Article

Cost Comparison between Digital Management and Traditional Management of Cotton Fields—Evidence from Cotton Fields in Xinjiang, China

Lantong Shao 1, Jiaqin Gong 2, Wenqing Fan 2, Zongyi Zhang 3,* and Meng Zhang 1,*

1 Nanjing Institute of Agricultural Mechanization, Ministry of Agricultural and Rural Affairs, Nanjing 210014, China; 82101205433@caas.cn
2 XAG, Guangzhou 510000, China; justin@xa.com (J.G.); 15524329398@163.com (W.F.)
3 China Institute for Agricultural Equipment Industry Development, Jiangsu University, Zhenjiang 212013, China
* Correspondence: 1000005613@ujs.edu.cn (Z.Z.); zhangmeng@caas.cn (M.Z.)

Abstract: Cotton, as an important cash crop and strategic material, is widely planted in Xinjiang, China. In the traditional way, the management of the cotton field is extensive and the cost is huge. This paper analyzed the economic benefits and the related influence factors of cotton field management digitalization by collecting costs from 2020 of four major tasks in field management in Xinjiang, China. These four main tasks included field scouting, plant protection, topping and irrigation. By analyzing the intersection of the average cost curves of each major task in field management, we obtained the critical size of digital agriculture replacing traditional agriculture. Then, we used sensitivity analysis to find the main factors affecting the promotion and application of digital agricultural equipment. The results show: (1) at a certain critical size, the use of digital agricultural equipment can reduce the cost of production compared to traditional agriculture. However, the critical size varies for different management segments. (2) Fixed equipment costs, labor costs, water costs and energy costs have a large impact on the critical size. On large-scale cotton farms, digital agriculture tends to be more economical than traditional agriculture. In the future, as the cost of fixed equipment decreases, and labor costs and water costs rise, the critical size of digital agriculture replacing traditional agriculture will get smaller, and the scope of the economic benefits of digital cotton field management will increase further.

Keywords: technological progress in agriculture; digital agriculture; cotton field; cost analysis; sensitivity analysis

1. Introduction

Cotton is the most significant cash crop and the backbone of the global textile industry [1]. China is the most important consumer and producer of cotton in the world [2,3]. Cotton is not only the main commercial crop but also an important strategic material. Cotton plays a vital role in the development of the national economy. The cotton region of Xinjiang was the first major cotton-producing area in China [4]. The cotton sowing area was 2,540,500 ha in 2019, accounting for 76.07% of the national planting area [5]. Cotton planting is beneficial to the development of the local economy and farmers’ income, in Xinjiang. At the same time, Xinjiang cotton has played an important role in protecting the stability of the international cotton textile supply chain. China has always attached great importance to the development of the cotton industry and the interests of cotton farmers in Xinjiang. In 2014, China launched the target price policy of cotton and considered the reform undertaken in Xinjiang as a pilot. We are increasingly aware of the urgent need to promote the cotton industry in developing high-quality, high-yielding and efficient processes in line with the current economic and social situation.
In recent years, the cost of cotton production has been increasing. In 2018, the cost of cotton production in China was 3.4 times that of the United States and 4.3 times that of India. Among the cotton production costs [6], the labor cost was the highest, which is rising at an average annual growth rate of 7.9%, accounting for 55.9% of the total cost, followed by service costs and the cost of agricultural materials, such as chemical fertilizers and pesticides, accounting for 31.2% of the total cost [7]. The “China Agricultural Products Cost-Benefit Compilation of Information” showed that, in 2018, the labor cost of cotton production in Xinjiang was 13,950 CNY per ha, accounting for 50.6% of the production costs. Therefore, how to effectively reduce the cost of cotton cultivation, to improve the profitability of cotton farmers and the international competitiveness of cotton, is one of the outstanding issues that needs to be addressed. Hou et al. [8] found that improving agricultural mechanization, reducing labor costs, and taking technical measures to save on water and fertilizer costs helped to reduce cotton production costs and increase farmers’ returns. However, the “China Agricultural Mechanization Yearbook” showed the production of cotton in China in 2020, where the mechanized plowing rate was 98.76%, the mechanized sowing rate was 88.16% and the mechanized harvesting rate was 60.08%. In the production of cotton in Xinjiang, the mechanized plowing rate was 99.91%, the mechanized sowing rate was 99.34% and the mechanized harvesting rate was 75.58%. In the case of cotton planting, harvesting mechanization has reached a high level and we must continue to reduce costs, not only from the dimension of mechanization, but also from the dimension of information technology and intelligence, to save costs and improve efficiency [9]. Cotton has a long growth cycle and is greatly affected by natural factors [10]. Its management process is relatively complex; therefore, the management link of the cotton field has always been at a low level of mechanization and intelligence in China [11]. At present, high labor costs are required for the cotton field management process, particularly field scouting, plant protection, topping and irrigation [12]. In terms of water and fertilizer irrigation, this has mainly relied on the experience of farmers. This not only led to poor farming results but has also caused a lot of wasted water, fertilizer and pesticides [13–16]. Therefore, we should improve the level of information technology and intelligence in cotton fields as it is conducive to promoting the quality and efficiency of the cotton industry in Xinjiang and the international competitiveness of Xinjiang cotton.

With the advent of the 5G era, the development of the Internet of Things, big data and artificial intelligence has brought a new definition to agriculture. Tang et al. [17] proposed that the framework of digital agriculture was composed of basic information databases of agriculture, real-time information collecting systems, digital network transmission systems, central processing systems and digitized agricultural machinery. We can collect agricultural data through field sensors, agricultural drones and smart agriculture decision systems. Data-based farm management decisions effectively have improved economic and environmental benefits [18–21]. Farmers can also access new information through the internet to change traditional agricultural operations. For example, early warning of pests and diseases [14] and improved efficiency of fertilizer [22] have been achieved through diversified information.

In the case of cotton production, Chen et al. [23] proposed to improve the mechanization, precision and intelligence of the cotton field management through the development of digital agriculture. He argued that this could help reduce the cost of cotton production and increase the profitability of farmers. Jamil et al. [24] found that it was important to achieve climate resilient agriculture (CRA) through digital technologies in the cotton production process to help improve cotton productivity and sustainability. Meanwhile, a study found that, in the practice of cotton production in Xinjiang, application of Beidou satellite navigation technology effectively improved automation in the cotton production process. This had good economic, social and ecological benefits for cotton production [25]. In addition, the application of digital agriculture technology has allowed farmers to minimize the costs and maximize the benefits of cotton management using a minimum number of managers.
It could be seen that digital management is an important way to achieve “cost reduction and efficiency gains” in modern cotton fields.

The digitalization of agricultural production not only reduced farmers’ costs but also promoted farmers’ economic efficiency [26,27]. As with many mechanical technologies, the economic benefits of applying digital technologies on large farms seems to be the greatest [28]. However, the fact is that not all farmers would reduce their operating costs through digital agriculture. Wang et al. [29] showed that land size affected the decision to innovate in cotton production. Because of the difference in the size of operation, farmers would make different cotton field management decisions from a cost–benefit perspective. The following questions therefore remain: What is the critical size for digital management compared to traditional management? What are the factors that have a crucial impact on the critical size of digital management instead of traditional management? In this paper, through cost–benefit analysis and sensitivity analysis, cotton fields A, B and X are used as examples to address the above questions.

2. Methods and Data

Cost–benefit analysis is an analogy of financial analysis in a business; it also assesses social benefits and costs, which have an effect on agriculture [30]. There are some researchers who have conducted a cost–benefit analysis of agricultural production. The cost side of the analysis contained investment costs (purchase and installation of equipment, consultations associated with the implementation of technology) and operating costs (labor, agricultural materials, maintenance) [31–33]. Verlicchi et al. evaluated the technical and economic feasibility of the corresponding construction, operational and maintenance costs of a treatment train for zootechnical farm wastewater by means of a cost–benefit analysis [34]. Meanwhile, Erdal et al. found that the highest energy costs of sugar beet production were labor, land renting, depreciation and fertilizer [35]. Some studies also conducted a sensitivity analysis to further illustrate the impact of each factor on cost. Coppola et al. studied that the economic profitability of hazelnut production in central Italy, where conventional and organic farming systems were evaluated using the cost–benefit analysis and sensitivity analysis methodology [36]. Current problems in cotton field management are often used as a pilot study for new methods and technologies. There remains the management cost aspects of cotton fields, about which relatively little is researched. Therefore, this paper uses a cost–benefit analysis and sensitivity analysis to compare the cost of different cotton field management methods.

2.1. Methods

2.1.1. Cost–Benefit Analysis

Cost–benefit analysis is a method to analyze and judge the implementation effect of decision-making [37] and evaluate the value of a project according to the relationship between benefit and cost. Under the same conditions of “cultivation and harvest”, we analyzed the advantages of different management methods for the cotton fields from the perspective of economics. Assuming that the output (income) of cotton is the same, we compared the input (cost) of different technologies in cotton management. In this paper, we studied the cost advantages of digital agriculture based on modern equipment instead of traditional agriculture based on human operation.

Firstly, the cost of different management methods for the cotton fields should be calculated. According to the nature of cost, it can be divided into fixed costs and variable costs. In terms of each management link of the cotton field, the fixed costs include the investment of fixed equipment. The variable costs include the investment of labor, water, electricity, fertilizer, purchasing agricultural machinery services and the costs associated with a supporting software system (theoretically, the supporting software system is a fixed input, but the wisdom of the cotton field system development industry leader X developed smart agriculture systems, for example, based on the billing method for small- and medium-sized farms, including the first year fixed costs and variable costs; renewal
years only include variable costs. At the same time, the supporting software system service costs are converted into the 2 links of field scouting and irrigation according to the variable cost calculation.) [29]. Therefore, the total cost ($C_T$) of cotton field management is:

$$C_T(S) = C_f + nSC_v$$

(1)

where $C_f$ represents fixed costs under cotton field management (CNY/year); $C_v$ represents variable costs under cotton field management (CNY/(ha. time)); among them, the variable costs refer to the investment of labor, water, electricity, fertilizer, purchasing agricultural machinery services and the costs associated with a supporting software system; $n$ represents the number of annual operations (time/year); $S$ represents the cotton field size (ha).

$$C_f = \frac{(E + R)}{T}$$

(2)

where $E$ represents the purchasing price of equipment (CNY/unit); $R$ represents the total maintenance cost within the service life of the equipment (CNY/unit); $T$ represents the service life of equipment (year); $N$ represents the number of pieces of equipment required in the cotton field (unit).

$$N = \left\lfloor \frac{S}{fT} \right\rfloor$$

(3)

where $f$ represents work efficiency (ha/(unit. day)); $t$ represents the optimal operation time (day).

$$C_A(S) = \frac{C_T(S)}{S}$$

(4)

where $C_A$ represents average cost per unit area.

$$S^* = \frac{C_{f,i} - C_{f,j}}{n(C_{v,j} - C_{v,i})}$$

(5)

where $S^*$ represents the critical planting size of two technologies or equipment adoption (ha/year) (that is, it is more economical to choose equipment $i$ operation in a scale smaller than $S^*$, and it is more economical to choose equipment $j$ operation in a scale larger than $S^*$); $C_{f,i}$ and $C_{f,j}$ represent the fixed cost of $i$ and $j$ technologies or equipment (CNY/(ha. time)); $C_{v,i}$ and $C_{v,j}$ represent the variable cost of $i$ and $j$ technologies or equipment (CNY/(ha. time)).

2.1.2. Sensitivity Analysis

Sensitivity analysis refers to analyzing the degree of influence and sensitivity of this variable on economic evaluation indicators by considering changes in one factor, while the factors remain relatively independent and other factors remain constant [38]. If a certain factor changes in a small range, the research results change in a large range. This shows that these factors are key factors and should be taken into account when making decisions. If a factor changes in a large range, the research results change in a small range. This shows that these factors are not key factors and should not be considered first in decision making. Through sensitivity analysis, we studied the influence of changes in the cost of fixed equipment, maintenance, operation efficiency, labor, the supporting software system, water, electricity, and fertilizer and pesticides on the critical planting size of different management methods of the cotton field, which is expressed by $p$.

$$p = \frac{S^*_{(+20\%)}}{S^*}$$

(6)
2.2. Data Source

The geographical area considered in this study is the province of Xinjiang, more specifically the Korla (41°45'20.24" N, 86°8'51.16" E) area (Figure 1), where cotton production is concentrated. The data used for the study were collected from traditional corporate farm A, traditional individual farm B and digital corporate farm X, in 2021. These three cotton fields contained the current management method in Xinjiang. The managers of traditional corporate farm A and traditional individual farm B had many years of experience in cotton farming and a detailed mastery of all aspects of cotton production. They provided data with a certain degree of professionalism and representativeness. Super Cotton Field was China’s first application of the digital management of cotton fields; its data had a certain typicality and representativeness. The Super Cotton Field was a project that managed cotton fields by using the digital equipment and data services provided by X enterprise. They were responsible for 200 ha of cotton field plowing, sowing, management and harvesting links. Through unmanned equipment, robots, IoT equipment, artificial intelligence and other technologies, they achieved scientific production planning, and accurate and efficient production operations. Because the current cotton production of plowing, sowing and harvesting links are mechanized at a higher level, this paper focuses on the field management link for analysis.

![Figure 1. Survey areas in China (created by the authors using Gaode Maps).](image-url)

To ensure the accuracy of the research data, questionnaires and data forms were designed and detailed interviews were recorded face-to-face with cotton field managers. The data were returned and verified with the accountant, enterprise manager, and farmers around the cotton fields. We repeatedly verified this information to ensure that the basic parameters were as accurate as possible.

According to the available literature and research, the cotton field management process included 4 parts: field scouting, plant protection, topping and irrigation. Unlike the traditional labor-based management of cotton fields, the digital management method was managed through a combination of automated equipment and agricultural AI technology. In the digital management process, by pairing it with the use of smart agriculture systems, we can have precise information on the farm. This made possible the automatic sensing, unmanned collection, automatic analysis and execution of farm data, which enabled the use of digital technology in agriculture.

In the field scouting segment, skilled agricultural workers and long-time agricultural workers were employed to scout the fields in the traditional method. The skilled agricultural workers were responsible for controlling the quality of the cotton. The long-time agricultural workers were responsible for the environmental, pest and weed monitoring, and a series of specific tasks in the cotton field during the growth process. However, all of those jobs were carried out by remote sensing drones and agricultural IoT equipment in the digital method. The high-definition maps and AI prescription maps of the cotton fields were taken by remote sensing drones. Then, the images, and the meteorological and soil
Agricultural IoT equipment

- **Smart agriculture system**
  - Function: Sensory flight (smart identification), decision making (planting plan, traceability: view operation records/problems), execution (generate tasks to send to drones, self-pilot devices, irrigation systems, etc.)
  - Advantage: This is conducive to improving the quality and management efficiency of cotton field management and precise operation to effectively reduce costs [40].

- **Agricultural smart camera**
  - Function: Monitoring crop growth, remote crop management
    - Accurate measurement of meteorological elements such as air pressure, temperature, humidity, light, rainfall, wind speed and wind direction
  - Advantage: This improves data accuracy and accessibility and reduces human capital investment [41].

- **Agricultural weather stations**
  - Function: Monitoring soil temperature, water content, conductivity

- **Soil monitor**
  - Function: Monitoring soil temperature, water content, conductivity

- **Remote sensing drone**
  - Function: Intelligent identification of plot boundaries, generation of multispectral images to monitor pests and weeds
  - Advantage: This improves the efficiency of cotton field operations and saves a lot of labor [42].

- **Agricultural drone**
  - Function: Spraying pesticides, defoliants, chemical weed control, etc.
  - Advantage: This improves the utilization rate and operational efficiency of pesticides and saves a lot of labor [43].

- **Automatic water and fertilizer irrigation system**
  - Function: Irrigation water and fertilizer
  - Advantage: This improves the utilization of resources such as water and electricity, reduces the waste of fertilizers and saves a lot of labor [44].
Figure 2. Agricultural equipment: (a) Smart agriculture system; (b) Agricultural IoT equipment; (c) Remote sensing drone; and (d) Agricultural drone.

To calculate the critical planting area of digital and traditional methods, we collected parameters related to 4 aspects of the two cotton field management processes: field scouting, plant protection, topping and irrigation. The main data that were collected included equipment purchase costs, maintenance costs, operational efficiency, labor wages, smart agriculture system costs, water costs, electricity costs, fertilizer costs, pesticide costs, operation times and optimal operation days [32]. We set the life cycle of the equipment to 3 years, with a zero salvage value and an annual maintenance cost of 2% of the purchase price of the machinery. Since the automated water and fertilizer irrigation system was a new type of equipment, there were no perfect related products on the market for electric valves. The failure rate was high, and the annual maintenance cost was 5% of the equipment purchase price. Especially considering the short life cycle of the equipment, the time cost of capital was ignored in order to simplify the calculation. At the same time, the pricing model of the smart agriculture system was based on the area and time of use. It was known that its first year price was (165 + 300,000/S) CNY. Where S represented the area of cotton field. The system also played a role in the sensory flight, decision making and execution stages of the cotton production process. Therefore, it was assumed that the cost of the smart agriculture system in field scouting and irrigation was 0.3 of the total cost of the smart agriculture system, respectively. The collected data were organized as shown in Table 2.
Table 2. Operational cost parameters for cotton field management.

<table>
<thead>
<tr>
<th>Management Link</th>
<th>Operation Method</th>
<th>Equipment Purchase Cost/(CNY/unit)</th>
<th>Equipment Cost/(CNY/Year)</th>
<th>Maintenance Cost/(CNY/Year)</th>
<th>Purchase Agricultural Machinery Service cost/(CNY/m²)</th>
<th>Crop Damage from Mechanical Operations/(CNY/ha)</th>
<th>Operation Efficiency/ha/(Unit. Day)</th>
<th>Labor Wage/(CNY/ha)</th>
<th>Smart Agriculture System Cost/(CNY/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field scouting</td>
<td>Traditional method</td>
<td>Manual work</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Super Cotton Field</td>
<td>Remote sensing drone</td>
<td>17,000.00</td>
<td>5666.67</td>
<td>340.00</td>
<td>-</td>
<td>-</td>
<td>320.00</td>
<td>15.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IoT equipment</td>
<td>900.00 CNY/ha</td>
<td>300.00 CNY/(ha.year)</td>
<td>18.00 CNY/(ha.year)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Plant protection</td>
<td>Traditional method</td>
<td>Tractor</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>60.00</td>
<td>312.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Super Cotton Field</td>
<td>Agricultural drone</td>
<td>60,000.00</td>
<td>20,000.00</td>
<td>1200.00</td>
<td>-</td>
<td>-</td>
<td>32.00</td>
<td>45.00</td>
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<td>-</td>
<td>90.00</td>
<td>-</td>
<td>-</td>
<td>32.00</td>
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<td>Traditional method</td>
<td>Manual work</td>
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<td>-</td>
<td>-</td>
<td>750.00</td>
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<td></td>
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<td>Agricultural drone</td>
<td>60,000.00</td>
<td>20,000.00</td>
<td>1200.00</td>
<td>-</td>
<td>-</td>
<td>32.00</td>
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<td>-</td>
<td>90.00</td>
<td>-</td>
<td>-</td>
<td>32.00</td>
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<tr>
<td>Irrigation</td>
<td>Traditional method</td>
<td>Traditional water and fertilizer irrigation system</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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<tr>
<td></td>
<td></td>
<td>Automatic water and fertilizer irrigation system</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>130,000.00</td>
<td>43,333.33</td>
<td>2600.00</td>
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<td></td>
<td>Super Cotton Field</td>
<td>Electric valve</td>
<td>3150.00 CNY/ha</td>
<td>1050.00 CNY/(ha.year)</td>
<td>157.50 CNY/(ha.year)</td>
<td>-</td>
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<tr>
<td>Field scouting</td>
<td>Traditional method</td>
<td>Manual work</td>
<td>-</td>
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<td>-</td>
<td>-</td>
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<td></td>
<td>Super Cotton Field</td>
<td>Remote sensing drone</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>42.00</td>
<td>2.00</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Agricultural IoT equipment</td>
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<td>Plant protection</td>
<td>Traditional method</td>
<td>Tractor</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>120.00</td>
<td>10.00</td>
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<tr>
<td></td>
<td>Super Cotton Field</td>
<td>Agricultural drone</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>75.00</td>
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<td>Purchasing machinery</td>
<td>Manual work</td>
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<td>-</td>
<td>-</td>
<td>75.00</td>
<td>9.00</td>
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<tr>
<td></td>
<td></td>
<td>Agricultural drone</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>75.00</td>
<td>9.00</td>
<td></td>
</tr>
<tr>
<td>Topping</td>
<td>Traditional method</td>
<td>Tractor</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>300.00</td>
<td>1.00</td>
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</tr>
<tr>
<td></td>
<td>Super Cotton Field</td>
<td>Agricultural drone</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>300.00</td>
<td>1.00</td>
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<tr>
<td></td>
<td>Purchasing machinery</td>
<td>Manual work</td>
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<tr>
<td></td>
<td></td>
<td>Agricultural drone</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
<td>Traditional method</td>
<td>Traditional water and fertilizer irrigation system</td>
<td>1200.00</td>
<td>3750.00</td>
<td>1200.00</td>
<td>5250.00</td>
<td>-</td>
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<td></td>
<td>Super Cotton Field</td>
<td>Automatic water and fertilizer irrigation system</td>
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<td>2610.00</td>
<td>375.00</td>
<td>4995.00</td>
<td>-</td>
<td>10.00</td>
<td></td>
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</tbody>
</table>

Note: The “S” in smart agriculture system cost represents the area of cotton field.
3. Results

3.1. Cost–Benefit Analysis Results

In the study of the cotton field management segment, according to the cost parameters in Table 2 of the different operations in the cotton field. We analyzed the economic advantages of a digital operation and a traditional operation, and the economic advantages of purchasing agricultural machinery and agricultural machinery services. According to Equations (1)–(5), we calculated and compared the average total fixed cost, average total variable cost, minimum average cost, critical size and average cost saving for a year of smart equipment operation, instead of the traditional equipment operation. We also calculated the critical size and average cost saving of purchasing agricultural equipment instead of purchasing agricultural machinery services in each section of the cotton field. The results are shown in Tables 3–5. In this case, the minimum average cost was the average cost of the maximum operating scale of a piece of equipment during the optimal operation time. In particular, it was noted that agricultural drones can be used in both plant protection and topping segments, in which plant protection and topping were not carried out at the same time. Therefore, we increased the combination of plant protection and topping segments.

Table 3. The results of the evaluation of the economics of the Super Cotton Field X management link and the traditional management link operation.

<table>
<thead>
<tr>
<th>Management Link</th>
<th>Operation Method</th>
<th>Fixed Cost/(CNY/Year)</th>
<th>Variable Cost/(CNY/ha)</th>
<th>Lowest Average Cost/(CNY/ha)</th>
<th>Critical Size/(ha)</th>
<th>Average Cost Saving/(CNY/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field scouting</td>
<td>Manual work</td>
<td>-</td>
<td>2250.00</td>
<td>2250.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Remote sensing drone and agricultural IoT equipment</td>
<td>6006.67</td>
<td>997.50 + 90,000/S</td>
<td>1065.75</td>
<td>9.59</td>
<td>1184.25</td>
</tr>
<tr>
<td></td>
<td>Purchase tractor service</td>
<td>-</td>
<td>2112.00</td>
<td>2112.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Plant protection</td>
<td>Purchase agricultural drone service</td>
<td>-</td>
<td>1485.00</td>
<td>1485.00</td>
<td>0.00</td>
<td>627.00</td>
</tr>
<tr>
<td></td>
<td>Manual work</td>
<td>-</td>
<td>750.00</td>
<td>750.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Purchase agricultural drone service</td>
<td>-</td>
<td>390.00</td>
<td>390.00</td>
<td>0.00</td>
<td>360.00</td>
</tr>
<tr>
<td>Topping</td>
<td>Traditional water and fertilizer irrigation system</td>
<td>-</td>
<td>12,900.00</td>
<td>12,900.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Automatic water and fertilizer irrigation system</td>
<td>45,933.33</td>
<td>11,127.00 + 90,000/S</td>
<td>11,646.30</td>
<td>29.29</td>
<td>1253.70</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Traditional method</td>
<td>-</td>
<td>2862.00</td>
<td>2862.00</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: The “S” in variable cost represents the area of cotton field.

Table 4. The results of the economic evaluation of the traditional operation and purchase of agricultural drones for plant protection and topping operations.

<table>
<thead>
<tr>
<th>Management Link</th>
<th>Operation Method</th>
<th>Fixed Cost/(CNY/Year)</th>
<th>Variable Cost/(CNY/ha)</th>
<th>Lowest Average Cost/(CNY/ha)</th>
<th>Critical Size/(ha)</th>
<th>Average Cost Saving/(CNY/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant protection</td>
<td>Purchase tractor service</td>
<td>-</td>
<td>2112.00</td>
<td>2112.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Purchase agricultural drone</td>
<td>21,200.00</td>
<td>1080.00</td>
<td>1411.20</td>
<td>20.54</td>
<td>700.80</td>
</tr>
<tr>
<td></td>
<td>Manual work</td>
<td>-</td>
<td>750.00</td>
<td>750.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Purchase agricultural drone</td>
<td>21,200.00</td>
<td>345.00</td>
<td>565.80</td>
<td>52.35</td>
<td>184.20</td>
</tr>
<tr>
<td>Topping</td>
<td>Traditional method</td>
<td>-</td>
<td>2862.00</td>
<td>2862.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Purchase agricultural drone</td>
<td>21,200.00</td>
<td>1425.00</td>
<td>1756.20</td>
<td>14.75</td>
<td>1105.80</td>
</tr>
</tbody>
</table>
Table 5. The results of the economic evaluation of the purchase of agricultural drone services and the purchase of agricultural drones for the operation of plant protection and topping.

<table>
<thead>
<tr>
<th>Management Link</th>
<th>Operation Method</th>
<th>Fixed Cost/(CNY/Year)</th>
<th>Variable Cost/(CNY/ha)</th>
<th>Lowest Average Cost/(CNY/ha)</th>
<th>Critical Size/(ha)</th>
<th>Average Cost Saving/(CNY/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant protection</td>
<td>Purchase agricultural drone service</td>
<td>-</td>
<td>1485.00</td>
<td>1485.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Purchase agricultural drone</td>
<td>21,200.00</td>
<td>1080.00</td>
<td>1411.20</td>
<td>52.35</td>
<td>73.80</td>
</tr>
<tr>
<td>Topping</td>
<td>Purchase agricultural drone service</td>
<td>-</td>
<td>390.00</td>
<td>390.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Purchase agricultural drone</td>
<td>21,200.00</td>
<td>345.00</td>
<td>565.80</td>
<td>0.00</td>
<td>-175.80</td>
</tr>
<tr>
<td>Plant protection and topping combinations</td>
<td>Purchase agricultural drone service</td>
<td>-</td>
<td>1875.00</td>
<td>1756.20</td>
<td>47.11</td>
<td>118.80</td>
</tr>
<tr>
<td></td>
<td>Purchase agricultural drone</td>
<td>21,200.00</td>
<td>1425.00</td>
<td>1756.20</td>
<td>47.11</td>
<td>118.80</td>
</tr>
</tbody>
</table>

According to Tables 3–5 we can see that:

In the field scouting segment, we used remote sensing drones and agricultural IOT equipment to scout the fields. This is more economical than manual scouting. The lowest average cost of remote sensing drones and agricultural IOT equipment is 1065.75 CNY/ha, which saves 1184.25 CNY/ha compared to the cost of manual field scouting. Therefore, remote sensing drones and agricultural IOT equipment are more cost-effective than manual field scouting when the planting size exceeds 9.59 ha. It can be seen that the use of smart equipment will significantly reduce production costs by saving a large amount of labor. With the lower cost of smart equipment, a smaller land size could achieve an economy of production for farmers. As the scale of land operations increases, the more obvious it becomes for farmers to produce economically.

In the plant protection segment, the economy of purchasing agricultural drone services for plant protection is always higher than the economy of purchasing tractor services for plant protection. The lowest average cost of purchasing agricultural drone services is 627.00 CNY/ha lower than the lowest cost of purchasing tractor services. At the same time, when farmers’ planting size exceeds 20.54 ha, the cost of directly purchasing agricultural drones for plant protection is 700.80 CNY/ha lower than the cost of purchasing tractor services. When farmers’ planting size exceeds 52.35 ha, the cost of directly purchasing agricultural drones for plant protection is 73.80 CNY/ha lower than the cost of purchasing agricultural drone services.

In the topping segment, the economy of purchasing agricultural drone services for topping is always higher than the economy of manual topping. The cost for farmers to purchase agricultural drone services is 360 CNY/ha less than the cost of manual topping. Meanwhile, when farmers’ planting size exceeds 52.35 ha, the cost of directly purchasing agricultural drones for topping is 184.20 CNY/ha lower than the cost of manual topping. However, the cost of directly purchasing agricultural drones for topping alone is always higher than the cost of directly purchasing agricultural drone services for topping.

In fact, the same agricultural drone can be used for both plant protection and topping. If we do not consider the optimal operation time when the planting size is larger than 14.75 ha, it is more cost-effective to purchase an agricultural drone operation than traditional tractor operation and manual operation, saving 1105.80 CNY/ha. When the planting size is larger than 47.11 ha, it is more economical to purchase an agricultural drone operation than agricultural drone service operation, saving 118.80 CNY/ha. If the optimal operation days for the agricultural drone is 2 days, then the maximum operating size of agricultural drones is 64 ha. Among them, the traditional method of operation is not limited by the maximum operating size. As can be seen from Figure 3, the cost of purchasing agricultural drone services is always lower than the cost of operating by traditional methods. When the average cost of traditional operation methods is lower than the average cost of purchasing...
agricultural drones, the planting size is 14.75 ha. When the average cost of purchasing agricultural drone services is lower than the average cost of purchasing agricultural drones, the minimum planting size is 47.11 ha. If the planting size is larger than 64 ha, the farmer needs to purchase another agricultural drone, but then the average cost is higher than the cost of purchasing agricultural drone services. In this instance, farmers should buy agricultural drone services to make up for this, rather than buying more agricultural drones. If the planting size reaches 94.22 ha, the farmer should purchase an agricultural drone operation according to the actual planting size.

**Figure 3.** Effect of planting size on the average cost of plant protection and topping.

In the irrigation segment, an automated water and fertilizer irrigation system can irrigate up to 100 ha of land, and one electric valve controls an average of 0.67–1 ha of land. Consequently, automated water and fertilizer irrigation systems have a high cost, while traditional water and fertilizer irrigation systems have a relatively low cost. From the calculation, when the farmer’s planting size is greater than 29.29 ha, the economy of the automated water and fertilizer irrigation system shown in Figure 4 is always greater than that of traditional water and fertilizer management systems, saving 1253.70 CNY/ha. However, the application of automated water and fertilizer system is based on high-standard farmland. If we include the drip irrigation cost of 15,000 CNY/ha invested by the government for the renovation of high-standard farmland, the cost of automated water and fertilizer irrigation is much larger than that of traditional water and fertilizer irrigation systems.

**Figure 4.** Effect of planting size on the average cost of water and fertilizer irrigation.
In general, with the improvement in agricultural digitalization, although there are some fluctuations in the average cost of various aspects of the cotton field management process, the general trend in the average cost is declining. Digitization of agriculture provides efficient and accurate data on crop growth and environmental conditions. Through the application of unmanned technology, scientific production planning, and precise and efficient farming execution can be realized. At the same time, this reduces a large amount of input resources such as labor, water, fertilizer and pesticides. Digital development in agriculture not only improves agricultural production and productivity but also reduces production costs and increases farmers’ income.

3.2. Sensitivity Analysis Results

According to the sensitivity analysis, the eight influencing factors of fixed cost, variable cost, labor wage, wage for farm machinery operator, smart agriculture system cost, water cost, electricity cost, and fertilizer and pesticide cost were increased by 20%, and the degree of change in the critical planting size of a smart equipment operation instead of a traditional operation was calculated, as shown in Table 6.

<table>
<thead>
<tr>
<th>Operation Method</th>
<th>Fixed Equipment Cost</th>
<th>Variable Equipment Cost</th>
<th>Labor Wage</th>
<th>Wages for Farm Machinery Operators</th>
<th>Smart Agriculture System</th>
<th>Water Cost</th>
<th>Electricity Cost</th>
<th>Fertilizer and Pesticide Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital field scouting</td>
<td>10.01</td>
<td>5.35</td>
<td>−26.43</td>
<td>11.19</td>
<td>10.87</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Purchase agricultural drone for plant protection</td>
<td>20.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.15</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>−2.66</td>
</tr>
<tr>
<td>Purchase agricultural drone for topping</td>
<td>20.00</td>
<td>0.00</td>
<td>−27.03</td>
<td>2.27</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>17.39</td>
</tr>
<tr>
<td>Purchase agricultural drone for plant protection and topping</td>
<td>20.00</td>
<td>0.00</td>
<td>−9.45</td>
<td>6.68</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>−3.04</td>
</tr>
<tr>
<td>Automatic water and fertilizer irrigation system</td>
<td>17.69</td>
<td>15.77</td>
<td>−10.59</td>
<td>0.00</td>
<td>2.89</td>
<td>−11.39</td>
<td>−8.51</td>
<td>−2.80</td>
</tr>
</tbody>
</table>

Fixed equipment costs are the main factor in whether the digital method is economical to replace the traditional method. However, the impact of variable equipment costs on the critical scale cannot be ignored. When fixed equipment costs increase by 20%, the critical planting size increases by more than 10%. When variable equipment costs increase by 20%, the critical planting size increases by more than 5%. The higher the cost of digital equipment, the larger the critical planting size for the digital management method. In the future, with the development of science and technology and the cost of digital equipment continuing to reduce, it will be possible for small-scale land operators to achieve digital management of cotton fields.

Labor wages are a major factor in whether the digital method is an economical alternative to the traditional method. When labor wages increase by 20%, the critical planting size reduction is greater than 9%. The higher the labor wages, the higher the cost of traditional operation methods and the smaller the critical planting size for the digital method. In the future, as the cost of agricultural labor increases, more farmers will choose digital management methods to manage their land.

Water costs are also an important factor in whether the digital method is an economical alternative to the traditional method. In the irrigation segment, when the cost of water increases by 20%, the critical planting size decreases by 11.39%. Where there is water, there is agriculture. The conservation of water resources is of great importance for the protection of the ecological environment and the economics of cotton fields. In the future, water will
be a scarce resource. As the price of water increases, farmers will be more willing to adopt digital management equipment to improve water utilization and reduce production costs.

To some extent, electricity costs have a greater impact on the digital method versus the traditional method. In the irrigation segment, when the cost of electricity increases by 20%, the critical planting size decreases by 8.51%. Furthermore, cotton fields can reduce electricity by approximately 70% by using automated water and fertilizer systems for irrigation. In fact, the current electricity supply is still mainly generated by thermal power, and the effective use of electricity resources can reduce the tension of energy required for power generation, thus improving the social economy. As people pay more attention to electricity resources in the future, more farmers will choose to use energy-saving and environmentally friendly methods for agricultural production.

To some extent, wages for farm machinery operators have an impact on the digital method instead of the traditional method. When the wage for farm machinery operators increases by 20%, the critical planting size increases by about 5%.

The impact of fertilizer and pesticide costs on the critical planting size cannot be ignored either. Although the use of pesticides and fertilizers can increase the yield of cotton under certain circumstances, the excessive use of pesticides and fertilizers not only decreases the yield of cotton but also causes pollution to the ecological environment. In the future, green agriculture will be an important direction for the development of various countries. The application of digital technology not only realizes the precise operation of agriculture but also improves the utilization rate of pesticides and fertilizers. Therefore, it is beneficial to reduce the cost of agricultural production.

The cost of smart agriculture systems has an impact on the economics of the digital method, as an alternative to the traditional method. When the cost of smart agriculture systems increases by 20%, the critical planting size increases by 2% to 10%. However, as the cost of agricultural software development decreases in the future, more farmers will choose to purchase smart management systems to manage their agriculture.

In summary, it can be seen that fixed equipment costs, labor wages, water costs and electricity costs have a large impact on the critical planting size of cotton fields. Variable equipment costs, mechanic wages, agriculture system costs and wages for farm machinery operators also have an impact on the critical planting size of cotton fields. In the future, we will face problems such as an increasing aging population, a shortage of agricultural labor, a deteriorating ecological environment and a shortage of resources. In the presence of rising human and natural capital costs, farmers can use digital equipment to replace manual management of cotton fields at a lower critical scale. This can effectively reduce production costs and improve the economics of cotton fields.

4. Discussion

This paper analyzed the economic advantages of digital management, mainly from a theoretical cost perspective. In fact, digital management methods could be effective in achieving increased agricultural production and income, which contributes to the development of agriculture in the world [45]. Unlike traditional management decisions that rely on experience, digital management improved the monitoring accuracy of cotton and provided effective solutions [46]. Among them, IoT equipment and agricultural drones were two of the most important technologies to transform traditional agriculture into digital agriculture [47]. Remote sensing drones were less costly and time-consuming than manual labor for the field scouting. Agricultural IoT equipment can collect agricultural production information more accurately and comprehensively. This contributed to the systematic popularization of the agricultural farming experience. Otherwise, optimizing the data collection helped to minimize operating costs and maximize agricultural profits [48]. Agricultural drones were beneficial for improving the quality of pesticide sprays, reducing the number of pesticides and amount of water used, increasing the utilization rate of pesticides and fertilizers [49,50] and reducing the harm of pesticides to operators. Automated water
and fertilizer irrigation systems improved the reliability and accuracy of irrigation and fertilization, and had the advantages of saving water, fertilizer and labor [51,52].

In addition, digital management also had the advantage of social and ecological benefits. The application and development of digital technology have brought smart equipment into farmland to solve the problem of the agricultural labor shortage. It also realized the traceability of agricultural production. This ensured the quality and safety of agricultural products. The development of agricultural technology not only created new agricultural employment opportunities but also promoted the cultivation of new agricultural business models. At the same time, in the agricultural production process, it reduced water consumption, pesticide used and agricultural equipment carbon emissions, and promoted ecological sustainability. Therefore, the digital management of cotton fields in the future is an inevitable trend. We should vigorously develop agricultural technology, reduce the cost of equipment and improve the level of agricultural digitalization.

In this study, we focused on the feasibility of the digital method in improving the economic benefits of cotton production. The comparisons were obtained by calculating the cost of cotton fields with traditional and digital methods. This paper presents a cost analysis of three typical cotton field production operations in Xinjiang, China, as an example. By using a cost–benefit analysis and sensitivity analysis, we can see that, when the farmers’ planting area reaches a certain scale, the digital management of each link is less costly than traditional management. The critical planting scale was positively influenced by the cost of equipment, the wage for farm machinery operators and the smart agriculture system cost. On the contrary, the critical planting scale was negatively influenced by the labor wage, water cost and electricity cost. Fertilizer and pesticide cost has different impacts on the critical planting scale in different management links. The acquisition of these data provides some reference value for the study of the digital management of cotton fields. In particular, it provides some data support and experience for the cost acquisition of cotton fields in the coming year.

However, there are several limitations to this research. First, cotton cultivation is a complex production project and any unnoticed factors may affect production costs. In particular, with the improvement of high-standard farmland construction in China, more cost influencing factors can be added to better evaluate the economics of the digital management of cotton fields. Second, with the cost data from the first digital cotton field management in China for analysis, the technology of digital management may not be mature yet. However, with the maturity of digital technology, the cost–benefit of digital management will be more favorable. Last, in Xinjiang, the weather is unpredictable, therefore the weather is a greater uncontrollable factor in the production of cotton. This also poses great limitations and challenges to the digital management of cotton fields.

Therefore, interdisciplinary discussions would also augment the potential value of these findings. This is not an immediate approach and research will continue to be conducted to digitally manage crops to increase profits. Future studies will focus on multi-dimensional analysis in terms of region, environment, crop yield, annualized earnings, etc. I also hope to do some cost analysis on the digital management of other crops. This will help to further reflect the cost difference between traditional management and digital management.

5. Conclusions

The results of a cost–benefit analysis and sensitivity analysis study on cotton fields showed that:

The economics of digital management of cotton fields was optimal when the farmers’ planting area was larger than the critical planting size. We assumed that the equipment was fault-free and at the best operating efficiency during the optimal operation time. The critical planting size was 15.94 ha. We took 200 ha of Super Cotton Field X as an example; the current management method can save 3463.20 CNY/ha for the whole year. However, this value may be greater, as the automated water and fertilizer system is currently in
the experimental stage. At the same time, China’s agricultural labor force population is decreasing; agricultural mechanization and intelligent development are the inevitable trend of future agriculture to solve the problem of having an aging population. However, the current smart agricultural machinery is in its infancy, and digital technology is not widely used. Further cost reductions will be achieved in future market applications.

The main factors affecting the critical planting size of the digital management economy were equipment costs, labor wages, water costs and electricity costs. This meant that the lower the cost of equipment, the higher the cost of labor, water and electricity. Consequently, the smaller the critical planting size of the digital management of cotton fields to replace traditional management, the easier it will be to promote digital management models.

**Author Contributions:** Conceptualization, L.S. and Z.Z.; methodology, L.S., M.Z. and Z.Z.; software, L.S., M.Z. and Z.Z.; validation, W.F., J.G., L.S., M.Z. and Z.Z.; formal analysis, L.S.; investigation, W.F. and L.S.; resources, J.G.; data curation, W.F.; writing—original draft preparation, L.S.; writing—review and editing, M.Z. and Z.Z.; visualization, J.G.; supervision, Z.Z. All authors have read and agreed to the published version of the manuscript.

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**References**


10. Mahan, J.; Payton, P. An agroecentric analysis of regional rain patterns as they relate to a rained cotton cropping system on the Southern High Plains of Texas. *Agriculture 2017*, 7, 93. [CrossRef]


47. Boursianis, A.D.; Papadopoulou, M.S.; Diamantoulakis, P.; Liopa-Tsakalidi, A.; Goudos, S.K. Internet of Things (IoT) and agricultural Unmanned Aerial Vehicles (UAVs) in smart farming: A comprehensive review. Internet Things 2020, 18, 100187. [CrossRef]


