VII. Agriculture

1 Engineering research fronts

1.1 Trends in top 11 engineering research fronts

The top 11 engineering research fronts in the agriculture field can be classified into two groups: 1) in-depth research on established research fronts including "origin, evolution, and genetic variation of animal viruses," "precision animal and plant breeding by design," "mining of crop functional genome structure," "efficient use of agricultural resources and circular economy," "soil biodiversity and ecosystem functions," "interaction of important animal viruses with hosts," "interaction mechanisms between pathogen and crop," "microbial driving mechanism of carbon cycling in forest soil," and "molecular basis and regulatory mechanism of sex and development in aquaculture animals," and 2) emerging research fronts including "intelligent sensing of agricultural life information and environmental information" and "object recognition and localization of agricultural robots." The number of core papers for these research fronts ranges from 8 to 109 with an average of 50, and citations per paper range from 7 to 87 with an average of 43. Most core papers were published in 2015 and 2016 whereas the core papers of "efficient use of agricultural resources and circular economy" and "soil biodiversity and ecosystem functions" were mostly published in recent three years and showed an increasing trend (Tables 1.1.1 and 1.1.2).

(1) Origin, evolution, and genetic variation of animal viruses

The tracing process of animal viruses is the process of finding the most primitive natural survival hosts, intermediate reservoir hosts/intermediate transition hosts, and terminal infection hosts. Through the study of the origin of animal viruses, the source host, vector host, cross-species transition reservoir host, and terminal host of the virus can be understood. It is of great biological significance for cutting off the source of infection, avoiding long-term circulation and spread of viruses in different hosts, and preventing and controlling infectious diseases from the source. The core scientific problem of virus traceability is to find pathogens that fulfill the Koch's postulates, analyze the genomic characteristics of the virus and the biological phenotype of virus-infected source host, vector host, and terminal host. Evolution and genetic variance are a kind of natural selection for viruses to antagonize, escape, and avoid the complex immune system of the host to maintain the replication life cycle and adapt to a new host, and is an

Table 1.1.1 Top 11 engineering research fronts in agriculture

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Origin, evolution, and genetic variation of animal viruses	58	4 480	77.24	2015.4
2	Intelligent sensing of agricultural life information and environmental information	89	3 370	37.87	2015.9
3	Object recognition and localization by agricultural robots	77	2 879	37.39	2016.7
4	Precision animal and plant breeding by design	109	8 871	81.39	2015.4
5	Mining of crop functional genome structure	39	655	16.79	2016.5
6	Efficient use of agricultural resources and circular economy	8	57	7.13	2018.1
7	Soil biodiversity and ecosystem functions	55	2 189	39.80	2017.4
8	Interaction of important animal viruses with hosts	61	740	12.13	2016.5
9	Interaction mechanisms between pathogen and crop	31	1 934	62.39	2016.8
10	Microbial driving mechanism of carbon cycling in forest soil	12	1 042	86.83	2015.3
11	Molecular basis and regulatory mechanism of sex and development in aquaculture animals	10	180	18.00	2016.3

Table 1.1.2 Annual number of core papers published for the top 11 engineering research fronts in agriculture

No.	Engineering research front	2014	2015	2016	2017	2018	2019
1	Origin, evolution, and genetic variation of animal viruses	15	20	10	9	4	0
2	Intelligent sensing of agricultural life information and environmental information	16	23	21	15	8	6
3	Object recognition and localization by agricultural robots	0	10	23	26	14	4
4	Precision animal and plant breeding by design	23	37	31	16	2	0
5	Mining of crop functional genome structure	10	2	7	5	9	6
6	Efficient use of agricultural resources and circular economy	0	0	0	1	5	2
7	Soil biodiversity and ecosystem functions	3	4	9	9	13	15
8	Interaction of important animal viruses with hosts	11	8	15	6	8	13
9	Interaction mechanisms between pathogen and crop	3	5	6	6	3	7
10	Microbial driving mechanism of carbon cycling in forest soil	2	6	3	1	0	0
11	Molecular basis and regulatory mechanism of sex and development in aquaculture animals	1	4	1	1	1	2

extremely complex life phenomenon. What are the driving forces of virus evolution and genetic variance? What are the ways? What is the transmission mechanism and method of the virus breaking through the species barrier? How does the host influence the genetic variation and evolution of the virus? How does the living environment of viruses and hosts affect the evolution of the virus? These questions remain unanswered. Analyzing the evolution and genetic variation mechanisms of viruses will help in understanding how viruses respond to the complex immune system of their host to maintain life and overcome interspecies barriers to achieve cross-species transmission, also this will help in understanding the regularity of intermittent recurrence virus or infectious disease after vaccine immunized animals, and thus has great epidemiological significance.

(2) Intelligent sensing of agricultural life information and environmental information

Intelligent sensing of agricultural life and environmental parameters refers to the *in-situ*, fast, and real-time measurement of plant and animal life status, the environmental conditions in plant growth, and the environmental factors in animal houses. There are two main research directions: The first direction is research on novel sensing mechanisms of plant and animal life parameters. A major trend in recent years is the novel sensing methods based on aptamer sensor, immunosensor, machine vision, and hyperspectral imaging. Using these methods, the behaviors, genders, hormones, and metabolites of plants or animals can be measured, as well as the various biological and chemical parameters of plants, such as crop biochemical components, crop diseases, and pests. High-throughput plant phenotyping has also been studied based on these sensing techniques. The second direction is research on sensing mechanisms of plant and animal environmental parameters. With the emergence of new physical sensing methods and the fast development of the performance of sensing devices, such as the better monochromaticity, power and cover bands of lasers, an emerging approach in recent years is the development of new agricultural environmental sensors. These sensors include *in-situ* sensors for soil factors, e.g., soil nitrogen, heavy metals, and microorganism. As for the sensors for animal environment, a major development is the E-nose for harmful gases measurement in livestock, which based on various principles, e.g., metallic oxide sensors, infrared absorption sensors, and mass spectrometry.

It is predicted that the techniques of intelligent sensing of agricultural life and environmental parameters will quickly develop with advances in basic science. For the sensing mechanisms, the measuring ranges, precision, and sensitivity will improve with the promoting of photoelectricity, chemistry, and nano-sciences. For the sensing parameters, the key focus in next few years will be the microcosmic and other important parameters that cannot be measured *in-situ* by current methods.

(3) Object recognition and localization by agricultural robots

Object recognition and localization by agricultural robots solve the problem of distinguishing the object from environment and calculating the distance of the object. It includes information collection and processing methods. The object recognition by agricultural robots focuses on distinguishing the object from environment, particularly developing optimization methods to improving the accuracy of object recognition for agricultural robots in complex environments, for example, crop, weed, pest, and crop disease recognition algorithms based on multi-feature and image fusion; insect and disease detection algorithms based on hyperspectral imaging. Increasing numbers of optical components are used in the object positioning and sensing of agricultural robots, such as using binocular, depth camera, and other equipment to obtain the three dimensional information about the object. The research foci mainly include: optimizing the calculation method to get the shape and position parameters of the object, and designing optimization algorithms that prevent the robotic arm from touching the object.

To achieve stable and accurate identification and location of objects in a complex and unstructured environment, the trend of agricultural robots in object recognition and positioning technology is to develop low-cost information collection equipment and optimize algorithms for recognizing and positioning the objects of interest.

(4) Precision animal and plant breeding by design

Precision animal and plant breeding by design has become the strategic core of animal and plant germplasm resources innovation, international agricultural science and technology competition, and seed industry competition. The concept of "breeding by design" was proposed in 2003. The main technical links include gene location, selection of excellent trait alleles, and aggregation of excellent genes from different individuals to achieve the goal of design breeding. With the development of multi-omics technologies, big data platforms, gene-editing, and other emerging approaches, it has brought opportunities for the analysis of genetic regulatory network of complex biological traits, built the scientific foundation for the innovation of animal and plant directional breeding by molecular design, and has provided accurate solutions for creating new types of high-production, high-quality, disease-resistant animals and plants. The main technical goals include: 1) exploring the key functional genes, quantitative trait locus (QTL), and regulatory modules that control breeding traits, and clarifying the relationships between genotype, phenotype, and environment; 2) analyzing and designing genotypes with specific breeding objectives, such as high reproduction, high quality, and disease resistance, using big data bioinformatics platform and technology; and 3) analyzing the approaches needed to achieve the target genotypes and to formulate breeding programs to breed excellent new genotypes.

(5) Mining of crop functional genome structure

The important agronomic traits of crops are underscored by related genes. The functions of a gene are not only affected by its own structure, its expression is also affected by its genome context, including the degree of the chromatin openness, the extent of epigenetic modification, and the spatial structure of the locus the gene resides. These factors not only affect the expression level of the gene, but also affect its splicing that may result in new functions. As the main component of the genome, transposable elements (TEs) can affect the structure and function of genes by inserting into various parts of a gene. TEs are closely related to the epigenetic modification, the status of chromatin openness, and remote interactions, strongly impacting the structural variation and expression dynamics of a gene. Polyploids are organisms with more than two sets of genomes. Most angiosperms (approximately 70%) have polyploidy in their history and approximately 40% of the cultivated species are polyploids including wheat, cotton, and rapeseed. Compared with diploids, polyploids are advantageous in yield and adaptability, or so called polyploid vigor.

Crop germplasms stored abundant genomic variations is present. These genetic variations, together with those in mutant libraries, transcriptomes, epigenomes, phenomes and metabolomes, form platforms of technology, information, and genetic materials for mining crop functional genes. Combined with linkage analyses and association analyses, candidate genes for high yield, high efficiency, high quality, disease resistance, and stress resistance have been obtained and experimentally verified by mutants, transgenic technology or gene editing techniques. Therefore, the molecular mechanism of target genes, the number and function of alleles, their breeding values and the path for efficient utilization are interpreted. Eventually, breakthrough progresses will be made in revealing the molecular mechanism of polyploid heterosis and its development and utilization.

(6) Efficient use of agricultural resources and circular economy

Efficient use of agricultural resources refers to the actions and methods to achieve the purpose of resource conservation and producing more agricultural products with less consumption of resources. The agricultural resources include water, soil, fertilizers, and the inputs applied in agricultural production, and also the environment. Techniques and methods can be utilized to improve the use efficiency of agricultural resources in aspects of land use and farming systems design, including germplasm screening, water-saving technologies, fertilizer management, recycling use of agricultural wastes, integrated management of feed and livestock, and crop production. Circular economy is the sustainable development model characterized by resource conservation and recycling for achieving a harmonious situation between ecological environment and economy development. The core idea of circular economy is to establish a feedback loop process of "resource input–product production–resource regeneration" through the entire agricultural production and economic value chain. It can be achieved by strengthening the recycling and promoting the rational and sustainable use of materials and energy, thereby leading to the minimum negative impacts of economic activities on the natural environment. The efficient use of agricultural resources and circular economy are considered from the perspective of the entire chain, including saving resource inputs, improving resource use efficiency, and recycling of waste. The efficient use of agricultural resources and recycling is a way to maximize the economic and ecological benefits, and an important pathway for achieving the sustainable agricultural development and the global sustainable development goals.

(7) Soil biodiversity and ecosystem functions

Soil biodiversity refers to the variability and diversity between soil animals, microorganisms, and plants in the belowground ecosystem, as well as the diversification of interactions between organisms and the environment. It includes species, genetic, structural and functional diversity. Ecosystem function is a concrete manifestation of the value of soil biodiversity. Soil biodiversity is critical for biogeochemical cycles, such as litter degradation and nutrient conversion. It also determines other ecosystem functions like soil development, soil erosion control, soil pollution remediation, agricultural pest control, climate regulation, and maintenance of primary productivity. For human society, soil biodiversity can also provide a variety of ecosystem services such as food supply, water purification, medicine, and industrial raw materials. The maintenance of soil biodiversity is the basic guarantee for the continuous improvement of soil health and productivity, and is the basis for the survival and sustainable development of human society. Currently, affected by human activities, climate change and other factors, the protection of soil biodiversity and the cultivation of healthy soil have been highly valued by governments and relevant international organizations. Conducting comprehensive and in-depth basic research on soil biodiversity protection, establishing a soil biodiversity detection network and ecosystem function evaluation system, and formulating scientific and reasonable soil biodiversity protection strategies are of great significance to ensuring human well-being and sustainable social development.

(8) Interaction of important animal viruses with hosts

Infection and immunity are the results from interaction of pathogens with hosts. Pathogens survive via infection of hosts and the hosts need to maintain a healthy status by clearing the invading pathogens. Some animal pathogens acquire capability of evading immune response of host during long time evolution, escaping from host immunity, causing persistent infections or epidemics in animals, posing an enormous threat to food safety, and leading to severe economic losses. Particularly, recent occurrence and epidemics of viral diseases in animals have adversely affected the development of animal husbandry, causing considerable economic losses, such as African swine fever, highly-pathogenic porcine reproductive and respiratory syndrome, porcine vial diarrhea, pseudorabies, avian influenza, infectious bursal disease, infectious respiratory disease, foot-and-mouth disease, and peste des petitis ruminants, all of which caused huge economic losses. As administration of standard vaccines cannot offer effective protection of animals, development of novel effective and protective vaccines requires complete understandings of the viral pathogenesis, which cannot be achieved without elucidating the mechanism of virus–host interaction. Thus, research on the interaction of important animal viruses with hosts to address these issues will always be a key focus and area needing of innovation. Viruses invade cells via binding to the specific receptors on the cell surface, and then interact with the host cells at protein and nucleic acid levels. At a protein level, viruses express some viral proteins to inhibit antiviral immune signaling of host, creating suitable conditions for their replication. However, the host senses the invaders by recognizing pathogenic features (pathogen-associated molecular pattern, PAMPs) via pathogen recognition receptors to initiate innate immune response and suppress viral replication. At a nucleic acid level, some DNA viruses directly encode microRNA (miRNA) while RNA viruses may smartly regulate miRNA expression of host, inhibiting antiviral immune signaling of host, while the host, upon recognizing PAMPs, directly target viral genomes or negative immune regulators via expressing specific miRNAs to inhibit viral replication. A successful development of novel effective vaccine for animals by reverse genetics or gene-editing techniques requires greater understanding of viral pathogenesis obtained by investigation of virus–host interactions, which will lay a foundation in the future prevention and control of animal infectious diseases of concern.

(9) Interaction mechanism between pathogen and crop

The mechanistic study of pathogen and crop interactions provides insight into sustainable crop disease management. A series of conceptual breakthroughs in the plant–pathogen interaction, as well as novel technologies to modulate crop resistance, have been made over the last decade. Based on the genomes of crops such as rice and wheat, as well as the genomes from aggressive phytopathogens, a number of genes with important theoretical and application values were cloned, such as resistance genes from crops and virulence genes from pathogens. The functional mechanisms of a few essential resistance genes were revealed. Particularly, the structure of the first plant resistosome provided novel insights into the operation of resistance genes. The key mechanisms of plant resistance led to generation of an approach to balance the crop immunity, productivity, and quality. Crops possessing elite resistant gene alleles were created through the clustered regularly interspaced short palindromic repeats (CRISPR)-based gene-editing techniques. Mechanistic study of molecules such as metabolites, effector proteins, and small RNAs enable new concepts of pathogenesis. Meanwhile, scientists have also identified the underlying mechanisms of how pathogens adapt to resistant crops and trigger epidemics in the field. In addition, the newly discovered molecules with crop immune priming function or with antimicrobial activity inform the development of new strategies on rational crop disease management.

(10) Microbial driving mechanism of carbon cycling in forest soil

About 70% of the forest carbon is stored in soil. The input of forest soil carbon mainly includes decomposition of plant litter, root exudates and turnover, soil microbes and animals, and the output mainly includes leaching and organic matter decomposition. In the face of global climate change, it is necessary to better understand the regulation and driving mechanism of specific functional microbial community to maintain the stability of soil carbon sequestration in forest ecosystems. Soil microbes regulate and affect the accumulation of soil organic carbon through active microbial communities (dissimilation metabolism) and microbial death residues (assimilation metabolism). Rhizosphere microbial community has higher carbon sequestration efficiency than wider microbial community in the soil. Ectomycorrhiza and hyphae reduce the activity of saprophytic decomposers and the production of enzyme through their competitive advantages with nitrogen and thus reduce soil respiration and increases soil carbon storage. Arbuscular mycorrhizal fungi do not only form soil aggregates through the action of hyphae to prevent the decomposition of organic matter, but also exude carbohydrates substances that are readily used by decomposers to promote saprophytic microbes to approach the rhizosphere soil and accelerate the decomposition of organic matter. With the application of soil microbial high-throughput sequencing and biogeochemical structure analysis of soil organic carbon at the molecular level, the microbial functional genes and their encoded proteins that regulate the decomposition of different carbon components in soil organic matter have been continuously discovered. However, forest ecosystem is particularly rich in soil microbial diversity, and the processes of environmental change affecting soil microbial and soil carbon cycle are extremely complex. Therefore, it is still necessary to integrate multiple disciplines concepts and methods in the future to further clarify the microbial regulation mechanism in the forest soil carbon cycle.

(11) Molecular basis and regulatory mechanism of sex and development in aquaculture animals

Sex determination and development have always been a research focus in life sciences. Compared with mammals, the sex determination mechanisms of aquaculture species are more complex and diverse. For example, there are sex determination systems such as XX/XY, ZZ/ZW, XO/XX. Characteristic hermaphroditism or sex reversal can be observed in some aquaculture species, which makes them unique material for the study of sex determination mechanisms in animals. Meanwhile, these studies also provide potential solutions to several pressing problems in aquaculture. Natural sex reversal traits are common for ricefield eels and groupers. Conversion from genetic females to physiological males of *Nile tilapia* is induced by high temperature. For aquaculture of semi-smooth tongue sole, brown flounder, and loaches, females are preferred due to their higher growth rate than males. In view of the key scientific issues during aquatic germplasm creation, such as the molecular mechanisms and regulatory networks for sex determination and gonadal development, it has been proposed to study the molecular mechanisms of sex determination and differentiation of finfish, shellfish, soft-shelled turtle, crab, sea cucumber and others; to explore the key genes and regulatory elements for sex determination, while clarifying functions and regulatory networks of related molecules; to research the associations between sex development and important production traits; to analyze the patterns and mechanisms of sex conversion responses to the environmental factors; to screen sex-specific molecular markers; and to study the reproductive characteristics of new germplasm with economic value and to clarify their regulatory mechanisms.

Using aquaculture animals with sexually dimorphic phenotypes, including finfish, shellfish, soft-shelled turtle, crab, and sea cucumber, the mechanism and evolution process of sex determination, gonadal development and environmental interaction for aquaculture animals will be investigated. Based on genomics, transcriptomics, and epigenetics analysis, research on sex determination and development of various aquatic animals will be conducted to identify the factors associated with sex differentiation or development and their expression patterns, as well as the epigenetic modification characteristics. Future research interests will include genomic analysis of aquaculture animals and identification of sex-linked genetic markers, regulatory mechanisms of sex determination and development, sex reversal and environmental factor interaction mechanisms, the effect mechanism of genome ploidy on sex and fertility, and the association mechanisms of sex development and production traits.

1.2 Interpretations for three key engineering research fronts

1.2.1 Origin, evolution, and genetic variation of animal viruses

Since 2000, humans have experienced many major infectious diseases: 2002–2004, Severe Acute Respiratory Syndrome (SARS); 2009, H1N1 Influenza A; 2009–2010, meningitis in West Africa; 2013–2016, Ebola in West Africa; 2012 to present, Middle East Respiratory Syndrome, and the COVID-19 that emerged in 2019. Recent viral diseases of economic animals have included reemergences of old viruses and continuously appearing of novel viruses.

Tracing the source of animal viruses and analyzing the origin, evolution, and genetic variation of animal viruses is important for the development of effective ways to prevent and control the spread of infectious diseases, and it has attracted considerable attention in epidemiology for many years. In the research on virus traceability, established methods include detailed epidemiological and comprehensive distribution investigations of viruses in animals and the environment. However, new methods benefit from the application of bioinformatics techniques, which makes it possible to determine the genetic relationship between different viruses through gene homology comparison and the topological results of the evolutionary tree. Accurate tracing of animal-derived viruses and understanding the mechanisms in genetic variation of viruses can intercept the source of infection in time, effectively monitoring, preventing and controling the occurrence of infectious diseases. In fact, the virus traceability work is difficult with the research process being complicated and uncertain. For example, COVID-19, which appeared at the end of 2019, has rapidly spread globally since its appearance. Scientists around the world are actively exploring the origin of SARS-CoV-2, but the source is still unresolved. Studies have shown that the virus may appear in the population earlier than expected, but it was not detected due to limitations in monitoring, and it was interspersed among other pneumonia cases. During the zoonotic transmission phase, the virus gradually acquired key mutation sites, making it fully adapted to humans. Retrospective blood tests or subgenome studies for respiratory infections may help to determine if this interpretation is correct. The exploration of the source of the SARS virus of 2003 has made substantial progress, bats are generally considered as the natural hosts, while palm civets were thought to be the intermediate hosts before the virus entered the population, but further research is needed.

In the established methods of tracing the source of a virus, the epidemiological investigation generally starts from the contact history of the first patient, known as patient zero, but sometimes it is difficult to determine the identity of patient zero, such as the tracing of patients with HIV; the investigation of the distribution of viruses in animals and the environment is the most direct and important method in the tracing process. This method has been successfully applied to research on simian immunodeficiency viruses. Compared with established methods, bioinformatics technology combines genome sequence with computational epidemiology and uses molecular clock theory to estimate the evolution time of viruses to infer the relative distance between viruses. For example, the genome comparison results of the SARS-CoV-2 and the bat-coronavirus carried by bats show that the SARS-CoV-2 completes the evolutionary transmission from bats to humans and requires at least one intermediate host as a transmission vector. Every part plays an important role in the process of virus tracing. Due to the various uncontrollable factors, the epidemiological monitoring of animal viruses should increase to effectively prevent and control the emergence and spread of new infectious diseases in the context of One Health.

The survival of the fittest in Darwinian evolution theory also applies to the survival of viruses, which means that the virus can only survive through continuous mutation and evolution. Viruses can mutate through a variety of mechanisms, and their genome can rearrange, which allows newly replicated viruses to show different characteristics from previous generations. In addition, the bases on the genetic material of the virus will mutate randomly, and this genetic drift phenomenon can also cause mutations in the virus. Studies have shown that RNA viruses are more prone to genetic mutations because, compared with DNA viruses, RNA viruses are more prone to errors in the replication process and have lower stability, such as the cross-host transmission of avian influenza viruses. The H3N2 subtype of canine influenza virus (H3N2 CIVs) appeared in dogs in Asia around 2005 and originated from avian hosts. H3N2 CIV can be divided into seven major clades and some mutation sites provided evidence for adaptive evolution. The main lineages of viruses have similar predicted genomic evolution rates, but compared to other in avian reservoir viruses, H3N2 CIV consistently shows proportionally more nonsynonymous substitutions at each site, which indicates that there has been a large-scale change in selection pressures. According to the evolution rate and amino acid site mutation analysis, it was found that the avian influenza has evolved relatively quickly after entering a mammalian host (dogs), and is more adapted to the transmission between mammalian hosts.

Given that viruses, especially RNA viruses, are prone to mutation and their evolution rate is relatively high, mastering the genetic evolution mechanisms of viruses has become a key factor in controlling virus transmission. In order to solve related problems, the genome sequence and related information are combined with bioinformatics and statistical methods that rely on high-performance computers to better analyze the genetic variation and transmission mechanisms of viruses through big data. In the study of virus traceability, evolution, and mechanisms of genetics mutation, the use of epidemiological knowledge combined with statistical science and computer algorithms has become an emerging discipline that can better serve in prevention and control strategies for viral epidemics.

Considering the distribution of papers by country, it can be seen that the main contributors of core papers on the “origin, evolution, and genetic variation of animal viruses” were the United States (62.07%), the United Kingdom (29.31%), and France (20.09%) (Table 1.2.1). The citations per paper in this field ranged from 51 to 109 across the top 10 countries, and the citations per paper for the Netherlands and India exceeded 100. The distribution of papers by research institution shows that the number of core papers were the highest for the University of Oxford and the US Centers for Disease Control and Prevention (Table 1.2.2). The collaboration networks among the major countries were common, with the United Kingdom, the United States, and France sharing the closest collaborative relationship (Figure 1.2.1). From the network diagram of collaborations among the major contributing institutions (Figure 1.2.2), it can be seen that collaborative relationships existed among all institutions. The main contributors of core paper citations were the United States, China, and the United Kingdom (Table 1.2.3), the number of citing papers in the United States accounts for more than one third, United Kingdom and China both account for more than 10%, and the average citation year of core papers was also relatively recent, which is indicative of the strong developmental momentum of research in this field. From the list of the major core paper citation-contributing institutions (Table 1.2.4), it can be seen that the US Centers for Disease Control and Prevention and the Institute Pasteur were far ahead of all other institutions, and the Chinese Academy of Sciences ranked sixth.

Table 1.2.1 Countries with the greatest output of core papers on "origin, evolution, and genetic variation of animal viruses"

No.	Country	Core papers	Percentage of ore papers	Citations	Citations per paper	Mean year
1	USA	36	62.07%	3 292	91.44	2015.5
2	UK	17	29.31%	1 648	96.94	2015.2
3	France	12	20.69%	609	50.75	2015.3
4	Australia	10	17.24%	873	87.30	2015.4
5	China	8	13.79%	743	92.88	2016.0
6	Belgium	6	10.34%	547	91.17	2015.2
7	Germany	6	10.34%	449	74.83	2015.5
8	Netherlands	5	8.62%	540	108.00	2014.4
9	Spain	4	6.90%	205	51.25	2015.8
10	India	3	5.17%	327	109.00	2014.3

Table 1.2.2 Institutions with the greatest output of core papers on "origin, evolution, and genetic variation of animal viruses"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	University of Oxford	7	12.07%	861	123.00	2015.3
2	US Centers for Disease Control and Prevention	7	12.07%	823	117.57	2016.0
3	Fred Hutchinson Cancer Research Center	6	10.34%	1 007	167.83	2015.8
4	National Institutes of Health	6	10.34%	639	106.50	2015.2
5	University of Sydney	6	10.34%	468	78.00	2016.0
6	Institute Pasteur	6	10.34%	318	53.00	2015.8
7	U.S. National Library of Medicine	5	8.62%	287	57.40	2016.6
8	University of Edinburgh	4	6.90%	790	197.50	2015.8
9	Harvard University	4	6.90%	495	123.75	2016.2
10	University of Melbourne	4	6.90%	451	112.75	2015.3

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "origin, evolution, and genetic variation of animal viruses"

1.2.2 Precision animal and plant breeding by design

Precision animal and plant breeding by design has become the strategic core of animal and plant germplasm resources innovation, international agricultural science and technology competition, and seed industry competition. In 2018, the United States released the *Science Breakthroughs to Advance Food and Agricultural Research by 2030*, which listed genomics and biological precision breeding as one of the major directions of agricultural development in the future. The precision breeding comes from the concept of "breeding by design" proposed by Peleman and Van Der Voot in 2003. It is mainly aimed at plant breeding. The technical links include gene mapping, screening of excellent alleles, and clustering of excellent genes from individuals, so as to achieve the goal of

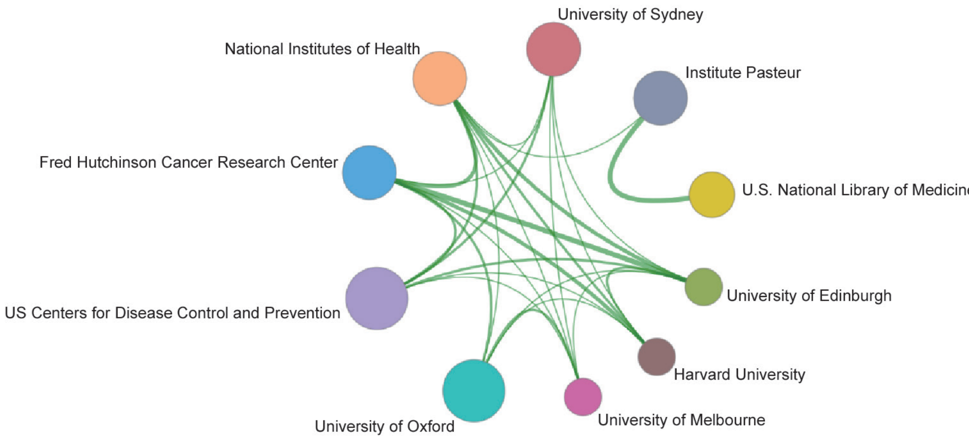

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "origin, evolution, and genetic variation of animal viruses"

Table 1.2.3 Countries with the greatest output of citing papers on "origin, evolution, and genetic variation of animal viruses"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	1 724	36.29%	2017.8
2	China	613	12.90%	2018.5
3	UK	513	10.80%	2017.8
4	France	374	7.87%	2017.6
5	Germany	319	6.71%	2017.9
6	Australia	279	5.87%	2017.9
7	Canada	213	4.48%	2018.0
8	Brazil	197	4.15%	2018.2
9	Spain	181	3.81%	2017.9
10	Italy	181	3.81%	2018.3

Table1.2.4 Institutions with the greatest output of citing papers on "origin, evolution, and genetic variation of animal viruses"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	US Centers for Disease Control and Prevention	170	14.66%	2018.0
2	Institute Pasteur	134	11.55%	2017.6
3	University of Oxford	121	10.43%	2018.0
4	Harvard University	115	9.91%	2017.9
5	University of Sydney	108	9.31%	2017.6
6	Chinese Academy of Sciences	104	8.97%	2018.3
7	National Institute of Allergy and Infectious Diseases	99	8.53%	2017.7
8	National Institutes of Health	82	7.07%	2017.2
9	The University of Texas Medical Branch	79	6.81%	2017.2
10	University of Cambridge	77	6.64%	2017.6

design breeding. At present, precision breeding by molecular design has been extended to the field of animal breeding. Around the world, in-depth research has been conducted in plants, mammals, and aquatic animals, and remarkable results have been achieved. The continuous innovation of agricultural precision breeding technology is changing the established agricultural production mode toward a more modern agriculture.

Over recent years, with the rapid development of multi-omics technologies for genomes, epigenomes, transcriptomes, proteomes, and metabolomes, the analysis of functional genes, QTLs, and regulatory modules related to important traits of animals and plants has been deepened, and the interaction mechanisms of genes, phenotypes, and environment have been increasingly clarified, which has laid a theoretical foundation for precision animal and plant breeding by design. The rapid development of bioinformatics, whole genome selection, and gene editing provides technical support for precise design of animal and plant traits. Based on the omics databases, bioinformatics technology and computer-aided means have been used to simulate the breeding process, design breeding materials according to the breeding objectives, and breed new lines. Whole genome selection technology is based on the high-throughput genotype analysis and prediction model, which aggregates excellent genotypes at the whole genome level and improves important traits of animals and plants. Gene-editing technology can precisely modify a target gene in a genome, such as deletion, substitution, and insertion, break the species boundary, and realize gene directional transfer across species. In particular, the development of CRISPR-Cas9 system significantly improves the efficiency and accuracy of gene editing, which has become one of the important means of precision breeding. The combined application of multiomics genetic information, whole genome selection, and gene-editing technology makes animal and plant breeding more efficient, accurate, and controllable, thus realizing the leap from crossbreeding to precision breeding, and solving major production problems that cannot be solved by established methods.

As standard cross-breeding is difficult to combine multiple superior genes into one line, its selection efficiency is low and the time period involved is long. Precision animal and plant breeding by design focuses on the important demand of directional breeding of new genotypes of animals and plants with high yield, high quality, and disease resistance. Taking plants and aquatic and farm animals as examples, the regulation network of genes for important economic traits was clarified, a new generation of precise design and breeding technology system of animals and plants was established, and new lines and breeding materials with important values were created. In 2018, the global planting area of genetically modified crops has reached 191.7 million hectares and 70 countries and regions have approved the planting or import of genetically modified crops and products. The popularization and application of transgenic crops significantly increased the yield of crops, reduced the amount of pesticides, and produced huge economic and social benefits. The industrialization process of gene-edited products, such as drought tolerant corn, herbicide resistant and phosphorus efficient maize, low temperature storage potato, and high-oleic-acid soybean, has been accelerated. The whole genome sequencing of wheat and rice has been completed. On the basis of clear function of major agronomic traits genes, a range of new cultivars with high yield, high quality, and disease resistance were bred through cutting and polymerization of favorable genes. The physiology of animals are more complex than plants. At present, the research is mainly based on molecular marker technology for gene polymerization, gene infiltration, and breeding of new lines by using gene-editing technology. High-yield and disease-resistant livestock, such as CD163 gene-edited pig, hornless cow with polled gene replacement, and double-muscular livestock with MSTN knockout, have been obtained. In 2015, AquaBounty Company in the United States bred a fast-growing salmon, which was approved for production and sale. This event accelerates the commercialization of gene-edited animals. The continuous innovation of agricultural biological precision design breeding technology is rapidly changing the established production mode.

The top three countries in the research on precision animal and plant breeding by design are the United States, China, and the United Kingdom. The top three countries with the highest citations per paper are Germany, Japan, and France (Table 1.2.5). Among the top 10 countries, the United States had cooperation with Mexico, Kenya, the United Kingdom, China, France, Germany, India, and Austrilia while Japan had no cooperation with other countries (Figure 1.2.3). Cornell University, Agricultural Research Service, United States Department of Agriculture (USDA ARS), and the International

Maize and Wheat Improvement Center (CIMMYT) are the top three institutions in the number of core papers published (Table 1.2.6). A paper entitled, "Genomic selection and association mapping in rice (*Oryza sativa*): effect of trait genetic architecture, training population composition, marker number and statistical model on accuracy of rice genomic selection in elite, tropical trice breeding lines" published by Jennifer Spindel and colleagues of Cornell University and many other institutions is the most cited paper (205 citations). This paper evaluated the effect of genome selection in rice inbred line breeding. Among the top 10 institutions, Cornell University, USDA ARS, CIMMYT, and Kansas State University have had more cooperation (Figure 1.2.4). The top three countries with the greatest number of citing papers are the United States, China, and India (Table 1.2.7). The main output institutions of citing papers are USDA ARS, Chinese Academy of Agricultural Sciences, and Chinese Academy of Sciences (Table 1.2.8).

1.2.3 Soil biodiversity and ecosystem functions

Healthy soil is rich in biodiversity, including bacteria, fungi, actinomycetes, nematodes, vertebrates, earthworms, mites, and insects. These soil organisms are important in promoting plant growth, enhancing soil fertility, promoting the decomposition of organic matters, suppressing pests, parasites, and pathogens, and maintaining the stability of the soil ecosystem. At present, human activities have put increasing pressure on biodiversity and ecosystem services. Deforestation, intensive farming, and excessive use of fertilizers and pesticides have greatly exacerbated the decrease in number and species of soil organisms. Subsequently, ecosystem stability is becoming more fragile, which will endanger the sustainability of soil productivity and the function of soil ecosystem. Faced with the loss of biodiversity, the United Nations officially launched the "Millennium Ecosystem Assessment" project

Table 1.2.5 Countries with the greatest output of core papers on "precision animal and plant breeding by design"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	48	44.04%	4 004	83.42	2015.8
2	China	28	25.69%	2 120	75.71	2015.8
3	UK	14	12.84%	1 155	82.50	2014.8
4	Mexico	13	11.93%	1 090	83.85	2015.3
5	Germany	10	9.17%	922	92.20	2015.2
6	France	9	8.26%	775	86.11	2015.4
7	India	8	7.34%	641	80.12	2016.3
8	Kenya	7	6.42%	435	62.14	2015.8
9	Australia	6	5.50%	389	64.83	2014.8
10	Japan	5	4.59%	452	90.40	2014.4

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "precision animal and plant breeding by design"

Table 1.2.6 Institutions with the greatest output of core papers on "precision animal and plant breeding by design"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Cornell University	12	11.01%	1018	84.83	2014.8
2	USDA ARS	12	11.01%	953	79.42	2015.2
3	CIMMYT	11	10.09%	908	82.55	2015.2
4	Kansas State University	8	7.34%	549	68.62	2015.0
5	Chinese Academy of Agricultural Sciences	7	6.42%	660	94.29	2016.1
6	University of Minnesota	7	6.42%	345	49.29	2014.7
7	DuPont Pioneer	5	4.59%	740	148.00	2015.2
8	University of Arizona	5	4.59%	604	120.80	2015.4
9	Chinese Academy of Sciences	5	4.59%	578	115.60	2016.2
10	The Sainsbury Laboratory	5	4.59%	485	97.00	2015.0

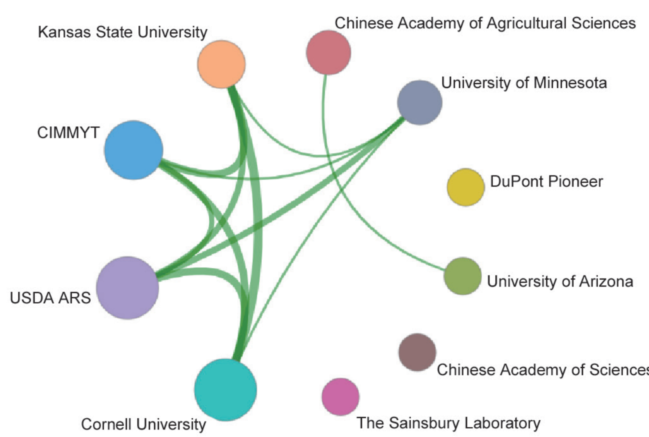

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "precision animal and plant breeding by design"

Table 1.2.7 Countries with the greatest output of citing papers on "precision animal and plant breeding by design"

No.	Country	Citing papers	Percentage of citing papers	Mean Year
1	USA	1 640	29.39%	2017.8
2	China	1 413	25.32%	2018.0
3	India	400	7.17%	2018.0
4	Germany	384	6.88%	2017.8
5	UK	333	5.97%	2017.8
6	Australia	323	5.79%	2017.7
7	Brazil	252	4.52%	2018.2
8	France	247	4.43%	2017.6
9	Japan	223	4.00%	2017.9
10	Mexico	190	3.40%	2017.8

Table 1.2.8 Institutions with the greatest output of citing papers on "precision animal and plant breeding by design"

No.	Institution	Citing papers	Percentage of citing papers	Mean Year
1	USDA ARS	262	16.18%	2017.8
2	Chinese Academy of Agricultural Sciences	253	15.63%	2018.1
3	Chinese Academy of Sciences	194	11.98%	2017.8
4	CIMMYT	137	8.46%	2017.6
5	Cornell University	133	8.21%	2017.6
6	Huazhong Agricultural University	131	8.09%	2018.0
7	University of Florida	120	7.41%	2018.1
8	Iowa State University	101	6.24%	2017.5
9	China Agricultural University	98	6.05%	2018.2
10	University of Minnesota	97	5.99%	2017.6

in 2001, scientifically assessing the status and trends of global ecosystems and the services they provide and proposing various restoration, protection or improvement countermeasures for the sustainable development and use of ecosystems. In 2012, under the leadership of the United Nations Environment Programme, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services was formally established, which is another intergovernmental environmental assessment plan after the United Nations Intergovernmental Panel on Climate Change. Soil contains a quarter of global biodiversity; therefore, the protection of soil biodiversity is essential to soil health, soil productivity, and food security.

The research on the relationship between soil biodiversity and ecosystem functions has developed rapidly over the past 40 years, and has become an important cross-disciplinary research area in ecology, agronomy, microbiology, environmental science, humanities, and economics. From the beginning, attention was given to the impact of species loss on the structure and function of the ecosystem, and gradually developed to the use of experiments or theoretical models to study the contribution sizes and mechanisms of biodiversity for primary production, biogeochemical cycles, environmental purification, climate regulation, pest control, and economic value. At present, researchers of soil biodiversity and ecosystem services and functions have basically formed a consensus in five aspects: 1) Biodiversity can improve ecosystem productivity and resource utilization efficiency. 2) Biodiversity improves ecological stability, and the longer the time, the more significant the effect. 3) The impact of biodiversity on a single process or function in the ecosystem is nonlinear and saturated. 4) The impact of species losses between different trophic levels on ecosystem functions is greater than the species losses within the trophic level. 5) The functional traits of organisms have an important impact on the performance of ecosystem functions.

Based on a large number of published studies, four research fronts have emerged. 1) Soil biodiversity and ecosystem functions under the global changes background. In addition to biodiversity itself, changes in climate and environmental conditions such as drought, warming, and soil acidification may affect the functioning of ecosystems. Therefore, analyzing the impact and contribution of soil biodiversity, climate and environmental factors on ecosystem functions, and how global changes affect soil biodiversity and ecosystem functions, is a major challenge facing the future global sustainable development. 2) Temporal and spatial scale characteristics of soil biodiversity and ecosystem service functions. Current researches mostly focus on small areas and short time scales, and there are few studies on larger landscape scales and variability over time scales. Therefore, clarifying the temporal and spatial scale characteristics of soil biodiversity and ecosystem services is of great significance for landscape-level protection and sustainable use. 3) Soil biodiversity and ecosystem multifunctionality. Maintaining multiple ecological functions requires the participation of more species than one ecological function. Therefore, soil biodiversity and the realization of multifunctionality in ecosystems has become a research hotspot in recent years. 4) Relationships between ecological benefits of soil biodiversity and species evolution.

With the development of molecular analysis technology, studies have shown that the greater the phylogenetic distance between species, the more conducive to the performance of ecosystem functions, which may be related to the increase in functional traits caused by genetic diversity between species.

The countries where core papers are published were mainly from the United States, China, and Spain. The number of citations was highest in Switzerland and the Netherlands (Table 1.2.9). In terms of the distribution of research institutions, Rey Juan Carlos University (Spain), the Chinese Academy of Sciences, and the University of Colorado Boulder (USA) were ranked at the top with core paper publications, while the number of citations was highest for papers published by the University of Zurich and the Agroscope (Table 1.2.10). A highly cited paper entitled “Soil biodiversity and soil community composition determine ecosystem multifunctionality” published in the journal *PNAS* in 2014 was cited 544 times. This work was collaboratively completed by scientists from the Agroscope and the University of Zurich, focusing on the effects of soil biodiversity and soil community composition on ecosystem multifunctionality. It showed that the reduction of soil biodiversity and the simplification of community composition would impair multiple ecosystem functions, including plant diversity, decomposition, nutrient retention, and nutrient cycling, indicating that changes in soil communities and the loss of soil biodiversity would threaten ecosystem multifunctionality and sustainability.

In terms of cooperation network among countries, the United States, Australia, Spain, and China have relatively close collaborative relationships (Figure 1.2.5). From the network diagram of collaborations among the major contributing institutions (Figure 1.2.6), every institution has a certain

Table 1.2.9 Countries with the greatest output of core papers on “soil biodiversity and ecosystem functions”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	24	43.64%	450	18.75	2017.5
2	China	18	32.73%	241	13.39	2018.2
3	Spain	17	30.91%	368	21.65	2017.4
4	Australia	14	25.45%	276	19.71	2017.4
5	Germany	11	20.00%	260	23.64	2017.3
6	Switzerland	10	18.18%	1 506	150.60	2016.4
7	Netherlands	5	9.09%	1 359	271.80	2016.4
8	France	5	9.09%	618	123.60	2017.0
9	Sweden	5	9.09%	173	34.60	2017.0
10	UK	5	9.09%	142	28.40	2016.8

Table 1.2.10 Institutions with the greatest output of core papers on “soil biodiversity and ecosystem functions”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Rey Juan Carlos University	15	27.27%	302	20.13	2017.5
2	Chinese Academy of Sciences	10	18.18%	176	17.60	2018.0
3	University of Colorado Boulder	8	14.55%	95	11.88	2018.4
4	Western Sydney University	7	12.73%	79	11.29	2018.0
5	Northern Arizona University	6	10.91%	162	27.00	2016.0
6	University of Minnesota	6	10.91%	114	19.00	2017.5
7	University of Zurich	5	9.09%	1 349	269.80	2016.4
8	Agroscope	5	9.09%	1 106	221.20	2017.2
9	Swedish University of Agricultural Sciences	5	9.09%	173	34.60	2017.6
10	Chinese Academy of Forestry	5	9.09%	152	30.40	2017.0

collaborative relationship with other institutions. The main contributors of core paper citations were China and the United States, and the average citing year was 2018, showing strong developmental momentum of research in this field. (Table 1.2.11). From the list of the major core paper citation-contributing institutions (Table 1.2.12), the Chinese Academy of Sciences was far ahead and the average citing year was 2018.

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "soil biodiversity and ecosystem functions"

2 Engineering development fronts

2.1 Trends in top 9 engineering development fronts

Based on global patent applications and authorization documents related to agriculture during 2014–2019, the top 9 engineering development fronts were identified (Table 2.1.1). These engineering development fronts can be roughly divided into three categories: (1) development fronts related to agricultural production equipment, including "intelligent equipment for unmanned farm," "the principles and techniques of advanced agricultural sensors," and "intelligent

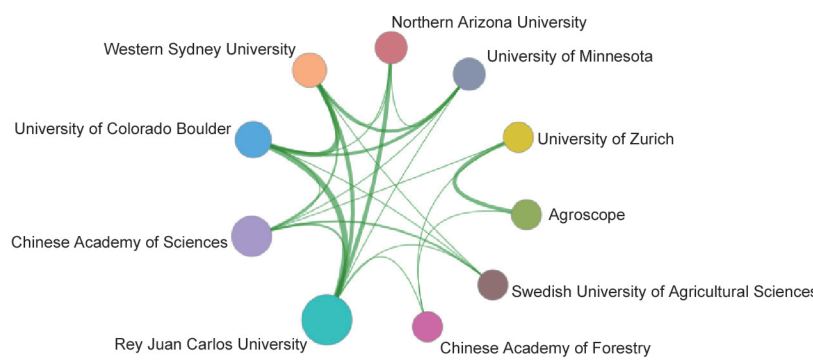

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "soil biodiversity and ecosystem functions"

Table 1.2.11 Countries with the greatest output of citing papers on "soil biodiversity and ecosystem functions"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	520	19.62%	2018.6
2	USA	475	17.92%	2018.0
3	Germany	279	10.52%	2018.0
4	UK	207	7.81%	2018.1
5	France	201	7.58%	2017.9
6	Spain	195	7.36%	2017.9
7	Switzerland	186	7.02%	2017.7
8	Australia	177	6.68%	2018.0
9	Netherlands	169	6.38%	2017.8
10	Canada	130	4.90%	2018.4

Table 1.2.12 Institutions with the greatest output of citing papers on "soil biodiversity and ecosystem functions"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	203	25.47%	2018.5
2	University of Chinese Academy of Sciences	84	10.54%	2018.6
3	University of Zurich	73	9.16%	2017.4
4	Swedish University of Agricultural Sciences	71	8.91%	2018.1
5	German Centre for Integrative Biodiversity Research (iDiv)	61	7.65%	2018.2
6	Rey Juan Carlos University	59	7.40%	2017.8
7	China State Shipbuilding Corporation Limited	55	6.90%	2017.6
8	Leipzig University	50	6.27%	2018.2
9	Agroscope	48	6.02%	2017.3
10	Utrecht University	47	5.90%	2016.9

identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection unmanned aerial rehicles (UAVs);" (2) development fronts related to environmental governance, including "resource utilization of agricultural and rural organic wastes" and "remediation of soil polluted by organic compounds;" and (3) development fronts related to the promotion of agricultural production and food safety, including "development of efficient and safe animal vaccines and diagnostic reagents," "artificial-intelligence-assisted breeding," "construction of economic forest high yield plant-type," and "research and application of formulated aqua-feeds."

Table 2.1.1 gives an overview of the core patents in these 9 engineering development fronts from 2014 to 2019. "Intelligent equipment for unmanned farm," "remediation of soil polluted by organic compounds," and "construction of economic forest high yield plant-type" are the three development fronts with the most core patents, each of which are more than 100. The citations per paper of "intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs" is the highest (9.3) and much higher than others. The two development fronts "resource utilization of agricultural and rural organic wastes" and "artificial-intelligence-assisted breeding," with latest mean year of core patents, have had a large number of applications and rapid technological updates in recent years.

Table 2.1.2 shows the publishing trends of core patents in these 9 engineering development fronts from 2014 to 2019. It can be seen that, the number of core patents published for the three development fronts, "intelligent equipment for unmanned farm," "resource utilization of agricultural and rural organic wastes," and "artificial-intelligence-assisted breeding," have shown a significant increase since 2017, and the growth momentum is strong.

(1) Intelligent equipment for unmanned farm

Unmanned farms are one of the possible production methods and realizations of smart agriculture. The unmanned farm is characterized by following points: 1) system covers the whole production chain, including tillage, planting, management, and harvest; 2) operating machinery can autonomously transfer between fields and garages; 3) operating machinery has the function of obstacle avoidance and emergency-triggered stop; 4) real-time monitor on the whole producing process; and 5) decision-making and precision operations are all intelligence-based and unmanned. Unmanned farms depend on the support of biotechnology, intelligent equipment, and information technology. Biotechnology provides unmanned farm with crop cultivars and cultivation modes suitable for mechanized operations. Intelligent equipment is used for intelligent perception, navigation, operation, and management. Information technology offers support on information acquisition, transmission, and processing, as well as navigation, automatic operation, and remote maintenance of agricultural machinery.

The cutting-edge technologies of intelligent equipment for unmanned farm mainly include intelligent perception, intelligent navigation, intelligent operation, intelligent

Table 2.1.1 Top 9 engineering development fronts in agriculture

No.	Engineering development front	Published patents	Citations	Citations per paper	Mean year
1	Intelligent equipment for unmanned farm	206	990	4.81	2017.2
2	Development of efficient and safe animal vaccines and diagnostic reagents	80	67	0.84	2016.8
3	The principles and techniques of advanced agricultural sensors	49	50	1.02	2017.4
4	Resource utilization of agricultural and rural organic wastes	90	45	0.50	2018.3
5	Remediation of soil polluted by organic compounds	116	421	3.63	2017.4
6	Artificial-intelligence-assisted breeding	56	15	0.27	2018.4
7	Intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs	45	419	9.31	2017.5
8	Construction of economic forest high yield plant-type	142	402	2.83	2016.9
9	Research and application of formulated aqua-feeds	65	88	1.35	2016.3

Table 2.1.2 Annual number of core patents published for the top 9 engineering development fronts in agricultural field

No.	Engineering development front	2014	2015	2016	2017	2018	2019
1	Intelligent equipment for unmanned farm	11	16	34	48	47	50
2	Development of efficient and safe animal vaccines and diagnostic reagents	15	8	11	12	10	24
3	The principles and techniques of advanced agricultural sensors	6	4	3	6	14	16
4	Resource utilization of agricultural and rural organic wastes	2	0	0	14	28	46
5	Remediation of soil polluted by organic compounds	12	18	5	13	9	59
6	Artificial-intelligence-assisted breeding	0	0	3	9	17	15
7	Intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs	6	2	2	7	11	17
8	Construction of economic forest high yield plant-type	13	20	23	27	30	29
9	Research and application of formulated aqua-feeds	16	5	5	12	8	15

management, and system integration. Intelligent perception consists of agricultural sensors, environmental information perception, animal and plant information perception, and intelligent data processing. Intelligent navigation requires technology of high-resolution map construction, route planning, precision positioning in complex environment, path following control, and multi-equipment collaborative operation. Intelligent operations include precision seeding, variable fertilization, variable pesticide application, and variable irrigation. Intelligent management includes status monitoring, remote operation, maintenance, and management of intelligent equipment.

(2) Development of efficient and safe animal vaccines and diagnostic reagents

Animal vaccines are used for preventing animal infectious disease and are typically prepared by artificially attenuating, inactivating or genetically engineering the pathogenic microorganisms (e.g., viruses and bacteria) and their metabolites. Standard inactivated vaccines have the limitations of high cost and incomplete immune effect and attenuated vaccine strains have the risk of virulence returning. Therefore, development of efficient and safe genetic engineering animal vaccines, such as DNA vaccine, gene-deleted vaccine, live vector vaccine, virus-like particle vaccine, and synthetic peptide vaccine, are the main direction of future research. New genetic engineering animal vaccines that have been licensed in China include avian influenza DNA vaccine, foot-and-mouth disease synthetic peptide vaccine, and gene-deleted vaccine against pseudorabies.

Effective diagnostic reagents are the key prerequisite for accurate diagnosis, prevention, and control of animal epidemics. The development of diagnostic reagents mainly include: research on pretreatment technology for testing samples; antigen or antibody detection technology based on immune response (such as monoclonal antibody, enzyme-linked immunosorbent assay, immune colloidal gold test stripe, immunofluorescence technology, and nano-antibody technology); molecular biological detection based on nucleic acids (such as polymerase chain reaction (PCR), quantitative PCR, loop-mediated isothermal amplification, fluorescent labeling aptamer technology, and whole genome sequencing); and simple, rapid, sensitive, accurate, high-throughput, and online detection are the development directions of diagnostic reagents.

(3) The principles and techniques of advanced agricultural sensors

Sensing principles and techniques are the basic supports of agricultural sensors. Agricultural sensors are the devices to measure and monitor the agricultural environmental parameters, life status, and the working status of agricultural machinery. Agricultural sensors consist of sensing materials, processing chips, and core algorithms, and are supported by specific physical mechanisms.

There are two main research directions. The first direction is the researches on novel sensing mechanisms and original sensing methods of agricultural sensors. In recent years, new physical, chemical, and biological sensing methods are increasingly applied in agriculture. Various sensors of different principles have been developed. This has the potential to realize the *in-situ* measurement of soil nitrogen, soil heavy metals, and water quality; non-destructive detection of crop nutrient, crop ions, and crop metabolic components; and online monitoring of animal estrus and the biochemical indicators of animal lactation. The second direction is the highly integrated design of agricultural sensors. A major focus for agricultural sensor development in recent years is the integration of sensor chips through the application of microelectromechanical systems (MEMS). Some countries, research institutes and companies have been involved in producing agricultural sensor chips, e.g., MEMS-chip-based sensors for agricultural environment parameters, and micro/nanosensors for animal rumen. Maintenance-free, reliable, low-power-consumption, and low-cost sensors can be developed through chip design and their fabrication.

One major trend of agricultural sensor techniques is the fast development of new sensing mechanisms. This will enable more agricultural parameters that can currently only be tested in laboratory to be measured online and *in-situ*. Another trend is the development of industrialization of agricultural sensors. A chain that covers sensor chip design, producing, standard test, and pilot plant test is essential for the development of an agricultural sensor industry.

(4) Resource utilization of agricultural and rural organic wastes

This development front belongs to the discipline of resource ecology science and is the frontier of established in-depth development. Agricultural and rural organic wastes are the sum of organic wastes generated by agricultural production and rural life. They mainly include agricultural byproducts, such as livestock excreta, straw, rice husk, peel (dregs), leftovers, and household kitchen wastes. There are many types and large quantities of organic wastes, which are scattered and complex. Their utilization is therefore difficult, and they pose great potential environmental risks, which seriously restricts the aesthetics of rural communities and the sustainable development of agriculture. The common ways of using these byproducts are returning them to soil directly, anaerobic fermentation, aerobic composting, incineration for power generation, and biomass carbonization. However, technical problems hinder developments, for example, the immature key technologies, low returns from resource utilization, and incomplete harmless treatment. In view of the potential damage of organic wastes to the rural ecological environment and the green development of agriculture, their resource utilization is currently a frontier technical issue that needs to be focused on.

(5) Remediation of soil polluted by organic compounds

Soil contaminated with organic substances is an important global problem, causing adverse impacts on agricultural production and food safety. The organic contaminants of organochlorine pesticides, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and phthalic acid esters are predominant in the agricultural soils of China. These organic contaminants are toxic and resistant to environmental degradation and even have potential carcinogenicity, posing significant risks to ecological function of soils and human health. Therefore, studies on remediation of soil polluted by organic compounds as well as the development of soil remediation techniques are very important to the soil protection in both developed and developing countries. Soil remediation refers to the process of restoring the functions of polluted soil through different techniques, including physical, chemical, and biological treatments as well as the integrated remediation techniques. Physical soil remediation treatment is a method that removes the organic pollutants in soil through physical processes, such as thermal soil remediation. Chemical soil remediation treatments, such as chemical oxidation and catalytic degradation methods, add chemicals to polluted soils to stabilize the pollutants and convert them to less toxic or nontoxic compounds. Biological soil remediation treatment is a method that decomposes the organic contaminants using animals, plants, and microorganisms. By combining the advantages of physical, chemical, and biological soil remediation treatments, the integrated remediation techniques are becoming highly promising treatments for soil remediation with low cost and high efficiency.

(6) Artificial-intelligence-assisted breeding

In recent years, artificial intelligence (AI) has been increasingly applied in breeding, making an even more accurate and effective industry. Faced by new opportunities and challenges, AI is supporting the advent of a new round of green revolution, in four aspects. 1) AI-assisted precision crossbreeding. Crossbreeding is the process of enrichment of beneficial alleles and purging of deleterious alleles by continuous crossing and selection. AI facilitates efficient mining of beneficial alleles, as well as pinpointing deleterious alleles, thereby guiding precision crossbreeding. 2) AI-guided genome editing. Genome editing is emerging as a pivotal tool in future breeding. However, genome editing itself does not tell us where to edit and how to edit to achieve favorable agronomic traits. AI, however, provides targets for genome editing by designing artificial beneficial alleles. 3) AI-based synthetic biology. Generative models in AI have been used to design novel genomic elements, proteins, genes, and even regulatory networks that do not exist in nature, providing blue prints for intelligent design of plants and animals. 4) AI-empowered phenomics. With the widespread application of sensors, drones, and robots, AI has been used to extract phenotypic data from multiscale and multidimensional image data, supporting the construction of breeding models and decision-making in breeding programs. In combination, by revolutionizing breeding, AI has become an area where competition around the globe is significant.

(7) Intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs

The system for intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs consists of a remote sensing system, a geographic information system, a precise navigation system, and a variable spraying system. The plant protection UAVs are equipped with various kinds of sensors to acquire farmland image and identify the information of crop diseases, pests, and weeds by processing, mining, and modeling the data. The remote sensing image of farmland can be acquired by digital, hyperspectral, multi-spectral, infrared thermal or laser radar camera. Classic statistical analysis, pattern recognition, and machine learning are three methods to analyze the remote sensing images. At present, the variable spraying system of plant protection UAVs is not well developed. The pulse width modulation (PWM) and change of liquid pump speed are two methods in the experimental stage for variable spray application. For precise targeted application according to the prescription map, the flight control system of UAVs needs to adjust the flight path in real time based on meteorological information such as wind speed and wind direction to ensure the spray of a precise dosage of agrochemicals in the proper area.

(8) Construction of economic forest high yield plant-type

Plant type is one of the important factors influencing the yield of an economic forest. The output of economic forests is mainly transformed from photosynthetic products. The architecture of the tree determines the distribution of the captured carbon, water, and nutrients in each part of the tree, which in turn affects the yield and quality. High-yielding plant types in the economic forests refers to tree architectures with suitable height, and the main trunks, main branches, and branch groups have certain quantitative relationship and a clear master–slave relationship. It also has a balanced ratio of nutrient branches and fruiting branches, reasonable density and distribution of branches and leaves, good ventilation and light conditions for the tree and the largest effective photosynthetic area of the canopy. A fundamental way to increase yield is to improve the photosynthetic performance of plants. The high-yielding plant type increases production mainly by increasing the photosynthetic area, i.e., trees with higher photosynthesis. The construction of high-yielding plant types of economic forests is achieved through selective breeding and plant type cultivating. The selective breeding of ideal plant types regulates and constructs high-yielding plant types for economic forests from the genetic level, while plant type cultivation adopts tree management measures such as shaping and pruning. Breeding new high-yielding plant types with a high utilization-rate of light energy is one research focus for high-yielding plant type construction. Using the apparent motions of the sun and spherical triangle related theories, studying the optimal tree parameters and mathematical models to construct the high-yielding plant types of economic forests is another research focus.

(9) Research and application of formulated aqua-feeds

In established aquaculture, direct feeding with feed ingredients such as grains and trash fish was common. This feeding strategy not only results in waste of feed ingredients but also causes pressure on the rearing environment. Spread of pathogens from trash fish to aquatic animals is also a severe problem. Formulated feeds are pellets which are made with modern machines based on comprehensive knowledge of nutrient requirements of specific aquatic animals. Formulated feeds are easier to transport and store compared to their ingredients. Based on category of processing technology, the formulated feeds mainly include extruded, pelleted, and powder feeds. Production of high-quality formulated feeds relies on deep, comprehensive, and detailed understanding of nutrient requirements of aquatic animals, including the discrepancy in nutrient requirement among different developmental stages, different rearing conditions, and different production systems. The one-sided emphasis of farmers on growth rate of aquatic animals inhibits the wide application of formulated feeds in aquaculture activities. Relevant regulations by government are needed to accelerate the application of formulated feeds. Compared to on-growing stage, formulated feed for larvae and broodstock has been less studied. Cooperative research between nutritional requirement study and processing technology are needed in this area.

2.2 Interpretations for three key engineering development fronts

2.2.1 Intelligent equipment for unmanned farm

Unmanned farms are one of the production systems and realizations for smart agriculture. Unmanned farms are characterized by the following: 1) The system covers the whole production chain of crops, including tillage, planting, field management (water, fertilizer and pesticide), and harvest. 2) Operating machinery can autonomously transfer between fields and garages; namely, the machinery can automatically travel from the garage to the field, and automatically returns after completing the given operations. 3) Operating machinery has the function of obstacle avoidance and emergency-triggered stop; in other words, the machinery can automatically avoid obstacles or stop itself when encountering abnormal conditions. 4) Real-time monitoring on the whole producing process; in detail, real-time monitoring of growth and disease, pests, and weeds during crop production. 5) Decision-making and precision operations are all intelligence-based and unmanned; to be specific, the system can make timely decisions based on the growth of crops and the conditions of diseases, pests, and weeds and automatically perform precision operations, including precision irrigation, precision fertilization, and precision pesticide application.

Unmanned farms depend on the support of biotechnology, intelligent equipment, and information technology. Biotechnology provides unmanned farms with crop cultivars and cultivation modes suitable for mechanized operations. Intelligent equipment is used for intelligent perception, navigation, operation, and management. Information technology offers support on information acquisition, transmission, and processing, as well as navigation, automatic operation, and remote maintenance of agricultural machinery.

Intelligent equipment refers to production equipment with the functions of perception, analysis, reasoning, decision-making, and control. It is the deep integration of advanced manufacturing technology, information technology, and intelligent technology.

Intelligent equipment for unmanned farms is a collective term for intelligent equipment and robots used in the entire process of agricultural production. It adopts new-generation technologies such as the Internet of Things (IoT), fifth generation mobile networks (5G), big data, cloud computing, and AI to form an intelligent system. Through remote intelligent management and control, it realizes full automatic or autonomous control of facilities, intelligent agricultural machinery equipment and agricultural robots, and completes all farm production operations. Sensors, IoT and 5G technologies realize the perception and transmission of farm agricultural production information and interconnect with intelligent equipment; big data and cloud computing technology complete agricultural information storage, analysis, and processing; AI, intelligent equipment, and robotics technology complete intelligent learning, intelligence decision-making, and autonomous and precise operation of equipment and robots.

The cutting-edge technologies of intelligent equipment for unmanned farm mainly include intelligent perception, intelligent navigation, intelligent operation, intelligent management, and system integration. 1) Intelligent perception consists of agricultural sensors, environmental information perception, animal and plant information perception, and intelligent data processing. 2) Intelligent navigation requires technology of high-resolution map construction, route planning, precision positioning in complex environment, path following control, and multi-equipment collaborative operation. 3) Intelligent operations contain precision seeding, variable fertilization, variable pesticide application, and variable irrigation. 4) Intelligent management includes status monitoring, remote operation, maintenance and management of intelligent equipment. 5) System integration includes X-by-wire control technology, chassis communication technology, and agricultural implement communication technology.

In addition, phenotypes of animals and plants, growth optimization and regulation models, and integration of intelligent equipment with advanced planting and agronomy will be important areas for research and development. Through application of unmanned fields, unmanned greenhouses, unmanned orchards, unmanned pastures and unmanned fishing grounds, providing a whole-process unmanned production mode, and intelligent equipment solutions for the cropping, animal production, and aquaculture will attract new attentions as well.

The major patent output countries, output institutions, inter-country cooperation networks, and inter-institution cooperation networks are shown in Tables 2.2.1 and 2.2.2 and Figures 2.2.1 and 2.2.2, respectively. The top two countries for core patent disclosure are China and the United States, while Colombia and South Korea tied in third place (Table 2.2.1). Among them, China is in leading position in terms of the number of patents. The top five patents mainly focus on agricultural machinery intelligent perception, intelligent control, and intelligent navigation, which are the key research directions of intelligent equipment for unmanned farm. There are few cooperation networks between countries, only a small amount of cooperation between Colombia and the United States (Figure 2.2.1).

The top three institutions with the highest number of core patents are Autonomous Solutions Inc., CNH Industrial America LLC, and RowBot Systems LLC (Table 2.2.2), which are all from the United States. However, there is only rare cooperation among these institutions (Figure 2.2.2).

2.2.2 Artificial-intelligence-assisted breeding

AI has brought innovation to a large number of fields, and

Table 2.2.1 Countries with the greatest output of core patents on “intelligent equipment for unmanned farm”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	102	49.51%	218	22.02%	2.14
2	USA	67	32.52%	668	67.47%	9.97
3	Colombia	8	3.88%	76	7.68%	9.50
4	South Korea	8	3.88%	3	0.30%	0.38
5	Russia	6	2.91%	8	0.81%	1.33
6	Japan	5	2.43%	39	3.94%	7.80
7	Netherlands	4	1.94%	17	1.72%	4.25
8	Germany	4	1.94%	10	1.01%	2.50
9	Switzerland	3	1.46%	6	0.61%	2.00
10	Israel	2	0.97%	20	2.02%	10.00

Table 2.2.2 Institutions with the greatest output of core patents on “intelligent equipment for unmanned farm”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Autonomous Solutions Inc.	USA	14	6.80%	39	3.94%	2.79
2	CNH Industrial America LLC	USA	11	5.34%	23	2.32%	2.09
3	RowBot Systems LLC	USA	8	3.88%	86	8.69%	10.75
4	Wuxi Kalman Navigation Technology Co., Ltd.	China	6	2.91%	14	1.41%	2.33
5	Deere and Company	USA	5	2.43%	39	3.94%	7.80
6	AGCO International GmbH	Switzerland	5	2.43%	9	0.91%	1.80
7	Jiangsu University	China	5	2.43%	5	0.51%	1.00
8	AgJunction LLC	USA	4	1.94%	95	9.60%	23.75
9	State Farm Mutual Automobile Insurance Company	USA	4	1.94%	37	3.74%	9.25
10	Kinze Manufacturing Inc.	USA	4	1.94%	34	3.43%	8.50

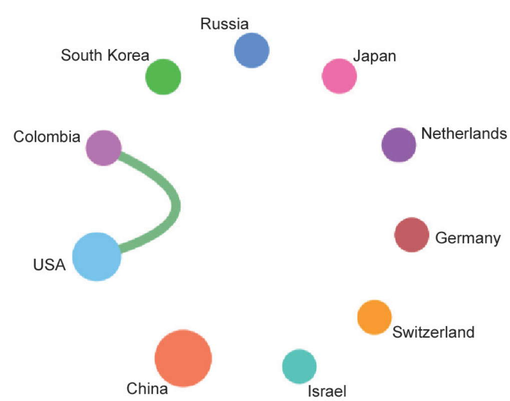

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “intelligent equipment for unmanned farm”

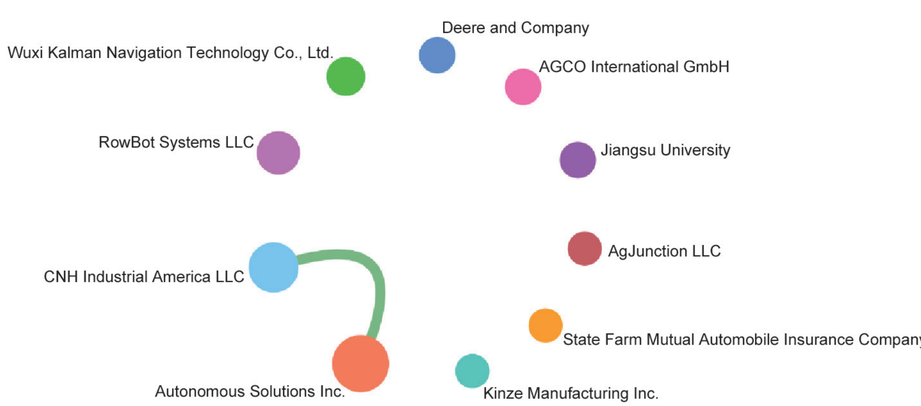

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “intelligent equipment for unmanned farm”

has become an area filled with intense competition. AI refers to theories and methods to extend human intelligence. A key branch of AI is machine learning, which uses computers, rather than human intelligence, to find solutions to problems. In machine learning, the technique that develops fastest is deep learning, which is based on deep neural networks. Currently, AI, especially deep learning, has been applied to animal and plant breeding, in four aspects.

First, identification of functional variants for precision crossbreeding. Numerous genomic variants are present in animal and plant natural populations. However, only a small fraction of them, referred to as functional variants, impact phenotypes. In crossbreeding, favorable alleles are enriched (meanwhile, deleterious alleles are depleted) by crossing and selection, thereby achieving genetic improvement of plants and animals. However, an important question is how to prioritize functional variants impacting phenotypes from huge amounts of genomic variants. Since functional variants impacting terminal traits (such as mRNA and protein abundance, or biochemical activities of proteins) by impacting molecular phenotypes at various levels (such as human disease traits, livestock and poultry quality), deep learning models can be trained to predict molecular phenotypes from genomic sequences, and then use these models to scan genomic variants to identify function variants precisely. Deep learning shows advantages in four aspects: 1) It does not rely on natural populations and therefore reduces the cost compared to association analysis. 2) It prevents the harmful impacts from low minor allele frequencies. 3) It has the ability to identify causal variants among highly linked loci. 4) It facilitates transfer learning between different loci, populations or even species. Deep learning has been widely used to predict functional variants in human diseases, and its utilization in plant and animal breeding has also been developing .

Second, design superior alleles for genome editing. Standard crossbreeding depends on functional variants that occur naturally. However, natural alleles occur at a low frequency and their effects are random. Moreover, favorable alleles are also linked with deleterious alleles. An important question is how can the limitations of natural variants be overcome to rationally design superior alleles for breeding. With the advent of the CRISPR/Cas9 system, it is possible to rationally design functional variants based on breeding goals and then incorporate designed variants into plant and animal genomes by genome editing. However, where to edit and how to edit the genome in order to improve the terminal traits needs to be determined. This will be the key problem in genome editing-based breeding. Deep learning models that predict molecular phenotypes based on biological sequences can solve this problem efficiently as it can efficiently provide guidance to genome editing.

Third, designing novel functional genomic elements for synthetic biology. Currently, generative models in deep learning has been widely applied in synthetic biology. This technique can learn from large amount of biological sequences, thereby gaining the ability to design genomic elements with specific biological functions, such as proteins and cis-elements with desirable biochemical activities. Trait improvement of plants and animals can be achieved by incorporation of such new elements into plant or animal genomes by genome editing. Synthetic biology guided by AI will bring about new ideas and technological innovations to genetic improvement of plants and animals.

Fourth, extraction of phenotypic data from images. Recent years witnessed great advances in high-throughput phenotyping systems. Drones and robots equipped with sensors generate huge amount of image data. Using machine learning, especially deep learning techniques, to extract phenotypic data (such as photosynthetic rate and canopy temperature) is becoming a routine in phenomes.

There have been 56 core patents in this field. The top countries in terms of core patent disclosure volume in this field are China (47) and South Korea (5). The citations per patent in China is 0.32 (Table 2.2.3). Patent output institutions are relatively scattered. Anhui Dongchang Agricultural Technology Co., Ltd. produced two patents and each of the other institutions had one patent. The patent of Xiangchuang Technology Beijing Co., Ltd. was cited most with four times (Table 2.2.4). The majority of patents in this development front come from China and there is no cooperation between countries. Among the top 10 output institutions (Table 2.2.4). There are enterprises and universities but no cooperation exists between these institutions.

2.2.3 Intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs

Agricultural production is becoming more precise and economical. In the future, agricultural production will be

Table 2.2.3 Countries with the greatest output of core patents in the engineering development front of “artificial-intelligence-assisted breeding”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	47	83.93%	15	100%	0.32
2	South Korea	5	8.93%	0	0%	0.00
3	Australia	1	1.79%	0	0%	0.00
4	Germany	1	1.79%	0	0%	0.00
5	India	1	1.79%	0	0%	0.00
6	Japan	1	1.79%	0	0%	0.00

Table 2.2.4 Institutions with the greatest output of core patents in the engineering development front of “artificial-intelligence-assisted breeding”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Anhui Dongchang Agricultrual Technology Co., Ltd.	China	2	3.57%	0	0.00%	0
2	Xiangchuang Technology Beijing Co., Ltd.	China	1	1.79%	4	26.67%	4
3	Yunnan Agricultural University	China	1	1.79%	3	20.00%	3
4	Beijing Aojinda Agricultural Technology Development Co.	China	1	1.79%	1	6.67%	1
5	Cangnan Boya Technology Co., Ltd.	China	1	1.79%	1	6.67%	1
6	Qinghai University	China	1	1.79%	1	6.67%	1
7	Anhui Rays Agricultural Science and Technology Co., Ltd.	China	1	1.79%	0	0.00%	0
8	Asami Agricultural Combination Legal Person	Japan	1	1.79%	0	0.00%	0
9	Beijing Zhongnong Zhiyuan E-Commerce Co.	China	1	1.79%	0	0.00%	0
10	Bigstone House	South Korea	1	1.79%	0	0.00%	0

highly regionalized, integrated, mechanized, and intelligent. Intelligent plant protection machinery and precise application of pesticides has become the main trend for plant protection. Plant protection UAVs acquire the real-time geography information, plant condition, and diseases and pests information from crop canopy. According to meteorological, historical and other information, farmland is divided into several operation areas to make prescription maps for accurately forecasting and monitoring of pests and diseases. With the prescription maps, the precise targeted spraying system can be applied on a precise grid. The research on plant protection UAVs mainly include three parts.

First, farmland image acquisition by remote sensing. The crop information acquisition sensors include digital camera, multispectral camera, hyperspectral camera, thermal imager, and laser radar. Digital cameras can capture red, green, and blue visible light at low cost but low resolution. Multispectral cameras have a spectral resolution of 0.1 mm and can be modified to adapt the characteristic spectrum of diseases and pests, which basically meets the requirements of plant, disease, and pest identification. Commercial products of multispectral cameras have been introduced to agriculture. A hyperspectral sensor measures several to hundreds of bands in visible light and near-infrared region, with a resolution of nanometer level. With rich spectral information and high resolution, it can accurately distinguish the spectral of different crops in the field. Although hyperspectral sensors have many advantages for crop disease and pest monitoring, they are currently only used for research due to high cost. Laser radar is a novel remote sensing technology which can acquire 3D high-precision data. At present, the main application of laser radars in agriculture is to monitor plant height, biomass, and leaf area index. In the future, they could be combined with spectral imaging as a part of multisource remote sensing and analyze pests and diseases of crop comprehensively to improve the accuracy of crop pest and disease identification.

Second, remote sensing image interpreting. Image interpretation refers to the processing, mining, and modeling of remote sensing images in order to identify crops, diseases, pests, and weeds. Interpretation methods include classical statistical analysis and an interpreting method based on pattern recognition and machine learning. The latter method requires fewer samples and lower requirements for device performances and makes the model easier to understand. Deep learning and machine learning are new research directions with two significant features, feature learning, and deep structure, which can improve the classification accuracy of remote sensing images. At present, intelligent identification of crops, pests, and diseases is only at the feasibility stage for specific crops, fields, and diseases. In the future, it needs to be combined with agriculture, plant protection, and pathology to realize large-scale application.

Third, precise variable pesticide application. To realize precision pesticide application to a certain area based on the prescription map, the plant protection UAV needs the support of a variable pesticide application system and precise pesticide application technologies. At present, the variable pesticide application systems are Only experimental. There are two methods for variable application: One is PWM technology for hydraulic atomizing nozzles and the other is to change the speed of liquid pumps and nozzle flow for centrifugal atomizing nozzles. Precision pesticide application technology can make the real-time adjustment of flight trajectory according to wind speed, wind direction, flight altitude, flight speed, droplet size, crop characteristics and other factors to ensure that pesticide droplets can be accurately applied to the designated area.

Plant protection UAV is an emerging approach for plant protection, so the deposition and drift mechanism of drops is not well understood and it will be one of the key areas for research on precision pesticide application technology of plant protection UAVs in the future.

There are 45 core patents related to this development front. The major contribution countries are China (37 patents), the United States (7 patents), and South Korea (1 patent) (Table 2.2.5). The institutions with more patents are all from China, e.g., Guangzhou XAIRCRAFT Technology Co., Ltd., Wuxi Tongchun New Energy Science and Technology, and Zhongkai University of Agriculture and Engineering, while Working Drones Inc. and Elwha LLC from the United States each discloses one patent (Table 2.2.6). The patent of Working Drones Inc. for the navigation and control of drones using mobile terminals has 242 citations, which is the most influential patent for this development front and is one of the most important areas for drone research. Plant protection UAVs are mainly used in China and some applications in Japan and South Korea, but fewer applications in other countries. China is the largest patent output country and fewer patents of plant protection UAVs were published by other countries, so there is no cooperation between countries in this development front. In China, the competition of plant protection UAV market is intense, so there is more competition than cooperation among institutions. In addition, the development of plant protection UAVs involves commercial secrets, so no cooperation among institutions was as expected.

Table 2.2.5 Countries with the greatest output of core patents on “intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	37	82.22%	165	39.38%	4.46
2	USA	7	15.56%	254	60.62%	36.29
3	South Korea	1	2.22%	0	0.00%	0.00

Table 2.2.6 Institutions with the greatest output of core patents on "intelligent identification of plant diseases and pests, and precise targeted application of agrochemicals by plant protection UAVs"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Guangzhou XAIRCRAFT Technology Co., Ltd.	China	5	11.11%	51	12.17%	10.20
2	Wuxi Tongchun New Energy Science and Technology	China	4	8.89%	34	8.11%	8.50
3	Zhongkai University of Agriculture and Engineering	China	3	6.67%	5	1.19%	1.67
4	Beijing Research Center for Information Technology in Agriculture	China	2	4.44%	29	6.92%	14.50
5	Shenzhen Autel Intelligent Technology Co., Ltd.	China	2	4.44%	10	2.39%	5.00
6	Chengdu Youlide New Energy Co., Ltd.	China	2	4.44%	0	0.00%	0.00
7	South China Agricultural University	China	2	4.44%	0	0.00%	0.00
8	Working Drones Inc.	USA	1	2.22%	206	49.16%	206.00
9	Elwha LLC	USA	1	2.22%	25	5.97%	25.00
10	Beijing Expert Aviation-Technology Co., Ltd.	China	1	2.22%	13	3.10%	13.00

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