Analysis of Global Research Trends in UAV Applications for Agriculture and Forestry: Postprint

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Abstract

Unmanned aerial vehicles (UAVs) possess unique advantages such as high operational efficiency and excellent terrain adaptability. In recent years, their application scope in agriculture and forestry has continuously expanded, with the number of related research outputs exhibiting a rapid upward trend. To comprehend the global research landscape of UAV applications in agriculture and forestry, this study collected literature data on global UAV research in agriculture and forestry from the Web of Science Core Collection database spanning 2011–2020, and conducted scientometric analysis of the literature using statistical software such as VOSviewer. The analysis results demonstrate that since 2017, the number of publications on UAV applications in agriculture and forestry has increased rapidly, with research being conducted by 94 countries/regions and 1,778 institutions worldwide. The top three countries in terms of publication output are the United States, China, and Australia, indicating that these three countries possess strong scientific research capabilities and substantial academic influence in UAV applications for agriculture and forestry. A total of 398 journals have published articles on UAV applications in agriculture and forestry, accounting for approximately 1.90% of all indexed journals, which suggests that an increasing number of journals are beginning to focus on UAV research in agriculture and forestry. The journal with the most publications is Remote Sensing, published by MDPI. The most highly cited articles primarily focus on the current research status of sensing, navigation, positioning, and general data processing in UAV systems for photogrammetry and remote sensing. Furthermore, analysis of research hotspots in UAV applications for agriculture and forestry reveals that UAV pesticide application, UAV remote sensing for pest and disease monitoring, and plant phenotyping acquisition constitute the main research hotspots. This study can provide valuable references for innovative UAV research in agriculture and forestry and for collaboration among research teams.

Full Text

Investigation on Advances of Unmanned Aerial Vehicle Application Research in Agriculture and Forestry

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Abstract: Unmanned Aerial Vehicles (UAVs) offer unique advantages including high operational efficiency and excellent terrain adaptability, leading to expanding applications in agriculture and forestry with rapidly increasing research output. To understand global research trends in UAV applications for agriculture and forestry, this study collected relevant literature from the Web of Science Core Collection database and conducted bibliometric analysis using VOSviewer. Results show that since 2017, publication numbers have grown rapidly, with 94 countries/regions and 1,778 institutions conducting research. The top three countries by publication volume are the United States, China, and Australia, demonstrating strong research capabilities and academic influence. A total of 398 journals have published articles on this topic, representing approximately 1.90% of all journals in the database, indicating growing journal interest. *Remote Sensing* published the most articles, while the most-cited paper focused on UAV systems for photogrammetry and remote sensing, covering sensing, navigation, positioning, and data processing. Research hotspot analysis reveals that UAV pesticide application, pest/disease remote sensing, and plant phenotyping are the main research focuses. This study provides references for innovative UAV research and collaboration among research teams in agriculture and forestry.

Keywords: UAV; Web of Science; VOSviewer; bibliometrics; research trends; remote sensing; plant phenotype

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1 Introduction

Unmanned Aerial Vehicles (UAVs) were initially developed for military applications. However, with advances in flight control and navigation technologies, UAVs have gradually transitioned to broad civilian use, triggering a surge in academic research [1]. Agricultural and forestry UAVs primarily consist of flight platforms, operation management and monitoring systems, and onboard configurations. The onboard equipment mainly includes aerial spraying devices and remote sensing image acquisition systems, forming a complex operational system involving aerospace engineering, information technology, fluid mechanics, image processing, and plant protection [2]. UAVs overcome limitations of traditional ground machinery, offering unique advantages such as high operational efficiency, strong adaptability to complex terrain, operator safety, and low labor costs [3]. Applications in agriculture and forestry mainly include plant protection operations [4,5], information collection [6], and monitoring and early warning [7]. In recent years, UAV applications in agriculture and forestry have shown explosive growth [3], becoming an emerging industry in modern agriculture. Japan' s YAMAHA Company launched the world' s first pesticide-spraying UAV "R50" in 1990, after which plant protection UAVs developed rapidly in Japanese agriculture. By May 2018, Japan had 2,788 agricultural UAVs in operation and 10,545 certified operators [8]. China began researching agricultural UAV applications in 2008, with rapid development over the past decade. By 2019, over 200 manufacturers produced UAVs, with major companies including DJI, XAG, and Hanhe [9]. In October 2019, China had more than 55,000 plant protection UAVs in service, covering 30 million hectares of operation area—ranking first globally in both equipment quantity and operation area [10]. UAVs are widely used for pest and disease control in rice [11-14], wheat [15-19], sugarcane [20,21], corn [22-25], cotton [26,27], citrus [28-30], pine trees [31,32], and other crops.

Bibliometrics employs mathematical and statistical methods to quantitatively analyze literature characteristics, enabling evaluation and prediction of research status and development trends in science and technology. It reflects the academic influence of countries and institutions while revealing current research status and frontiers. Common bibliometric software includes VOSviewer, CiteSpace, and CitNetExplorer [33]. VOSviewer, developed by Dr. Van Eck and Dr. Waltman from Leiden University in the Netherlands [34], is a bibliometric analysis and scientific knowledge visualization tool capable of collaboration analysis, keyword co-occurrence analysis, co-citation analysis, bibliographic coupling analysis, and visual representation of results.

2 Data Sources and Analysis Methods

This study selected the Web of Science (WoS) Core Collection database, developed by the Institute for Scientific Information (ISI), as the data source. WoS [35] is a large-scale, comprehensive, multidisciplinary scientific citation index database. The Core Collection comprises six citation indexes—Science Citation Index-Expanded (SCI-E), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (AHCI), Conference Proceedings Citation Index (CPCI), Book Citation Index (BKCI), and Emerging Sources Citation Index (ESCI)—plus two chemical indexes, covering over 21,000 authoritative, high-impact academic journals. WoS is internationally recognized as a primary tool for scientific statistics and evaluation, with its inclusion status serving as an important basis for assessing research impact [36].

The search strategy was: TI=(UAV OR unmanned OR helicopter OR Drone OR aerial) AND TS=("aerial spray" OR "plant protection" OR "crop protection" OR "aerial application" OR "aerial spraying" OR "plant spraying" OR "crop spraying" OR pesticide OR deposition OR drift OR deposit OR "remote sensing" OR phenotype OR phenotyping) AND ALL=(plant OR tree OR field OR vegetable OR food OR forestry OR farmland OR agriculture OR fruit OR agricultural OR pesticide OR insect OR pest OR disease OR disease and pest). The search period was 2011-2020, conducted on July 7, 2021, retrieving 1,508 documents, including 1,464 research articles and 44 reviews.

Based on the WoS Core Collection database, this study employed bibliometric analysis using VOSviewer, WoS analytical tools, and Microsoft Excel to analyze global research trends in UAV applications for agriculture and forestry. The analysis covered development history, country/region influence, technology field distribution, institutional influence, publishing journals, research hotspots, characteristics, and deficiencies. In VOSviewer clustering diagrams, node size represents publication volume, colors represent different clusters, and temporal sequence is shown through red, green, blue, yellow, etc., with red indicating the earliest research institutions/countries.

3 Results and Analysis

3.1 Development Trajectory Over the Past Decade

Annual publication distribution intuitively demonstrates the emergence, development, and maturation of a research field, providing important insights into its evolution [37]. From 2011-2020, 1,508 papers related to UAV applications in agriculture and forestry were published, showing an overall growth trend (Figure 1 [Figure 1: see original paper]). In 2011-2012, annual publications were fewer than 50, primarily focusing on agricultural/forestry remote sensing, ecological environment monitoring, and engineering, with remote sensing as the main application. From 2013-2016, annual publications ranged from 50-90, showing slow growth. In 2017, publications reached 193, a 114.44% increase from 90 in 2016—more than doubling—driven primarily by rapid growth in articles related to aerial spraying technology. In 2018, publications reached 277, and by 2019-2020, annual publications exceeded 400.

Analysis of the rapid development over the past decade reveals several key factors: (1) Smart agriculture and forestry are current research hotspots, with UAV applications being a major focus attracting numerous scholars who have published extensively and shared valuable practical experience, accelerating development. (2) Rapid advancement in UAV hardware and software technologies, particularly in chips, batteries, inertial sensors, and open-source flight control systems, has enabled UAVs to become smaller and more energy-efficient, promoting agricultural/forestry applications [37,38]. (3) UAVs offer outstanding advantages in agriculture and forestry with high efficiency, low cost, and strong terrain adaptability. Against the backdrop of agricultural labor shortages and the trend toward large-scale operations, UAVs have become a market focus with huge potential [9]. (4) National and local policies have supported UAV applications, with central government documents emphasizing agricultural modernization, the Ministry of Agriculture' s "Zero Growth Action Plan for Chemical Fertilizer Use by 2020" and "Zero Growth Action Plan for Pesticide Use by 2020," and joint subsidies for UAV purchases, collectively promoting widespread adoption. (5) Capital markets have favored UAVs' broad application prospects, strongly driving development. Large-scale UAV R&D and production enterprises have obtained sufficient funding, accelerating R&D and production [39].

3.2 Country/Region Influence Analysis

3.2.1 Overall Analysis Bibliometric analysis of the WoS database shows that numerous research institutions and researchers worldwide have conducted key technology research on UAV applications in agriculture and forestry, with research output increasing rapidly in recent years. From 2011–2020, 94 countries/regions published articles on UAVs, with 23 publishing more than 20 papers (Figure 2 [Figure 2: see original paper]). The top five countries by publication volume were the United States (430 papers, 28.51%), China (405 papers, 26.86%), Australia (89 papers, 5.90%), Germany (89 papers, 5.90%), and Spain (83 papers, 5.50%).

The United States, as an early UAV developer, leads globally in technology development, government regulation, and civil applications. Policies such as the FAA Modernization and Reform Act of 2012 and the Integration of Civil Unmanned Aircraft Systems in the National Airspace System Roadmap opened airspace to civil UAVs and standardized their use [40]. UAV research funding primarily comes from the National Science Foundation, USDA, and NASA, with major projects including NASA' s UAS in the NAS Project [38]. Supported by these policies and projects, U.S. publications reached 22 in 2013 and 40 in 2017–2020, maintaining a leading position globally.

UAVs have received strong support from the Chinese government, social capital, and research institutions. Numerous research teams have invested in key UAV technologies and actively applied them in agricultural/forestry production, publishing many SCI-indexed articles with significant global academic influence. Since 2013, China's Ministry of Agriculture and Rural Affairs has promoted UAV application technologies nationwide [41]. In 2014, China established the "Agricultural Aviation Industry Technology Innovation Strategic Alliance," chaired by Academician Luo Xiwen of the Chinese Academy of Engineering. With support from national policies including the "Central No. 1 Document," "Zero Growth Action Plan for Chemical Fertilizer and Pesticide Use," and "UAV Purchase Subsidies," as well as national key R&D projects such as "Key Technology Research and Equipment Development for Agricultural Aviation Operations" and National Natural Science Foundation projects on UAV spraying droplet dynamics and deposition control, China began publishing articles on UAV aerial spraying in 2013. By 2016, aerial spraying articles accounted for over 30% of total

UAV agriculture/forestry publications. From 2017 onward, annual publications exceeded 40, reaching over 120 in 2019-2020, showing rapid growth.

3.2.2 Citation Analysis Citation counts more objectively reflect article quality and impact. The top five countries by total citations were the United States (9,940), China (6,216), Spain (4,744), Australia (3,155), and Germany (2,970), with 30 countries/regions receiving over 300 citations (Figure 3 [Figure 3: see original paper]). Both publication volume and citation counts demonstrate that China and the United States have significant advantages in agricultural/forestry UAV research.

3.2.3 International Collaboration Analysis Different countries/regions have different research strengths, and collaborative research enables complementary advantages and broader applications. VOSviewer analysis identified 92 countries/regions with research collaborations in agricultural/forestry UAV applications from 2011-2020, forming 16 clusters (Figure 4 [Figure 4: see original paper]). China-U.S. collaboration leads in publication volume, indicating close research ties focusing on vegetation remote sensing and aerial spraying. China also collaborates closely with Germany and Australia on aerial spraying, while the U.S. collaborates with the UK and Spain on ecological environment science and remote sensing. Collaboration shows obvious regional commonality, with Eastern European, Southeast Asian, and African countries maintaining close research ties.

3.3 Technology Field Distribution

UAV applications in agriculture and forestry involve diverse technologies. Comprehensive analysis of WoS data, keywords, and research content shows publications distributed across 70 technical research fields. The top five fields by publication volume were remote sensing technology (656 papers, 43.50%), ecological environment science (547 papers, 36.27%), image processing technology (484 papers, 32.10%), geological science (399 papers, 26.46%), and engineering application technology (268 papers, 17.77%). Twenty technical fields had over 20 publications (Table 1).

The distribution shows that UAV remote sensing research involves not only remote sensing technology itself but also ecological environment science and geological science characteristics of the sensing objects. Literature on UAV spraying control technology, flight control technology, sensor technology, and fluid computational modeling appears primarily in engineering application technology fields, reflecting the engineering development focus of UAV spraying research.

3.4 Highly Cited Literature and Characteristics

The most-cited paper was the 2014 review by Colomina and Molina [42] published in *ISPRS Journal of Photogrammetry and Remote Sensing*, with 1,157 citations. This article clarified that UAV systems consist of aerial vehicles, ground control stations, and communication data links, analyzed why UAV systems have become a hotspot in photogrammetry and remote sensing, reviewed their development history, and examined current status in sensing, navigation, positioning, and general data processing, highlighting nano-micro UAV systems. The authors are from the Centre Tecnologic de Telecomunicacions de Catalunya, a strong research team in communications, electrical engineering, photogrammetry, and remote sensing.

The top 10 most-cited papers on UAV applications in agriculture and forestry (Table 2) primarily focus on pest/disease remote sensing and ecological environment monitoring, including 2 review articles and 8 research articles, mostly published in *Remote Sensing*. These highly cited papers share three characteristics: (1) they are primarily review or methodological articles with instrumental or background value for citation; (2) published in high-impact journals (4 in Q1, 6 in Q2) with large publication and citation volumes; (3) published before the explosive growth period, making them more likely to receive widespread citations.

3.5 Institutional Influence Analysis

From 2011-2020, 1,778 institutions published research on UAV applications in agriculture and forestry, with 199 publishing 5+ papers. The top 10 institutions (Table 3) include 6 Chinese, 3 American, and 1 Spanish institution. The USDA led with 92 papers (6.10%), focusing on comprehensive UAV applications including pest/disease remote sensing, assisted breeding, orchard spraying, and mosquito control. The Chinese Academy of Sciences ranked second with 61 papers (4.05%), primarily on flight control technology, sensor technology, and remote sensing pods/image processing. Other major Chinese institutions include South China Agricultural University, China Agricultural University, Wuhan University, Beijing Academy of Agriculture and Forestry Sciences, and Chinese Academy of Agricultural Sciences. Major U.S. institutions include Texas A&M University and Florida State University, while Spain' s top institution is the Spanish National Research Council (CSIC).

3.6 Journal Analysis

From 2011-2020, 398 journals published UAV agriculture/forestry application articles. Fifty-two journals published 5+ papers, totaling 1,021 papers (67.71% of all literature). The citation network formed 4 clusters (Figure 5 [Figure 5: see original paper]): (1) *International Journal of Remote Sensing* cluster focusing on agricultural/forestry remote sensing; (2) *Computers and Electronics in Agriculture* cluster focusing on UAV spraying, pest/disease remote sensing, and comprehensive basic research on flight parameters, environmental parameters, and crop canopy interactions; (3) *Sensors* cluster focusing on flight control sensors and specialized payload sensors; (4) *Remote Sensing* cluster focusing on remote sensing research.

The top 10 journals (Table 4) are distributed across Switzerland, the U.S., Netherlands, UK, and China. *Remote Sensing* (Switzerland, MDPI) published the most papers (277) with an impact factor of 4.848 (Q2). The highest impact factor was *Remote Sensing of Environment* (U.S., 10.164, Q1) with 25 papers.

4 Research Hotspot Analysis

4.1 Technology Field Hotspot Analysis

Keyword accuracy and frequency are crucial for identifying research hotspots. After cleaning keywords for case, plurality, abbreviations, and synonyms [52], the 1,508 papers contained 4,160 keywords, with 133 appearing 5+ times. The top 10 keywords are shown in Table 5 .

The VOSviewer network of keywords with 5+ co-occurrences formed 8 clusters (Figure 6 [Figure 6: see original paper]). Results show UAV applications focus on precision agriculture (#3 cluster) and forestry (#4 cluster). Technical hotspots include plant phenotyping (#1 cluster), pest/disease remote sensing (#2 cluster), and UAV spraying (#5 cluster). UAV hardware/software systems research focuses on control systems (#6 cluster). The red zone (#1 cluster) covers plant phenotyping using hyperspectral remote sensing to estimate biomass and yield based on leaf area index and vegetation indices for rice, soybean, and grassland. The green zone (#2 cluster) covers remote sensing applications using thermal and hyperspectral imaging to obtain normalized difference vegetation indices, analyze canopy temperature and chlorophyll content, and develop UAV remote sensing systems for wheat and corn. The purple zone (#5 cluster) focuses on precision spraying research on droplet deposition and drift control. The light blue zone (#6 cluster) addresses control systems for path planning, obstacle avoidance, and autonomous cruising to improve operational efficiency and precision.

4.2 Application Characteristics Analysis

4.2.1 Agricultural Application Keyword Clustering UAV applications in agriculture cluster into three areas: agricultural remote sensing, precision agriculture, and aerial spraying (Figure 7 [Figure 7: see original paper]), with main keywords including UAV, remote sensing, deposition, system, and precision agriculture. Agricultural remote sensing leverages UAVs' high operational frequency and adaptability for multi-temporal crop canopy, growth status, and nitrogen content monitoring, obtaining spectral reflectance differences among crop types and structures to derive water, fertilizer, and pest/disease information for breeding guidance. Precision agriculture applications primarily use machine learning to process UAV images for leaf area index, normalized difference vegetation index, and biomass/yield estimation to support precision spraying and fertilization. The primary agricultural application is precision spraying, researching droplet penetration, deposition on crop leaves, and drift under UAV downwash and environmental wind fields to improve efficiency while reducing environmental pollution and phytotoxicity.

4.2.2 Forestry Application Keyword Clustering UAV applications in forestry cluster into two areas: forest resource inventory and forest health remote sensing (Figure 8 [Figure 8: see original paper]), with main keywords including UAV, remote sensing, forest inventory, classification, and lidar. Forestry applications focus on forest resource inventory (canopy structure, height, timber volume) and forest health monitoring. Given complex terrain and tall trees making manual surveys time-consuming and labor-intensive, UAVs enable forest pest/disease and fire monitoring, including pine wilt disease and citrus greening. Agricultural applications are more extensive than forestry applications due to more complex terrain and climate conditions in forests, requiring continued exploration of suitable UAV technologies and equipment.

4.3.1 UAV Application Technology Aspects

Keyword co-occurrence shows UAVs are mainly applied in vegetation remote sensing and aerial spraying, overcoming limitations of traditional ground machinery and greatly improving monitoring and spraying efficiency. However, challenges remain: remote sensing information acquisition suffers from surface interference and lacks multi-source information fusion, requiring improved accuracy in pest/disease severity and vegetation growth assessment. Novel multi-source fusion methods for crop pest/disease inversion and long-term prediction based on remote sensing information are needed to support early decision-making in farm management.

In UAV spraying, deficiencies include lack of precision spraying control devices and quality evaluation systems, causing pesticide waste and environmental pollution. Future research should optimize UAV-specific atomization equipment, explore innovative droplet formation mechanisms, develop narrow-droplet-size-spectrum precision spraying control devices, and advance real-time monitoring and evaluation technologies using novel sensing methods and machine learning to comprehensively analyze environment, pesticide [53-55], meteorology [56], aircraft type, and wind field [57] information for digital evaluation of droplet deposition characteristics and operational quality.

4.3.2 UAV Application Environment Aspects

Environmental challenges include restricted operational airspace and lack of technical standards. Airspace management limitations constrain UAV agricultural/forestry operations, hindering development. Compared to rapidly advancing UAV technology, the lack of operational specifications and control effect evaluation standards prevents objective assessment of aerial spraying effects. Comprehensive standards for UAV agriculture/forestry applications need urgent development.

5 Conclusions and Outlook

This study conducted bibliometric analysis of 1,508 papers from the WoS Core Collection (2011–2020) using VOSviewer, WoS tools, and Microsoft Excel, examining development history, country/region influence, technology field distribution, institutional influence, publishing journals, and research hotspots to characterize global research trends in UAV agriculture/forestry applications.

Key findings include: (1) Since 2017, publications have grown rapidly, with 94 countries/regions and 1,778 institutions conducting research. The top three countries are the U.S. (430 papers), China (405), and Australia (89). The USDA published the most (92 papers), followed by the Chinese Academy of Sciences (61). 398 journals published relevant articles, with *Remote Sensing* publishing the most (277). The most-cited paper (1,157 citations) was the 2014 review "Unmanned aerial systems for photogrammetry and remote sensing: A review." (2) Over the past decade, UAV applications have received strong government support, institutional attention, and capital investment, with rapid hardware/software development making them a smart agriculture hotspot. Collaborative publishing shows regional commonality, with publication volume closely related to national policies, research projects, and institutional investment. The U.S. and China lead globally in academic influence. Remote sensing is the most widely used technology field, involving remote sensing, ecological environment science, image processing, and geological science. Engineering is an important field covering control technology, sensor technology, and fluid computational modeling for aerial spraying. Citation counts correlate strongly with article type and journal impact, with review articles and high-impact journals receiving more citations. Top journals are distributed across Switzerland, the U.S., Netherlands, UK, and China, focusing on remote sensing and aerial spraying hotspots with high annual volumes and citations.

(3) Research hotspots include UAV spraying, pest/disease remote sensing, and plant phenotyping. Agricultural applications comprise remote sensing, precision agriculture, and aerial spraying, with spraying being the primary application focusing on droplet penetration, deposition, and drift. Forestry applications include forest resource inventory and health remote sensing, with health monitoring being the priority focus. Agricultural applications are more extensive than forestry applications, though forestry applications are maturing with technological advances.

(4) UAVs overcome limitations of traditional ground machinery regarding efficiency and complex terrain adaptability, offering broad prospects in China. However, challenges remain in short endurance, spray drift, and remote sensing accuracy. Future research should enhance autonomous operation capabilities for 24-hour autonomous scheduling, mission planning, implementation, and refueling to improve efficiency and accelerate smart agriculture/forestry development.

This study used the WoS database, which primarily indexes English-language journals and cannot retrieve non-English articles. To comprehensively understand research status in non-English countries like China, additional databases should be incorporated for more objective and comprehensive conclusions.

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