. A scientist in Stoneville, Mississippi, collaborates with a rice breeder in the Delta Research Center of Mississippi State University to use UAVs to fly over a 5 hectares rice field each year in the past three years with about 40 varieties planted repeatedly in 120 plots. The purpose of the study is to compare UAV-based crop phenotype observations with conventional human observations to automate the breading process and improve the results.

5 In the next decade

The next ten years will be a critical period for technological breakthroughs to provide better services for the world. The principal relevant technologies are from data science and engineering, Internet of Things, artificial intelligence, and automatic control for building cyber-physical infrastructure with revolutionized high-performance electronics and supercomputing. Development and application of the technologies will promote practical technical renovation and provide better management and service. With these technologies, modern agriculture will develop sustainably from precision agriculture to smart agriculture, with intelligent management schemes and techniques. Agricultural aviation, as an important part of modern agriculture, will be improved with the advanced technologies to better serve precision agriculture.

Soon, agricultural airplanes will be developed with high capacity of chemical loading up to 4,000 liters from the current capacity from 400 to 3,000 liters, for example, current Air Tractor 402B with 1, 500 liters and 802A with 3, 000 liters. UAV-based plant protection will be greatly developed and widely applied, especially in China. In the U. S., UAV spraying systems needs more research and development to focus on advanced technologies to make smart, data-driven decisions to optimize inputs for the unique conditions and variation in every field although they may not be as much used commercially as powerful manned aerial and ground-based systems which are widely and effectively used in the country.

With global technical advancement, agricultural aviation is moving to better serve precision agriculture practices in the Mississippi Delta with the joint efforts of aerial applicators, farm producers, consultants, state and federal scientists and engineers. In research, the efforts will be mainly focused on the following aspects:

a) All the aircraft systems for aerial spray applications are currently single functional. For farmers, aerial spray systems allow spray application close to the crop canopy so that the spray can be targeted with high precision and hence the drift and waste can be reduced. At the same time, if the farmers can have their field mapped, they not only save on the cost of hiring a pilot with an airplane, but they also know how much fertilizer or chemical to apply to specific portions of the field rather than applying it to the entire crop, thereby reducing input costs[68]. Yang et al.[69] developed airborne and high-resolution satellite imagery for site-specific treatment of cotton root rot through variable-rate technology with an average of 49% reduction of fungicide use. Scientists in Stoneville, Mississippi, have prototyped an Air Tractor 402B aircraft system with dual function of spray applications and field imaging operated either simultaneously or alternatively to offer the possibility of near real-time spray control response through rapid image processing[9]. Because Air Tractor typically sprays to cover large area while UAVs are relatively small and cannot help field scout completely in such area, the dual function two-in-one aircraft system is much more cost-effective compared with using any other one single-engine jet such as Cessna (Cessna Aviation Company, Wichita, Kansas, USA).

UAVs have been used for various agricultural applications. The primary driver was the payload, camera system for surveillance, or a boom to apply pesticides. Nevertheless, from the agriculture perspective, several issues still need to be addressed. As indicated by Cowley et al.[70] for archeological studies, "how does the survey methodology or source data improve our understanding of the specific research question, not how a technological development may affect a change in working practice?"

Furthermore, most research studies have been conducted using one type of payload on the UAV, such as a camera or spray boom. There is a growing interest in the research community on using a UAV that is retrofitted with a boom for spraying as well as having the ability to acquire imagery; the two-in-one UAV for dual use is a cost-effective option. Note in this scenario, we are not advocating using both items simultaneously but instead having a UAV that allows the user to interchange between using a camera system or using the sprayer for spray applications. Furthermore, gaps exist in the benefits of using high spatial resolution thermal imagery acquired from a UAV in weed detection and in measuring weed responses to herbicides. In row crops, more work is needed on the performance of UAV spray application systems, specifically focusing on spray deposition, vehicle suitability, and work rate data.

b) In the past few decades, agricultural aviation has been developed for precision agriculture in the center of the Mississippi Delta. For research and development, massive remote sensing images and meteorological data were collected, and platforms built to continually collect the data in the future. In order to provide guidance for local farmers and information for global researchers, the images and data need to be further processed and analyzed and then disseminated on internet-based web mobile applications[42,71]. To make the disseminatable image and data products, several works need to be conducted.

In agricultural remote sensing applications, space imagery obtained from satellite platforms is widely used in medium to large area studies. More recently, UAV based remote sensing has become increasingly popular for precision agriculture due to its low cost and flexibility in operation. The knowledge gap in the current stage of remote sensing research in precision agriculture is that it is difficult to establish a direct link between images acquired from different platforms, especially when dealing with data from spacecraft and UAVs. In agricultural remote sensing, it is critical to correlate information gathered from a small area, such as field level data collected by a low altitude flying UAV, with data collected over a larger region, such as data from agricultural aircraft and high-resolution satellites. With a properly calibrated UAV sensor, this task becomes possible as the data can be used to facilitate information extraction from large-area satellite imagery.

Various algorithms are needed to analyze the data and images. For guide of aerial applicators for spray timing during a day to avoid off-target drift caused by temperature inversion, we developed an algorithm using weather data by validating and localizing the "rule" summarized in Mississippi Delta and other regions in the US[40,42]. For remote sensing image processing and analysis, various pattern recognition algorithms are available for image classification and geospatial modeling with the features extracted from the images.

Remote sensing is one of the sources as big data with volume and complexity in the region, nation and world. Management and application of agricultural remote sensing data are critical to the success of precision agriculture. A new data-cube management structure is needed to coordinate data acquisition, processing, storage, analysis and visualization by integrating the data from various sensors at different scales[71,72].

c) The open-source concept of collaboration and sharing of ideas is increasingly being adopted by research and citizen scientist communities[73,74]. Advantages of open-source hardware include low cost, ease of use, and extensive array of electronic technologies offered with worldwide technical and programming support. A growing number of open-source cloud-based internet service providers, such as Thingspeak[75], offer internet-based platforms for remote uploading and sharing of user-generated data. We are using open-source hardware and software to develop practical applications in Mississippi Delta[43].

Overall, innovative methods, optimized algorithms, massive data, and super-computing power will be ready for smart/intelligent agriculture in the cyber-physical architecture, which will be gradually developed and applied in the Mississippi Delta and other regions in the US. Agricultural automation will dominate agricultural operations with advanced materials, mechanical and electronics science and technology. Control techniques will provide critical help for practical artificial intelligence. Ubiquitous collaborative robots will be in farmers' hands. Artificial intelligence with machine deep learning will be developed to advance plant phenotyping and perception of agricultural robotic systems. Real-time agricultural data processing, analysis, control and adaptation will take important roles for decision support in agricultural management.

6 Recommendations for China

As mentioned above, the Mississippi Delta is well-suited for mechanized agriculture for large-scale crop production and agronomically very productive under proper management. It is generally thought that the U. S. had completed agricultural mechanization and so did the Mississippi Delta. With high-degree agricultural mechanization, the U. S. could rapidly advance its technologies and move forward with new management ideas to significantly improve agricultural productivity. For example, in the 1980s, the U.S. rapidly created successes in technical applications and extensions of precision agriculture. In the 2000s, the U.S. strongly applied and extended new cropping systems with biotechnological innovations[76] at a large scale. Now, the U.S. is launching another round of agricultural innovation with a new-generation precision agriculture on the basis of advanced agricultural mechanization.

Agricultural mechanization is the foundation of agricultural modernization. Overall agricultural mechanization in China is still very limited so that it is difficult to rapidly embed or execute developed agricultural information and precision technologies. Therefore, it is the primary task to develop, apply and extend agricultural mechanization technologies that are suitable for China's agricultural conditions in order to realize agricultural modernization in China. Agricultural automation is the ultimate goal of agricultural modernization. Now, agriculture in China is seriously short of laborers. So, the ability to ensure agricultural productivity is a pressing problem to be solved for Chinese agriculture. Agricultural automation takes agricultural mechanization as the basis and on this basis it can be integrated with artificial intelligence, Internetworks, and data science and engineering to form a complete system to serve agricultural modernization.

Sixty years ago, Chairman Mao envisioned that "The fundamental way out for agriculture lies in mechanization" (From a "Party Communication" written by Mao Zedong in 1959). It is noted that Premier Li Keqiang noted the need to "advance the mechanization of entire agricultural production processes" in the 2019 Report on the Work of the Government and then he emphasized the importance of agricultural mechanization advancement in several other occasions. With the national policies made by all levels of leadership and technical efforts of scientists and engineers, it can be believed that it is in the near future that China can have a complete agricultural mechanization for eventual agricultural modernization.

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美国密西西比三角洲农业航空和精准农业技术研发现状、展望与启示

黄岩波

（美国农业部/农业研究服务局作物生产系统研究中心，斯通维尔，密西西比州38776，美国）

摘　要：作物生产管理已经进入智慧农业阶段。智慧农业是由最先进的农业信息技术、智能装备以及大量的数据资源所驱动的先进农业科技理念。智慧农业继承了精准农业概念，把农业生产管理由机械化和信息化提高到高度自动化和智能化的农业生产管理。精准农业从上世纪八十年代的粗略监测发展到本世纪10年代的详细监测和控制。在精准农业的发展过程中，农业航空在作物保护和肥料施用方面起到了关键的作用。而在作物保护和肥料精准施用方面，基于全球导航产生的带有空间信息遥感数据配方图是至关重要的。随着现代化农业的发展，农业航空会因更有效的土壤和植物健康监测和更加快速的机电系统响应，在推进精准农业实际应用上显得越发重要。本文具体从美国最重要的农业地区之一密西西比三角洲出发，总体介绍了农业航空在精准农业向智慧农业迈进过程中的状况。重点介绍了美国农业部在密西西比三角洲地区在航空应用技术和低空遥感方面的研发工作；为发展新一代精准农业和智慧农业，进一步研发农业航空技术的问题、挑战和机会进行了讨论；最后提出了中国发展智慧农业建议。

关键词：航空施药技术；农业航空；大数据；精准农业；遥感；智慧农业