

A Nine-Step Smart Agriculture Method for Cost Reduction, Yield Increase, and Efficiency Improvement in Grain Production (Postprint)

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Abstract

Food security is a paramount issue in state governance. Since the founding of the People's Republic of China, high-standard farmland construction, agricultural mechanization development, and agricultural technology advancement have all contributed to grain production increase and efficiency enhancement. Under the current situation of strictly adhering to the 1.8 billion mu (120 million hectares) arable land red line, the growth effect of increasing grain yield through heavy reliance on agricultural inputs such as extensive water and fertilizer use has entered a plateau phase, leaving limited room for sustained production increases. Against the backdrop of rapid development of new technologies including informatization, intelligence, Internet of Things, big data, and artificial intelligence, integrating the digital economy with traditional agriculture and developing smart agriculture will constitute a new growth point for grain production increase and efficiency improvement in China. Focusing on the three stages of grain production—pre-production, in-production, and post-production—and targeting the entire process from land preparation to grain storage, this article proposes a “nine-step method” for smart agriculture, namely “two precisions,” “three transformations,” “three reductions,” and “one utilization,” and elaborates on the connotation of each step, the existing technical bottlenecks, and their roles in cost reduction and efficiency enhancement in grain production. Finally, recommendations are proposed for the development of smart agriculture in China regarding big data acquisition, standardization, application, and security.

Full Text

Nine-Step Approach of Smart Agriculture for Cost Reduction, Yield Increase, and Efficiency Improvement in Grain Production

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Abstract

Food security is a paramount concern in national governance. Since the founding of the People's Republic of China, high-standard farmland construction, agricultural mechanization development, and technological advancement have all contributed significantly to grain production increases. However, with China strictly maintaining its 1.8 billion mu (approximately 120 million hectares) arable land red line, the input-intensive approach of heavy irrigation and fertilizer application has reached a plateau, offering limited potential for sustained yield growth. Against the backdrop of rapid development in information technology, intelligence, Internet of Things, big data, and artificial intelligence, integrating the digital economy with traditional agriculture through smart agriculture represents a new growth point for China's grain production enhancement.

Focusing on the three stages of grain production—pre-production, in-production, and post-production—this paper proposes a “Nine-Step Approach” for smart agriculture, comprising “Two Refinements, Three Changes, Three Reductions, and One Use.” For each step, we elaborate on its connotation, existing technical bottlenecks, and its role in reducing costs and increasing efficiency in grain production. Finally, we offer recommendations for developing smart agriculture in China, addressing data acquisition, standardization, application, and security.

Keywords: food security, smart agriculture, agricultural big data, Nine-Step Approach

1. Introduction: Digital Economy and Food Security

The digital economy represents the primary economic form following agricultural and industrial economies. From 2012 to 2021, China's digital economy scale grew from 11 trillion yuan to 45.5 trillion yuan, increasing its share of GDP from 20.4% to 39.8%, becoming a crucial engine for high-quality economic and social development [1]. As President Xi Jinping emphasized in his article “Strengthening, Optimizing, and Expanding China's Digital Economy,” we must promote the integration of digital and real economies, steering industries including agriculture toward digitalization.

Global food security challenges are intensifying. In 2022, approximately 690–780 million people worldwide faced hunger, with nearly 600 million projected to remain chronically undernourished by 2030 [2]. As the world's largest grain importer, China imported 150 million tons of grain in 2022, accounting for 21.4% of its total grain output. This substantial import dependency exposes China to significant risks from international market volatility. For a nation of 1.4 billion people, ensuring that the “Chinese rice bowl” is filled primarily with “Chinese grain” is essential. The CPC Central Committee, with Comrade Xi Jinping at its core, has established a national food security strategy for the new era: “self-reliance, domestic focus, ensured capacity, moderate imports, and technological support.”

While digital technology has revolutionized agricultural product sales and distribution in China, its application in production remains limited to point-based research and small-scale trials. There is a lack of digital technology application throughout the entire agricultural production process. Therefore, a critical challenge is establishing field-level data flows across vast areas, integrating the digital economy with traditional agriculture, and enabling data to generate high value in production—prerequisites for developing smart agriculture and achieving Chinese-style agricultural modernization.

2. Smart Agriculture as the Future of Cost Reduction, Yield Increase, and Efficiency Improvement

Food security forms the foundation of national security. Since 1949, China has made tremendous achievements in grain production, feeding approximately 20% of the world's population with less than 9% of global arable land. Key drivers of yield increases include improved agricultural infrastructure, enhanced material equipment, accelerated scientific and technological progress, and reformed agricultural management systems. Since 1978, China's grain yield per unit area has increased from 167.5 kg/mu (2,527 kg/hectare) to 387 kg/mu (5,805 kg/hectare) in 2021—a 2.3-fold increase. However, chemical fertilizer input increased 5.9-fold and pesticide input increased 4.7-fold during the same period. With fertilizer and pesticide utilization rates at only about 40%, the unabsorbed

portions cause severe environmental pollution. Agricultural water consumption reached 364.43 billion cubic meters, accounting for 61.5% of national water use in 2021.

Analysis of the relationship between grain yield and fertilizer application since 1978 reveals a highly significant correlation ($p < 0.001$). From 1978–2002, grain yield per unit of fertilizer decreased annually, indicating diminishing returns. From 2003–2015, total fertilizer application continued rising while yield per unit fertilizer remained nearly constant, demonstrating that grain yield increases had entered a plateau. Since 2015, following the national “double reduction” strategy, total fertilizer use has declined while yield per unit fertilizer has slowly increased [Figure 1: see original paper]. This demonstrates that China’s fertilizer use is excessive, not only failing to promote sustained yield growth but also causing agricultural non-point source pollution.

Developed regions including the United States, Japan, and Europe pioneered agricultural digitalization, building intelligent ecosystems supported by massive data accumulation. For example, Bayer’s Climate FieldView now serves over 1.3 billion mu globally, helping farmers optimize decisions through massive data collection to maximize productivity while minimizing management intensity and enhancing risk resistance. In contrast, China’s soybean and corn production suffers from low yields and high costs. In 2021, China’s soybean yield (140 kg/mu) was only 61% of the U.S. level (231 kg/mu), with costs 1.3 times higher (781 yuan/mu vs. 593 yuan/mu). China’s corn yield (507 kg/mu) was 69% of the U.S. level (735 kg/mu), with costs 1.5 times higher (1,149 yuan/mu vs. 806 yuan/mu) [3]. This indicates substantial potential for cost reduction and efficiency improvement. Advancing Chinese-style agricultural modernization to reduce costs while increasing yields and efficiency is an unavoidable imperative for healthy, sustainable agricultural development.

3. The Core “Nine-Step Approach” for Smart Agriculture Development

The 2005 No. 1 Central Document first proposed “strengthening agricultural information construction.” Subsequent work on crop growth, planting management, information collection, and quality detection has yielded achievements in agricultural IoT, sensors, and integrated water-fertilizer systems [5], providing foundations for agricultural big data acquisition. The 14th Five-Year Plan explicitly calls for “accelerating smart agriculture development and promoting digital transformation of agricultural production, operation, and management services.” With rural information infrastructure construction, agricultural scale management trends, and technological progress, smart agriculture is developing rapidly in China.

Agricultural production is a complex system influenced by natural environments, biological organisms, and human activities. With limited arable land, increasing

crop yield per unit area is essential. The Ministry of Agriculture and Rural Affairs has prioritized large-area yield improvement as the top priority. Yield fluctuations are affected by climate factors (light, heat, water), soil and terrain, input factors (fertilizer, pesticides), and variety improvement. Analysis of maize yield increases over the past 15 years shows climate factors account for 48% and field management for 39% [4], highlighting the enormous potential of precision management.

Smart agriculture applies information, digitalization, and intelligent technologies to establish agricultural models and algorithms that clarify crop growth patterns and resource requirements (light, temperature, water, fertilizer). It enables intelligent identification of pests and diseases, supporting management decisions on optimal timing and amounts for water, fertilizer, and pesticide application, as well as sowing and harvesting times. This intelligent, precise control of complex agricultural systems enhances the role of field management in yield increases while mitigating climate change impacts, transforming agriculture from “relying on heaven for food” to “knowing heaven to farm.”

We introduce cybernetics concepts into agricultural ecosystems [8] to propose the core “Nine-Step Approach” for smart agriculture: “Two Refinements, Three Changes, Three Reductions, and One Use” [Figure 2: see original paper]. Information technology connects data flows across the entire production chain. Agricultural big data accumulation enables algorithm and model development for decision-making systems, executed by intelligent agricultural machinery that simultaneously collects data, creating a closed data loop. As the system accumulates data, model training becomes increasingly sophisticated, enabling more accurate decisions and unlocking greater yield and efficiency potential.

3.1 “Two Refinements” : Precision Land Preparation and Precision Seeding

(1) Precision Land Preparation. Precise soil tillage is crucial for improving water-fertilizer-pesticide utilization, promoting crop growth, reducing greenhouse gas emissions, and increasing yields [9]. Key technologies include conservation tillage (reducing runoff, increasing organic matter, decreasing evaporation), deep loosening (breaking plow pans, improving permeability and structure), and laser leveling (directly affecting irrigation efficiency). Studies show laser-leveled land saves 21% irrigation water, improves water use efficiency by 19-22%, and increases yields by 5-11% [10]. It also reduces irrigation ditch and ridge area, increasing paddy land utilization by 3-6% [9]. Information technology can provide customized solutions based on soil types and crop germination/growth patterns, enhancing water-fertilizer retention and promoting seed germination.

(2) Precision Seeding. Sowing quality directly affects yield. Uneven spacing causes poor ventilation, uneven nutrition, and disease susceptibility. Advances in seeding machinery enable precision seeding, which requires determining optimal seeding rates, row spacing, and plant spacing. Crop growth models at the

population scale can simulate photosynthetic efficiency under different densities, supporting precision seeding decisions. Precision seeding ensures uniform, robust seedlings with balanced nutrition and development, increasing yields while saving labor and energy costs. For maize, precision seeding saves 2.7-3.0 kg/mu (40-45 kg/hectare) of seeds [13], equivalent to saving 1.72-1.94 million tons nationally based on planting area.

3.2 “Three Changes” : Variable-Rate Water, Fertilizer, and Pesticide Application

Water, fertilizer, and pesticide are essential production materials. Sustainable agriculture requires protecting water resources and the ecological environment. China is among the world’s 13 most water-scarce nations, with agricultural water use reaching 378.13 billion cubic meters in 2022 (63% of national consumption) [12]. China also uses 2.6 times more fertilizer and 2.5 times more pesticide per unit area than world averages. Excessive application increases costs and causes pollution. The Ministry of Agriculture and Rural Affairs issued action plans for zero growth of fertilizer and pesticide use by 2020, achieving 13.8% and 16.8% reductions respectively. New 2025 action plans aim for further reductions without yield loss.

(1) Variable-Rate Irrigation. Uniform irrigation wastes water and energy while reducing efficiency. Excessive irrigation causes runoff and deep percolation, potentially contaminating surface and groundwater. Center-pivot irrigation systems enable variable-rate irrigation, with studies showing water savings of 4-7% [14] and up to 53% in some field trials [15].

(2) Variable-Rate Fertilization. China’s fertilizer utilization rate is about 40%, 10-25% lower than developed countries. Excessive fertilization causes soil compaction and acidification. Variable-rate fertilization technologies include prescription map-based and real-time monitoring approaches, requiring prescription generation, soil fertility information collection, decision systems, and variable-rate applicators [16]. Studies in Northeast China’s black soil region show variable-rate fertilization saves 5-10% fertilizer while increasing maize yield by 6-10% [17].

(3) Variable-Rate Pesticide Application. Rapid pest detection and precise identification are key. Equipment includes ground and aerial sprayers. Aerial plant protection, particularly drones, improves efficiency by 15-35% and reduces costs by about 7 yuan/mu (105 yuan/hectare) [18], enhancing risk resistance. New technologies including high-throughput phenotyping monitoring, deep learning-based pest identification, and gamma spectrometry for soil detection enable intelligent prescription generation. Combined with meteorological data, optimal application timing can be recommended.

3.3 “Three Reductions” : Harvest, Transport, and Storage Loss Reduction

Post-production grain loss is a global issue. In 2021, China co-hosted the International Conference on Food Loss and Waste, where President Xi Jinping noted that reducing grain loss is crucial for food security. The UN FAO defines the Food Loss Index (FLI) as losses from post-harvest to pre-consumption, including transport, storage, and processing. Global FLI is about 13.8%, with cereals and pulses at approximately 8% [19].

China’s three major grain crops (rice, wheat, maize) experience average post-production losses of 7.9%: storage (4.5%, over 50% of total losses), harvest (2.5%), and transport (0.9%) [20]. With 2022 total grain output of 686.53 million tons, losses reached approximately 54.24 million tons—equivalent to the output of 140 million mu.

(1) Harvest Loss Reduction. Losses depend on timing, climate, and methods. Agricultural simulators integrating crop, climate, and soil modules can provide intelligent decisions on optimal harvest timing. Real-time yield monitoring enables timely adjustments. With mechanization rates of 95% for rice, 98% for wheat, and 80% for maize [21], improving intelligent combine harvesters, standardizing operations, and training operators can reduce losses [22].

(2) Transport Loss Reduction. Losses include weight reduction and quality degradation from packaging damage, improper handling, rain exposure, and temperature control issues. Automated environmental monitoring, intelligent regulation, and full-process weight supervision can reduce transport losses [23].

(3) Storage Loss Reduction. Losses depend heavily on drying and storage infrastructure. Information management systems for collection-transport-storage and intelligent environmental monitoring can reduce losses. Studies show that combined harvesters, bulk container transport, mechanized drying, and modern grain reserves can reduce post-production losses below 4% [20], equivalent to creating “invisible farmland” of 70 million mu.

3.4 “One Use” : Straw Utilization

Straw, like grain, is a photosynthetic product requiring water and soil resources, accounting for over 50% of above-ground biomass. It is a valuable biomass resource crucial for green, high-quality agricultural development. China’s straw resources total approximately 770 million tons [24], exceeding total grain output. Utilization includes fertilizer, feed, energy, substrate, and raw material applications. In 2021, comprehensive utilization reached 647 million tons (88.1% utilization rate), with 62% returned to fields, 20% used as feed, and 9% for energy [25]. However, incomplete decomposition can affect subsequent crops. Enhanced R&D can diversify and increase the value of straw utilization.

4. Recommendations for Smart Agriculture Development in China

Smart agriculture is built on big data—massive, multi-dimensional, multi-format information characterized by large volume, rapid flow, diverse types, and low value density. Only by combining big data with AI through deep learning and reinforcement learning algorithms can its value be realized. This requires integrating data acquisition, transmission, storage, processing, algorithm development, and model building. We recommend strengthening four key areas:

4.1. Develop and Apply Intelligent Agricultural Machinery as “Data Crawlers”

With 1.8 billion mu of arable land, rapid, low-cost acquisition of comprehensive, dynamic, field-level data is challenging. Since agricultural machinery participates in all production stages, equipping it as data collection platforms enables precise field-level data acquisition throughout the process. Advanced intelligent machinery can carry sensors for soil, crop growth, pests, environment, and operational parameters. China has over 4,000 types of agricultural machinery with total power of 1.078 billion kilowatts and comprehensive mechanization rates of 72% overall and 97.3%, 85.6%, and 90% for wheat, rice, and maize respectively [26], providing a foundation for data collection.

However, China still relies heavily on imported high-end machinery, with domestically developed sensors accounting for less than 10% of the global market. We must accelerate development of a third-generation agricultural machinery innovation system, integrating information technology with agricultural production across “devices, networks, clouds, data, and applications” to enable data acquisition, 3D communication, big data mining, and automated operations [26]. Future intelligent machinery will serve as “data crawlers,” collecting data during operations.

4.2. Establish Agricultural Data Collection Standards to Break “Data Silos”

Data on water, soil, climate, and biology exist in different formats and sources, creating multi-source heterogeneous data that cannot be directly integrated. We should establish a common agricultural big data platform to aggregate regional information and break “data silos.” Specific actions include: - Developing low-cost communication systems and integrated sky-ground-space communication terminals; - Creating data storage and cleaning platforms using distributed storage and database technologies to build national agricultural big data computing centers; - Establishing data collection standards for the entire production process to ensure comparability, compatibility, integrability, and consistency [27].

4.3. Develop Agricultural Simulators to Build Smart Decision Systems

The core of agricultural big data is data mining, which must combine with AI to create value. Sun et al. [28] proposed the concept of an agricultural simulator that integrates “numerical + data + intelligent” technologies into an online iterative system—the fifth paradigm of scientific research. The simulator follows the Observe-Orient-Decide-Act (OODA) loop, applicable to smart agriculture. Multi-source heterogeneous data is analyzed in information space, establishing relationships between data and models to create closed-loop feedback systems. This overcomes limitations of isolated, linear, and lagging agricultural models, enabling rapid iteration and more accurate, timely decision-making to replace traditional expert-based systems.

4.4. Ensure Agricultural Data Security

Data security is critical to national security and economic development, with agricultural data security being integral to food security. China’s Data Security Law took effect on September 1, 2021. As former U.S. Secretary of State Henry Kissinger noted, “Who controls the food supply controls the people.” The U.S., as the world’s largest grain exporter, has long used food as a strategic weapon [29]. With climate change, political conflicts, and economic instability making global food systems more vulnerable—9% of the world’s population faced severe food insecurity in 2022 [2]—strengthening agricultural data security is imperative.

Currently, most high-end agricultural machinery and advanced sensors are imported, creating significant data leakage risks. Therefore, we must: (1) accelerate R&D of proprietary high-end intelligent agricultural machinery and sensors to replace imports; and (2) establish management systems and standards for data collection, transmission, storage, and access to strengthen data governance and prevent leakage, ensuring food security remains firmly in our control.

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