Ecological Three-Dimensional Cultivation and Digital Development Model of Xinjiashan Specialty Coffee Base

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Abstract Under the strategic framework of rural revitalization and agricultural modernization, Xinjiashan Specialty Coffee Base, located in Zaotang Village, Lujiang Town, Longyang District, Baoshan City, has been proactively investigating innovative models for agricultural development. Through extensive communication and collaboration, this base has established close partnerships with research institutions including Kunming University of Science and Technology, Baoshan University, and Yunnan Academy of Agricultural Sciences, with a commitment to thoroughly exploring the potential for resource recycling and ecological complementarity. An innovative four-in-one three-dimensional integrated planting system incorporating "coffee, bananas, green manure, and bees" has been implemented. Concurrently, technological and digital management strategies have been comprehensively integrated to improve planting efficiency. Under this model, the proportion of specialty coffee attains 71%, and the per-unit yield is 17% greater than that of the conventional planting model. This approach not only substantially enhances economic returns but also promotes the integrated development of ecological and social benefits, offering a valuable practical example and experiential reference for the specialty and sustainable advancement of the coffee industry in comparable regions.

Key words Coffee, Three-dimensional planting, Digitalization, Ecological cycle, Xinjiashan

1 Introduction

Within the domain of plateau characteristic agriculture in Baoshan City, the coffee industry chain occupies a central role and has significantly contributed to enhancing farmers' incomes and fostering local economic development. Nevertheless, the conventional coffee cultivation model faces challenges including low resource utilization efficiency, considerable ecological and environmental pressures, and limited product added value[1]. Xinjiashan Specialty Coffee Base, situated in Zaotang Village, Lujiang Town, Longyang District, Baoshan City, benefits from a distinctive dry and hot river valley climate characterized by significant diurnal temperature variation and fertile soil. These natural conditions are highly conducive to coffee cultivation. Since 2020, Lushan Yunshu Agricultural Development Co., Ltd. has leveraged these unique resource advantages to establish a coffee cultivation base spanning 113.33 hm^2[2], actively pursuing a green development strategy. During its development, the base has effectively utilized its geographical advantages to establish long-term and stable collaborative relationships with scientific research institutions, including Kunming University of Science and Technology, Baoshan University, and Yunnan Academy of Agricultural Sciences. By capitalizing on the technological expertise and human resources of these universities and research institutions, the base has actively pursued scientific and digital planting methods, progressively creating a distinctive and highly advantageous development path. Through the comprehensive integration of industry, academia, and research, this base has successfully established an innovative model that combines ecological three-dimensional planting with digital management techniques. This approach effectively addresses the challenges inherent in traditional planting processes and facilitates the advancement of the coffee industry toward high-quality development[3]. This article presents a detailed analysis of the development model employed by this base, aiming to offer valuable insights for the advancement of the coffee industry in comparable regions.

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2 Main practices

2.1 Establishment of a green circular system through three-dimensional planting

2.1.1 Three-dimensional layout of crops. Xinjiashan Specialty Coffee Base has departed from the conventional monoculture approach by designating coffee trees as the primary crop and interplanting banana trees between the coffee rows to establish a natural shade canopy. The tall stature of the banana trees effectively mitigates intense sunlight, thereby creating an optimal growth environment for shade-tolerant coffee trees and alleviating the stress caused by high temperatures and strong light exposure[4]. In the interridge areas, green manure crops, such as alfalfa, are cultivated to optimize land utilization and enhance vegetation coverage. Additionally, beekeeping is practiced along the periphery of the coffee plantation, creating a three-dimensional planting system that integrates tall plants for shading, shorter plants to improve efficiency, and biological synergy. Regarding planting density, coffee plants are systematically planted with a spacing of 1.6 m × 2.0 m, resulting in a planting density of 1 950 - 2 400 plants/hm^2. Intercropping is implemented by planting one banana plant for every 4 - 6 coffee plants. The initial banana planting density is 600

plants/hm^2, which increases to a stabilized density of 900 – 1 200 plants/hm^2 as the banana trees mature. This planting arrangement not only meets the respective light, water, and nutrient requirements of different crops but also facilitates the stratified and efficient utilization of light and thermal resources.

2.1.2 Synergy of ecological functions. (i) Green manure for carbon sequestration and soil improvement. Green manure crops, such as alfalfa, exhibit significant ecological functions throughout their growth cycle. Due to its nitrogen-fixing capability, alfalfa can fix 120 – 150 kg/hm^2 of nitrogen annually, thereby substantially enhancing the nitrogen content of the soil. As these green manure crops grow, mature, and are incorporated back into the field, they contribute a considerable amount of organic matter to the soil, increasing the soil organic matter content to 2.5%, which is 0.8% higher than that observed under traditional planting systems. The high content of organic matter in the soil not only improves soil structure by rendering the texture looser and more aerated but also substantially enhances the soil's water retention capacity, increasing its efficiency by 20% compared to previous levels. These improvements create optimal conditions for the development of coffee tree roots, thereby promoting healthy growth in coffee plants.

(ii) Bee pollination. Beekeeping adjacent to coffee plantations has resulted in a mutually beneficial outcome, yielding both economic and ecological advantages. Specifically, bees gather nectar from coffee blossoms to produce high-quality coffee flower honey, generating an additional income of approximately 9 000 yuan/hm^2 annually. Besides, during pollen collection, bees facilitate the pollination of coffee flowers, significantly enhancing the fruit set rate of the coffee plants. Data indicate that following bee pollination, the coffee fruit set rate significantly increased from 75% under traditional monoculture practices to 92%, representing a 17% rise[5]. Additionally, bee pollination prolongs the coffee fruiting period, resulting in more uniform fruit ripening and establishing a robust basis for enhancing both the quality and yield of coffee.

(iii) Banana shade regulation. During the hot summer, banana leaves effectively shield coffee trees from intense direct sunlight, thereby reducing the ambient temperature and mitigating heat stress on the coffee plants. Furthermore, the combined presence of banana trees and green manure crops contributes to the establishment of a relatively stable microclimate, which decreases water evaporation and helps maintain soil moisture. This micro-environment is conducive to the growth of coffee trees, promoting photosynthesis and nutrient accumulation, and ultimately enhancing the quality of coffee fruits.

2.2 Technology-empowered smart agricultural management

2.2.1 Implementing integrated water and fertilizer management. Xinjiashan Specialty Coffee Base has implemented an advanced integrated water and fertilizer management system to optimize the utilization of water resources and fertilizers. This system combines drip irrigation infrastructure with soil sensors, enabling real-time and precise monitoring of soil moisture and nutrient levels. When the soil moisture content falls below a predetermined critical threshold, the automated system activates the drip irrigation mechanism and administers water according to specified volumes and scheduled intervals. This approach effectively reduces unnecessary water wastage and mitigates the incidence of root diseases and pests associated with over-irrigation, resulting in a 30% water savings. Based on the feedback data obtained from the soil nutrient sensor, the system can accurately estimate the required proportions of various fertilizers for coffee trees throughout their growth stages. Subsequently, utilizing the drip irrigation system, the prepared fertilizer solution is uniformly distributed around the roots of the coffee trees, thereby achieving precise fertilization. Compared to conventional fertilization methods, annual fertilizer consumption is reduced by 50%, thereby decreasing economic costs and mitigating the adverse environmental effects of chemical fertilizers. This approach promotes a sustainable and highly efficient agricultural model. Furthermore, the implementation of an integrated water and fertilizer system has optimized the growth cycle of coffee trees, reducing the time to initial fruiting to two years and achieving full yield within three years. This represents a one-year advancement compared to traditional planting methods, significantly enhancing economic returns.

2.2.2 Implementing intelligent unmanned aerial vehicle (UAV) operations. (i) Material transportation and plant protection. The base is situated in a mountainous region, where the complex terrain poses substantial challenges to the transportation of materials and the execution of agricultural activities. In this context, UAV technology has proven to be highly effective. UAVs can efficiently lift and transport bananas, fresh coffee fruits, fertilizers, and other materials, delivering them swiftly and precisely to designated locations. This capability significantly enhances transportation efficiency and reduces labor costs. UAVs, equipped with precise flight control and spraying systems, enable uniform pesticide application on crop surfaces. This technology mitigates issues commonly associated with manual spraying, such as missed areas and excessive application. Therefore, UAVs improve the efficacy of pesticide use, decrease the quantity of pesticides required, and reduce environmental pollution. Statistical data indicate that employing UAVs in mountainous agricultural operations has enhanced efficiency by 50% and lowered labor costs by 30%.

(ii) Growth monitoring. The ultra-fine imaging system and multi-spectral sensing device installed on the aircraft effectively captured the normalized difference vegetation index (NDVI) data of coffee and banana plants. By analyzing these data, technicians can dynamically evaluate the health, growth status, and yield estimates of the plants. For example, when the NDVI value of coffee trees in a specific area is observed to be abnormally low, technicians can promptly infer the presence of issues such as pest infestations, diseases, water shortages, or nutrient deficiencies. Con-

sequently, they can implement appropriate measures to address these problems, thereby providing scientific and precise data to support agricultural decision-making.

2.2.3 Achieving Internet of Things (IoT) digital management. Xinjiashan Specialty Coffee Base has developed a comprehensive IoT platform to facilitate refined and intelligent planting management. Utilizing the Agricultural Management Platform mobile application, the base systematically records and digitally stores detailed data throughout the coffee cultivation process. This data encompasses planting dates, fertilization history, irrigation conditions, and pest and disease control measures, thereby enabling thorough tracking and monitoring of the entire planting process. Meanwhile, the base has installed soil sensors, meteorological monitoring instruments, and other equipment. These devices are capable of collecting critical data in real time, including soil moisture, temperature, pH, air temperature, illuminance, and carbon dioxide concentration. The collected data are transmitted to mobile phone applications and data centers via wireless networks. All data operate in coordination with the AI platform, which is capable of conducting real-time analysis and processing. Upon detecting abnormal conditions, such as low soil moisture, excessively high temperatures, or indications of pest and disease risks, the system promptly issues alerts and automatically generates intelligent fertilizer allocation plans based on predefined rules. This guidance enables farmers to perform precise agricultural operations. Through IoT digital management, the agricultural base has achieved comprehensive intelligence throughout the entire process, from planting to management, thereby significantly enhancing management efficiency and the scientific rigor of decision-making.

3 Major achievements

3.1 Diversified income growth and cost optimization

3.1.1 Increase in comprehensive income. Under the integrated cultivation model, the annual comprehensive output value ranges from 249 000 to 309 000 yuan/hm^2, representing an increase of up to 50% compared to monoculture coffee cultivation. Fresh coffee cherries constitute the primary source of income, with an output value between 180 000 and 240 000 yuan/hm^2. Banana production can reach 22.5 t/hm^2, which, based on current market prices, corresponds to an output value of 54 000 yuan/hm^2. In addition to their ecological benefits, such as carbon sequestration and soil improvement, green manure crops also provide certain feed value. Furthermore, honey produced as a by-product of beekeeping contributes to the overall income, with these two sources collectively generating approximately 15 000 yuan/hm^2 annually. The diversification of income sources not only enhances the economic returns of the cultivation base but also improves its resilience against market fluctuations.

3.1.2 Significant decrease in cost. Regarding cost control, the three-dimensional integrated model exhibits significant advantages. The natural shading provided by banana trees effectively replaces traditional artificial shading nets, resulting in an annual cost saving of 7 500 yuan/hm^2 for the purchase and installation of shading nets. Additionally, the cultivation and incorporation of green manure crops into the soil have substantially reduced the reliance on chemical fertilizers. Statistical data indicate a 20% reduction in chemical fertilizer usage compared to previous practices, leading to an annual saving of 3 000 yuan/hm^2 in fertilizer expenses. Consequently, the total annual cost has been reduced by 10 500 yuan/hm^2, thereby further improving the profitability of the agricultural base.

3.2 Remarkable achievements in connecting and benefiting farmers During its development, Xinjiashan Specialty Coffee Base has actively fulfilled its social responsibilities and contributed to the economic prosperity of surrounding farmers through various initiatives, thereby achieving significant social benefits. The base annually pays 800 000 yuan in land transfer fees, benefiting 281 households. On average, each household's annual income increases by 2 850 yuan, effectively enhancing the farmers' property income. Additionally, the base recruits over 10 000 workers each year during its production and operations, disbursing a total of 1.2 million yuan in wages. This has generated substantial employment opportunities for local farmers and increased their wage earnings. The expansion of the base not only served as an exemplary model but also encouraged surrounding farmers to participate in coffee cultivation, encompassing a total area of 466.7 hm^2. This initiative benefited over 500 rural households, resulting in an average annual income increase of 2 500 yuan per household and generating a total economic benefit of 1.25 million yuan for the local region. Through industrial promotion, this effort has not only facilitated large-scale development of the local coffee industry but also provided significant momentum for rural revitalization.

4 Recommendations

4.1 Expanding three-dimensional planting model To further improve land use efficiency and economic returns, Xinjiashan Specialty Coffee Base has developed strategic approaches and is actively investigating the advanced development of a three-dimensional integrated planting system. Moving forward, the integrated model involving coffee and economic crops such as traditional Chinese medicinal plants and edible fungi will be continuously explored. In addition, planting arrangements and management practices will be optimized according to the growth characteristics and ecological requirements of various crops to establish diversified ecological agricultural solutions. Implementing a diversified and integrated planting system that addresses farmers' varied requirements for multiple integrated farming techniques can enhance the total income derived from agricultural production and broaden the range of agricultural products, thereby improving their market competitiveness.

4.2 Upgrading digital agricultural infrastructure Building upon the current digital management framework, the base will un-

dertake a comprehensive upgrade to modern facility agriculture and smart agriculture. This transition will advance from the present stage of data visualization to intelligent decision-making management by incorporating advanced AI predictive models, including production estimation and climate adaptability analysis models. By analyzing extensive historical and real-time monitoring data, the changing trends in coffee production and quality, as well as the impact of climate change on coffee cultivation, are predicted, enabling the formulation of proactive response strategies. Furthermore, through the continued optimization of intelligent equipment and systems, the development of facility agriculture is advanced toward an "automated management" model. This approach aims to enhance the level of automation and intelligence in agricultural production processes, reduce human resource input, and consequently improve production efficiency and management precision.

4.3 Establishing a training service system To cultivate multidisciplinary talents capable of meeting the developmental demands of modern agriculture, the base intends to establish a training center focused on "ecological agriculture integrated with digital technology". A variety of training programs have been developed to address the needs of diverse target groups. For farmers, practical courses such as ecological three-dimensional planting techniques and digital agricultural management are offered to enhance their cultivation skills and management competencies. For primary and secondary school students, labor class study tours are designed to foster labor awareness and ecological protection concepts through activities such as coffee planting experiences and ecological science popularization. For universities and research institutions, practical training platforms are established to provide hands-on opportunities for researchers, promote the comprehensive integration of industry, academia, and research, and cultivate advanced agricultural research professionals. By creating a comprehensive training service system, the initiative aims to provide robust talent support for the sustainable development of the coffee industry.

4.4 Developing an integrated complex for industry, academia, research, and tourism

4.4.1 Scientific research and innovation. A leading domestic coffee research and innovation platform has been established in collaboration with universities and research institutions, focusing on the development of new technologies for coffee cultivation and processing, as well as the breeding of novel varieties. Investment in scientific research has been increased, and exceptional scientific talents have been attracted. Key technical challenges in the coffee industry are addressed through cooperation of industry, academia and research. Within 5 years, the proportion of high-quality coffee produced in the designated area is projected to exceed 80%, thereby enhancing the intrinsic quality and added value of coffee products and reinforcing the core competitive advantage of the industry's value chain.

4.4.2 Talent cultivation. Relying on scientific research and innovation platforms, as well as training bases, a talent development cradle for the coffee industry has been established. A systematic talent cultivation plan has been formulated with the objective of training over 200 professionals annually in areas such as coffee planting, processing, and tasting. This initiative aims to create a robust talent pool to support the sustainable development of the coffee industry. Through the organization of academic discussions and vocational skills training courses, the continuous enhancement of professionals' knowledge and operational skills is promoted, thereby contributing high-quality talent resources to the coffee industry.

4.4.3 Integration of culture and tourism. The cultural significance of coffee is thoroughly examined, and the coffee industry is seamlessly integrated with the tourism industry. A diverse range of coffee culture experience activities has been developed, including coffee picking, coffee roasting workshops, and coffee tasting courses. Additionally, coffee-themed homestays, cafés, and coffee culture exhibition halls have been established to create a distinctive coffee tourism destination. By promoting the integration of "coffee and rural tourism", it is possible to attract a greater number of tourists, increase local tourism revenue, and simultaneously enhance the living standards and well-being of local residents. This approach fosters a positive synergy between industrial integration and rural revitalization.

5 Conclusions

Xinjiashan Specialty Coffee Base has significantly improved land productivity, increased farmers' incomes, and enhanced the ecological environment by integrating ecological planting models with digital technologies, thus achieving multifaceted value enhancement objectives. Its innovative development model not only addresses many challenges associated with traditional coffee cultivation but also offers a replicable and scalable example for the high-quality development of the coffee industry in tropical regions. In the future development trajectory, the gradual implementation of the three-dimensional cultivation model, ongoing enhancements in digital agricultural infrastructure, continuous improvements in training and service systems, and the progressive integration of industry, academia, research, and tourism are expected to enable Xinjiashan Specialty Coffee Base to play a more significant role in promoting the sustainable development of the coffee industry and supporting rural revitalization. Consequently, it will contribute substantial practical achievements to the accelerated realization of the Baoshan World Coffee Valley construction plan.

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Furthermore, longstanding issues such as inadequate road infrastructure and limited water sources in certain forested areas hinder the early detection and prevention of fires once they have started.

In the future, the management area can further optimize the intelligent sentry system by attempting to integrate it into the scenic area's big data center and exploring its compatibility with UAVs and other security systems. This approach aims to enhance the system's intelligence in forest fire prevention as well as its comprehensive prevention and control capabilities. Additionally, efforts will be made to overcome the limitations associated with monitoring a single type of disaster. Building upon the existing hardware infrastructure, system architecture, and early warning procedures, the system will be advanced toward a "Smart Forest and Grassland Resources Supervision Platform". This platform will integrate forest fire early warning, ecological environment monitoring, and pest and disease control, thereby establishing a robust safety defense mechanism to support the sustainable development of the Mount Tai Scenic Area.

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